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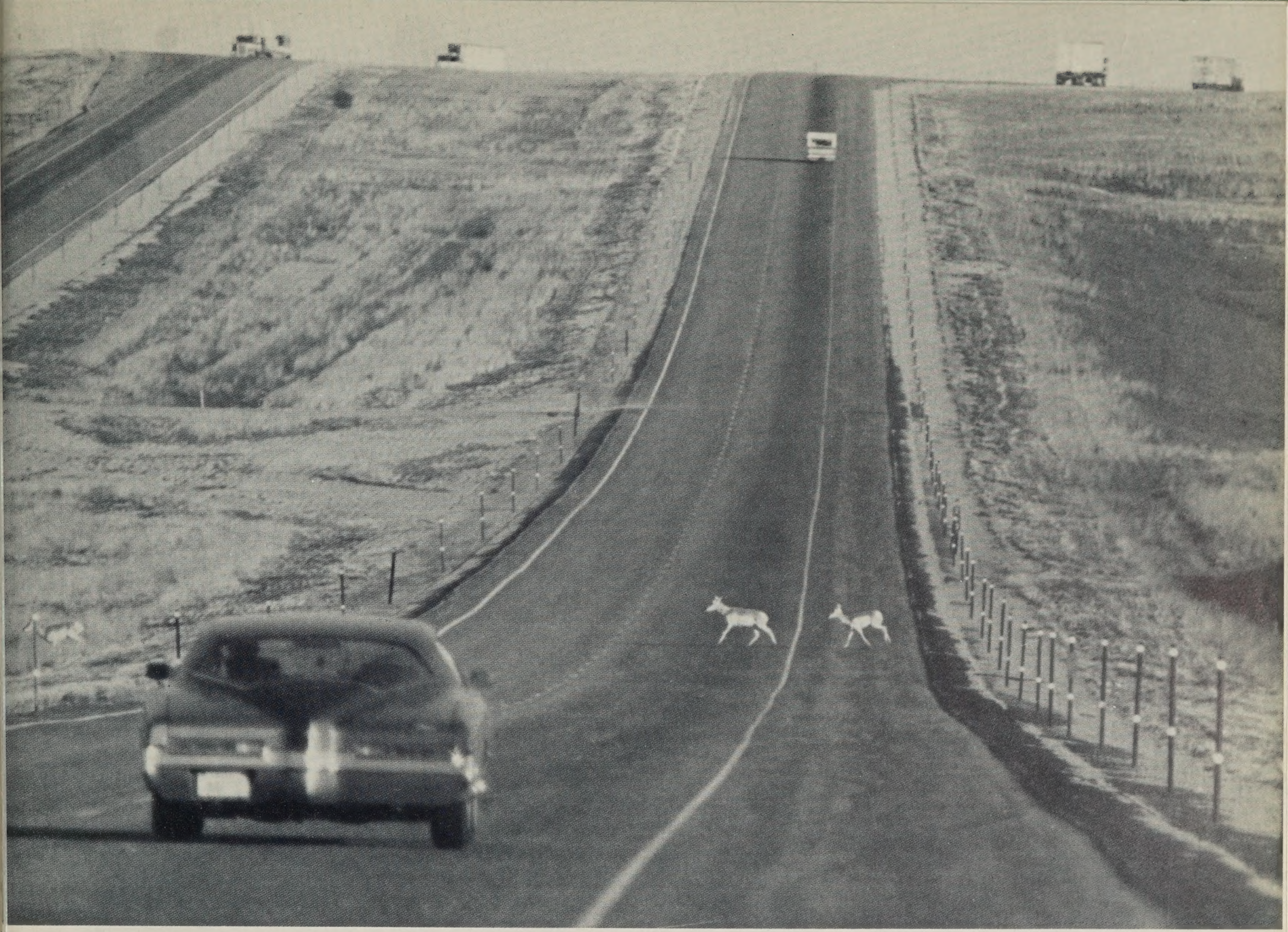

Pronghorn antelope crossing I–80 near Laramie, Wyo.

Highways and the Bioenvironment

by Leonard E. Wood and Douglas L. Smith

In establishing a compatible environment between wildlife and highways, a line must be drawn between bringing natural pleasures within view of the motorist and bringing wildlife so close that they become a hazard to the motorist or are themselves in danger. A number of research programs are addressing the interface between wildlife and the highway environment. Not only are the larger animals such as elk and deer being considered, but small game, birds, and fish are expected to share part of the highway environment. In addition, the biological control of some plant species and the effect of certain herbicides on the environment are under study by the States.

Introduction

Natural wonders abound throughout the United States, and most are accessible by highway. One of the objectives of the Federal Aid Highway Program is to provide the traveler with an uncluttered and pleasant scenic experience. Another objective is to provide vantage points for viewing the physical wonders of the terrain, the seasonal beauty of vegetation, and even an occasional glimpse of deer, elk, birds, and other wild animals. A line must be drawn, however, between bringing such natural pleasures within view of the driver and bringing them so close that they become a hazard to either the motorist or the wildlife.

The Environmental Design and Control Division, Office of Research, Federal Highway Administration (FHWA), and other highway and wildlife agencies are conducting a number of research studies of problems associated with the interface between highway operation and the bio and physical environment. The interface covers the full spectrum of the environment. Efforts include: establishing vegetation compatible with the environment, minimizing the conflict between wildlife and highway operation, negating the effect of water on the highway system and the highway system on water, and reducing the effects of noise and air pollution. Although for the most part wildlife tacitly and invisibly represent the highway bioenvironment, their presence is felt in many ways and must be protected. This article focuses on some of the research being conducted under the Federally Coordinated Program of Research and Development in Highway Transportation (FCP) to maintain a stable highway bioenvironment. Included are studies of large game, small animals, pests and herbicides, and fish.

Figure 1.—Mule deer bucks jump right-of-way fences with ease.

Research Program on Migratory Animals Versus the Highway

One of the more obvious conflicts between the motorist and the environment is the attraction of highways to large game, particularly deer and elk. More than 125,000 white-tail deer *(Odocoileus virginianus)* are killed annually on our Nation's highways. In Pennsylvania alone, some 30,000 white-tail deer are killed each year. There are a number of reasons why these animals wander onto the highways. They may be attracted to the vegetation along the highway right-of-way. In some localities they have a taste for the salt used in deicing road surfaces. In many places, highways cut traditional migration routes that the animals use to move between winter and summer feeding ranges.

In response to the problem, the FHWA is supporting a major wildlife study aimed at developing a better understanding of the effects of highway operation on several species of large animals. The study is being conducted through the FHWA Administrative Contract program by the U.S. Forest Service in Wyoming. Its objective is to investigate the impact of Interstate 80 on the migratory habits and patterns of elk *(Cervus canadensis)*, mule deer *(Odocoileus hemionus)*, and pronghorn antelope *(Antilocapra americana)*. Forest Service researchers are monitoring the movements of these animals to determine if they cross the highway, where they cross, how often they cross, and if they really need to cross. The animals are trapped unharmed in large cages or corrals where brightly colored collars equipped with radio transmitters are placed around their necks. By monitoring the transmitted signals, the researchers can locate the animals and ascertain their movements. By monitoring the movement of a few animals, the activity of the entire herd can be determined. The Wyoming research is also providing an insight into the reaction of these animals to highway operation and human activities. For example, elk normally will not approach closer than one-half mile to most human activity such as logging and camping. They will bed down, however, within 100 yards of a busy Interstate highway as long as the vehicles do not stop. Should a vehicle stop, the elk will move.

The Colorado Game, Fish, and Parks Division is working in cooperation with the highway departments of Colorado, Idaho, Nevada, Oregon, and Wyoming in a jointly funded Highway Planning and Research (HP&R) study designed to evaluate various methods of reducing deer-auto collisions. Some of the methods being studied include the use of deer-proof fences, one-way deer gates, overpasses and underpasses, improved highway lighting techniques, and design variations of the basic cattle guard. Because of the interrelationship between this study and the study in Wyoming, close coordination is being

Figure 2.—A one-way deer gate is tested by a doe mule deer.

maintained between the Colorado and U.S. Forest Service researchers.

Results of the Colorado study show that mule deer are reluctant to pass through an enclosed underpass or box culvert which appears confining and emits hollow sounds. They will pass through the underpass but not before they thoroughly investigate it. This has been documented by use of a closed circuit video camera at the entrance of a box culvert approximately 100 ft (30.5 m) long and 10 ft (3.0 m) square in the vicinity of Vail, Colo. By using the same technique, researchers have recorded deer using unconfined wooden bridges with little or no hesitation. The study also shows that deer-proof fencing—used in the place of conventional right-of-way fencing—channels the deer into selected underpasses and discourages the access to the highway. This indicates that deer-proof fencing is an effective method of keeping deer off the highways thereby reducing accidents (fig. 1). Along four sections of highway in Colorado, the reduction of the number of deer-vehicle accidents ranged from 59 to 84 percent with the use of deer-proof fencing. There are problems yet to be resolved with underpasses. Hunters sometimes stake out underpasses and the smell of humans is a strong deterrent to deer. Also in winter months snow often fills underpasses for long periods.

One-way deer gates are designed to permit deer to easily retreat from the highway should they penetrate the deer-proof fencing (fig. 2). By placing a gate at right angles to the line of fencing at intervals along the length of the fence, a deer following the fence can easily exit, but finds his route blocked should he attempt to return. In areas where fencing is not practical, such as at on- and off-ramps, researchers are trying to develop guards which will deter deer and not impede traffic. An agile deer has little or no difficulty traversing the standard cattle guard. A number of variations have been tested with little success in discouraging a persistent deer; however, many new design options will be tested.

Highway Impact on Small Game

Not all attention in the highway bioenvironmental research program is directed to large game. Small animals have their place in the bioenvironment, and although not seen as readily as large animals, they too must adapt to environmental changes or move to new ground. There are no conclusive data which measure the long term impact of new highways on small animals. McClure[1] studied small game kills on highways in Nebraska during 1941–1944. Since then numerous other studies have been conducted in local areas in individual States. Kills range from sand lizards and yellow-billed cuckoos to jack rabbits and turtles. It is difficult to extrapolate from one bioenvironmental regime to another and to generalize for all of the United States; however, the number of birds and small game killed on highways is undoubtedly considerable. Data indicate there is a correlation between losses and season and age of victims. That is, experience is a factor in coping with the highway environment, not only in the context of the vegetation, but more importantly with respect to the types and volumes of traffic and certainly the speed of vehicles. There is evidence that animals inexperienced in the approach speed of vehicles and in the judgment of these speeds are more apt to be killed.

It was theorized several years ago that highway wildlife kills would increase substantially with the increasing construction of super highways and faster driving. However, some researchers thought that this would be counteracted somewhat by the greater width and use of concrete and other hard surfaces making the road less attractive to wild animals.

Today the traveler can have the best of both worlds. He has modern highways at his disposal which need not be sterile and unattractive. Through careful right-of-way habitat planning, small game can coexist with the highways. McClure advocates allowing portions of rights-of-way to return to natural vegetation. Expected normal losses of the wildlife population will be replaced each year by

[1] "An Analysis of Animal Victims on Nebraska Highways," by Elliot H. McClure, *The Journal of Wildlife Management*, vol. 15, No. 4, 1951.

animals seeking unclaimed territories. Surviving generations will adapt to the highway environment and stabilization of the animal population can be expected.

A number of States are investigating the interface between highways and wildlife to determine the nature and extent of impacts, to define the degree of impact on various families of wildlife, to determine if the impact is temporary or permanent, and once an impact is established, to develop design, construction, and maintenance techniques that will reduce or eliminate the conflict between highways and wildlife.

Figure 3.—Massive tumble weeds create maintenance and safety problems.

National Small Game Impact Study

Under an FHWA contract the U.S. Fish and Wildlife Service is conducting a research study to evaluate the effect of highway development on wildlife populations and habitats. The study will develop a methodology for inventorying plant and wildlife communities to provide a means of evaluating the potential impacts associated with highway development. In four environmentally representative areas in the United States, data will be drawn from 600 randomly distributed points in approximately 18,000 sample plots. The 3,600 plots which are immediately adjacent to highways will be compared with over 14,000 plots located at varying distances from the roadway. Investigations will include surveys and analyses of breeding and wintering bird populations, reptile and amphibian populations, habitat characteristics, implications of highway management practices, and highway animal mortality. It is anticipated that the application of results from this study will go beyond the highway system. For example, local governments or utility companies can use the results in planning facilities and land use application.

The study will focus on small animals and birds. It is believed that small animals are very sensitive to man's activities and thus can serve as an index to the overall quality of the environment. It should also be possible to test the theory that if given a natural habitat within the right-of-way, wildlife population will stabilize.

State Highway Planning and Research (HP&R) Studies

The State of Maine is currently conducting an HP&R study which is sampling small animal populations as an index to the overall effect of highway construction and operation on wildlife populations. This regionally unique study will complement the larger Fish and Wildlife study being conducted in four other regions in the United States.

A number of other States are conducting wildlife research under the HP&R program in an effort to find solutions to particular problems within their State. West Virginia is completing a study which is looking primarily at the impact of highways on white-tail deer. Michigan is investigating still another facet of the bioenvironment in its study of the Ecological Effects of Highway Construction on Woodlots and Wetlands. Through a detailed examination of vegetation, upland game and waterfowl, water quality and soils, and the growth rate of trees in the highway environment, the study will formulate a logical and systematic basis to adequately explain and/or mediate controversy related to highway impact on woodlot and freshwater wetland areas.

The State of Louisiana is supporting a study which is determining the persistence of the herbicide Monosodium Methanearsenate (MSMA) in soils and waterways, and its translocation in vegetation. Two diverse animal and plant species which are economically important to the State—crayfish *(Procambarus spp)* and black berries *(Rubus spp)*—are being studied for MSMA uptake and retention, both in the highway environment and under controlled experiments in the laboratory.

As a further means of reducing the potential impact of herbicides, California is supporting two studies. One of the studies is investigating the use of nonchemical means of pest control,

Figure 4.—Single spans protect sensitive aquatic environment.

while the other is evaluating the effectiveness of several insects in the biological control of Russian thistle *(Salsola kali),* more commonly known as tumble weed (fig. 3). Both studies are investigating methods of controlling insect and plant species which have been introduced into the United States and have become pests.

Certain species are not pests in their native area because they have natural enemies which keep them under control. Not all plant and animal pests can be controlled in this manner. In order to employ natural controls, the pest's enemy must be identified; and more importantly, it must be determined that the controlling species can itself be controlled and will not damage beneficial plants or animals. While all pests cannot be controlled by this method, it is a good alternative to the use of chemicals. Although the California studies are unusual in their approach, a larger number of studies are being conducted throughout the States on a broad range of subjects related to vegetation in the highway environment.

Because they are rarely seen in their natural environment, the impact of highways on fish is often overlooked. Montana has completed a study and Arkansas is currently studying the effect of channel relocation on fish and aquatic organisms. The degree to which channel changes affect pH, turbidity, and temperature is related to habitat and feeding changes. By understanding such aquatic sensitivities it will be possible to make channel changes with a minimum of disturbance to the aquatic environment (fig. 4).

Conclusion

The bioenvironment is ubiquitous and ever changing; it may be visible and vocal, or invisible and silent. Impact on the intangible may lead to tangible degradation. To meet the challenge of bringing the highway system and the bioenvironment into compatibility, research must be flexible and dynamic. More importantly, however, researchers, planners, and construction and maintenance engineers must be sensitive to the delicate balance between man and nature. In the words of an old Indian proverb: "Thou shalt not damage the environment unless necessary. If it is necessary, thou shalt limit it and fix it."

The Bridge Deck Problem— An Analysis of Potential Solutions

by Richard E. Hay

The Problem

During the past 5 years there has been an intensive effort by private industry, State highway agencies, and the Federal Highway Administration (FHWA) to solve the bridge deck deterioration problem. As the results of the collective research efforts begin to reach fruition, it is appropriate to take a comprehensive look at the potential advantages and limitations of the various solutions or developments. The National Cooperative Highway Research Program (NCHRP) Synthesis Report No. 4 (*1*)[1] focused our attention on the problem of corrosion. However, freeze-thaw deterioration of bridge decks may also be a problem though in the past it may have been obscured by the earlier deterioration caused by corrosion of reinforcing bars. Therefore, in considering advantages and limitations of solutions to the bridge deck deterioration problem caused by corrosion, their potential for alleviating any possible freeze-thaw problems that may be present must also be considered.

There are two distinct categories of problems: (1) How to construct a new bridge so as to eliminate or control the corrosion caused by salting highways and bridge decks for snow and ice or frost removal, and (2) how to maintain existing bridges in a satisfactory condition. In solving the maintenance problem, the following conditions must be considered: sound decks that are not yet sufficiently contaminated with chloride ion to cause corrosion, sound decks in which corrosion has started or in which there is sufficient chloride ion to support corrosion, and decks that are in various stages of physical deterioration.

Potential Solutions

Potential solutions may be classified into three main groups that will accomplish the following:

[1] Italic numbers in parentheses identify the references on page 147.

Figure 1.—Applying preformed sheet membrane.

Figure 2.—Applying liquid membrane.

- **Keep the salt (chloride ion) out of the concrete.** Proposed techniques for doing this range from the waterproof membranes to impermeable concretes.
- **Keep chloride ion from rebar.** No special effort is made to prevent the chloride ion from getting into the concrete, but it is kept out of contact with reinforcing steel by such methods as barrier coatings on the steel itself or by providing sufficient concrete cover so the chloride ion will not reach the level of the steel.
- **Control corrosion.** This approach also does not prevent the chloride ion from penetrating the concrete, but prevents the potential damage by such methods as cathodic protection of the steel or periodic removal of the chloride ion before it reaches critical levels.

Some of these techniques are inherently more applicable to new construction than to protection or repair of existing bridges while the reverse may be true for others. Also, some procedures will afford protection from deterioration caused by repeated freezing and thawing of the concrete while others may actually aggravate the freeze-thaw deterioration problem if proper attention is not given to the quality of the concrete. Applicability of solutions to bridge deck deterioration is presented in table 1.

Advantages and Limitations of Solutions

Waterproof membranes

Waterproof membranes are presently the most widely used method of protecting new decks from chloride-ion contamination and are extensively used to protect existing decks from further contamination.[2] (*2, 3*) (See figures 1 and 2.) However, there is considerable controversy about the propriety of placing them over

Table 1.—Applicability of solutions to bridge deterioration

Solution	Problem			
	New construction	Existing bridges: No problem	Existing bridges: Sound, but critically contaminated	Existing bridges: Deteriorated
Keep chloride ion out of concrete				
Waterproof membranes	X	X	X[1]	X[2]
Surface polymer impregnation	X	X	X[3]	X[2]
Polymer impregnated concrete (PIC) precast deck panels	X			X[2]
Internally sealed concrete	X	X	X[3]	X[2]
Keep chloride ion from rebar				
Latex modified concrete	X	X	X[3]	X
Epoxy coated rebar	X			X[2]
Three-inch cover	X	X		
Control corrosion				
Galvanized rebar	X			X[2]
Cathodic protection	X	X	X	X[4]
Removal of chloride ion			X	
Deep surface polymer impregnation			X	
Epoxy rebonding				X[5]
Polymer rebonding				X[5]

[1] When chloride ion is first removed below critical level.
[2] When repaired by total removal and replacement.
[3] Used as waterproof membrane when chloride ion is first removed below critical level.
[4] With repair of deteriorated areas.
[5] Unknown value by itself.

[2] "Prevention of Bridge Deck Deterioration," by Russell H. Brink, Report to International Road Federation, 1972.

decks in which active corrosion of the reinforcing steel is taking place. Also, construction and maintenance problems are associated with their use. Consequently, some highway agencies strongly resist the use of membranes and their long term acceptance may be doubtful if other solutions that are competitive from a cost standpoint can be developed.

The greatest long term problem with the use of membranes is that the asphaltic concrete wearing course has a limited life. Since there is a limit to the dead load that can be placed on a bridge, additional layers of wearing course cannot be added indefinitely. This will necessitate the eventual removal of old wearing courses with an attendant removal of the waterproof membrane. Such removal and the subsequent reconstruction under traffic, particularly in high traffic density areas, is very difficult and costly. However, private industry is continually striving to improve the product and may overcome the current construction and durability problems. A distinct advantage of waterproof membranes is they afford freeze-thaw protection to the deck concrete as well as protection against the ingress of chloride ion.

Surface polymer impregnation

Surface polymer impregnation is an emerging solution which would provide the same type of protection as a waterproof membrane. The first full-scale application was made by the Bureau of Reclamation working under contract to the Office of Research, FHWA. (*4*) Since that time at least two other applications have been completed. At its current state of development, surface impregnation is initially more expensive than waterproof membranes. It has the potential, however, to provide lasting protection with one application and to provide a very durable concrete surface from the standpoint of abrasion as well as freeze-thaw durability. A disadvantage is that any cracks which may develop in a deck after treatment may require some maintenance in order to guarantee a salt-free structure. However, the use of surface impregnation to prevent further chloride-ion contamination of an existing deck would greatly minimize the cracking problem.

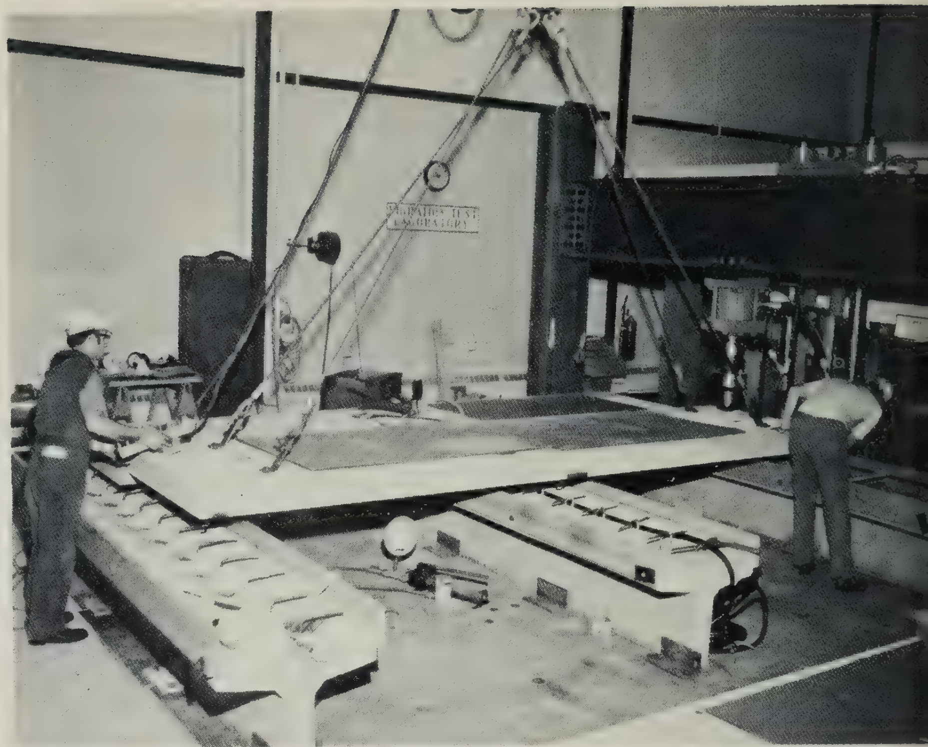

Figure 3.—Structural testing of totally impregnated precast panels.

Totally impregnated precast panels

Totally impregnated precast bridge deck panels are also an emerging solution for new construction or for use on bridges where total replacement of the deck is selected as the method of repair. (*5*) To date no decks have been constructed using such panels. However, a rather extensive laboratory evaluation shows that polymer impregnated concrete (PIC) panels provide a structurally adequate deck (fig. 3). Decks have been constructed using ordinary precast concrete panels. Present estimates indicate that totally impregnated precast panels may not be capable of competing with other possible solutions in normal construction. However, where reconstruction must be done as expeditiously as possible, particularly in urban areas, precast PIC panels may be less expensive than conventional techniques when the cost of traffic control and providing detours is considered.

Internally sealed concrete

Internally sealed concrete (concrete in which the capillary and void system is blocked at numerous points with wax) is the newest approach to providing an impermeable concrete. (*6, 7*) It could be used for new construction, as a waterproof overlay on an existing deck, or as a reconstruction material where complete replacement of critically contaminated concrete is the repair method. This material has the potential to compete costwise with any of the other techniques presently used. The raw wax is relatively inexpensive; there are no apparent problems with mixing it in the concrete; and fusion of the wax can be accomplished with presently available equipment. Like polymer impregnation, a possible disadvantage is that any cracks which occur after fusion of the wax may require some sealing to guarantee a salt-free structure. Sealing may not be necessary, however, as research has shown cracking to be of secondary importance in the initiation of destructive corrosion of reinforcing steel. (*8*) Internally sealed concrete also provides a freeze-thaw resistant deck surface. Barring unforeseen problems, it may well become the most useful solution for new construction.

Latex modified concrete

In the second group of solutions, those that keep chloride ions from coming in contact with the reinforcing steel (table 1), the most widely used approach is latex modified concrete. Some authorities may class it as a waterproof membrane as it is used as such on structural decks of normal portland cement concrete. This material has a relatively long and successful history as a repair material but has only recently been used on new construction. Presently, it is more expensive initially than waterproof membranes. However, it has the advantage of performing more satisfactorily on grades in excess of 4 percent and in areas where the pavement surface is subjected to shearing forces created by rapid changes in the velocity or direction of vehicles. It may also have the advantage of requiring less maintenance. If some of the other potential solutions develop as anticipated, latex modified concrete as presently priced may not be able to compete costwise on new construction. Perhaps its best use in the future will again be in the repair of partially deteriorated decks.

Epoxy resin coated rebars

Epoxy resin coated reinforcing steel has been tested on a significant number of bridges. (*9, 10*) Thus far its cost seems to be highly variable as is the incidence of manufacturing problems. This approach offers an alternative to the bridge designer. It is, of course, viable for only new construction or total reconstruction. A disadvantage is that it does not improve the freeze-thaw durability of the concrete. Consequently, if a quality concrete is not obtained, the value of the coated steel may be lost. A very good application may be in precast units where corrosion protection is required but the use of polymer impregnated concrete or internally sealed concrete is impractical. Also, it may offer some distinct advantages over other approaches in either building or bridge construction in marine environments.

Three-inch concrete cover over steel

An emerging solution is to provide 3 in (76 mm) of clear cover over the reinforcing steel. This is particularly attractive where it is possible to place a low water-cement ratio concrete (0.35 or less) that is highly impermeable to chloride ion.[3] (*11*) However, the number of places where such a concrete can be specified are limited unless special construction equipment or the new water reducers are used. The arbitrary use of thicker cover without specifying the indicated low water-cement ratio concrete and positive control of the degree of consolidation is of very doubtful value.

Galvanized reinforcing steel

In the third group of solutions, those which attempt to control the corrosion or stop it after it is started, the most widely used solution to date is galvanized reinforcing steel. As the zinc, of course, corrodes, the degree of protection this approach provides is presently unknown. There are structures in Bermuda where it apparently is providing satisfactory long term protection. On the other hand, some research data indicate that such long term protection cannot be depended upon. (*12*) Galvanized rebars have been used in a number of bridges but not long enough to determine their ultimate worth. Although the two should not be compared on a direct basis as they are entirely different products, galvanized steel is less expensive than epoxy coated reinforcing steel. Galvanized reinforcing steel, like epoxy resin coated steel, does not improve the freeze-thaw durability of the concrete.

Cathodic protection

Arresting corrosion of reinforcing steel cathodically by impressing a current on the steel through a conductive overlay is perhaps the newest approach that has been received with widespread interest by the highway community. (*13*) This method, of course, could be used on new bridges as well as on those that are already on the highway system. However, based on its cost compared with other potential solutions for new

[3] "Design and Construction of Bridges Which are More Resistant to Deterioration," by Bruce F. McCollom, *State Highway Commission of Kansas*, July 1974.

Figure 4.—Placing conductive overlay around anodes on an existing bridge.

construction, it appears that its best use would be on existing bridges that are critically contaminated with chloride ion (fig. 4) and very difficult to reconstruct. One distinct disadvantage is that the conductive overlay and its attendant wearing course may act as a mulch thereby keeping the deck moist or wet with salt solution. The result could be aggravation of any potential freeze-thaw deterioration problems. Consequently, a careful evaluation of the freeze-thaw durability of the deck should be made prior to application of this method of repair. Such an evaluation on existing decks should include linear traverse measurements of the entrained air void system to determine void size and spacing as well as total air content.

Electro-chemical removal of chlorides

An electro-chemical method for the removal of chloride ion from hardened portland cement concrete has been developed by Battelle under an FHWA research contract. However, at present, it is not known how practical the method will be for field use. Provided the technical problems can be overcome, it could have potential as a method to rehabilitate existing decks that are critically contaminated with chloride ion. If the chloride ion concentration can be reduced to a noncritical level in such decks, then a waterproof membrane or some other treatment such as surface polymer impregnation could be used to permanently protect the deck from further contamination. This would offer another alternative to eventual removal and reconstruction of critically contaminated bridge decks.

Deep polymer impregnation of existing decks

Deep polymer impregnation of existing bridge decks is another laboratory development by Lehigh University under an NCHRP contract. This effort differs from surface polymer impregnation previously discussed as it is directed toward the polymer impregnation of all critically contaminated concrete around the top mat of reinforcing steel, and thereby arrests any corrosion of the steel by cutting off the supply of oxygen and moisture required to support corrosion. This differs from previously discussed surface impregnation which is used only as a method to keep chloride ion out of new or rehabilitated concrete. If the deep impregnation process can be developed into a practical field process, it will offer another solution to the rehabilitation of existing critically contaminated decks.

Rebonding with epoxy resins or polymers

The last two items in table 1 are very similar. They differ only in that epoxy resin rebonding has been used for rebonding delaminated or cracked concrete whereas polymer rebonding has been directed toward the in situ reconstitution of totally deteriorated concrete. Epoxy resin rebonding of delaminated concrete alone may not offer a permanent repair. (*14*) However, when used in conjunction with cathodic protection, it does offer an excellent potential for permanence. Injecting epoxy resin into cracks such as are found in delaminated bridge decks is a practical process, and a number of private firms now specialize in this type of work on a contractual basis. Polymer rebonding of totally disintegrated concrete is not yet a routine field process. (*15*) The technique has been demonstrated to be feasible on a small scale, and a full-scale bridge repair is planned by the New York Department of Transportation (fig. 5). It has the potential to offer a totally new method of repair that would not require removal and replacement of deteriorated bridges with the attendant traffic problems of such repair methods.

Solution Selection

Collective efforts to solve the bridge deck problem have produced many new developments and many refinements of older processes or materials. Many types of problems are often grouped under the heading *bridge deck problem,* and consequently it is fortunate that there are alternative solutions from which to choose. The question then is how to select the best solution for the particular problem. Based on the author's experience as a researcher and as an operating engineer, he has given his intuitive selection for the

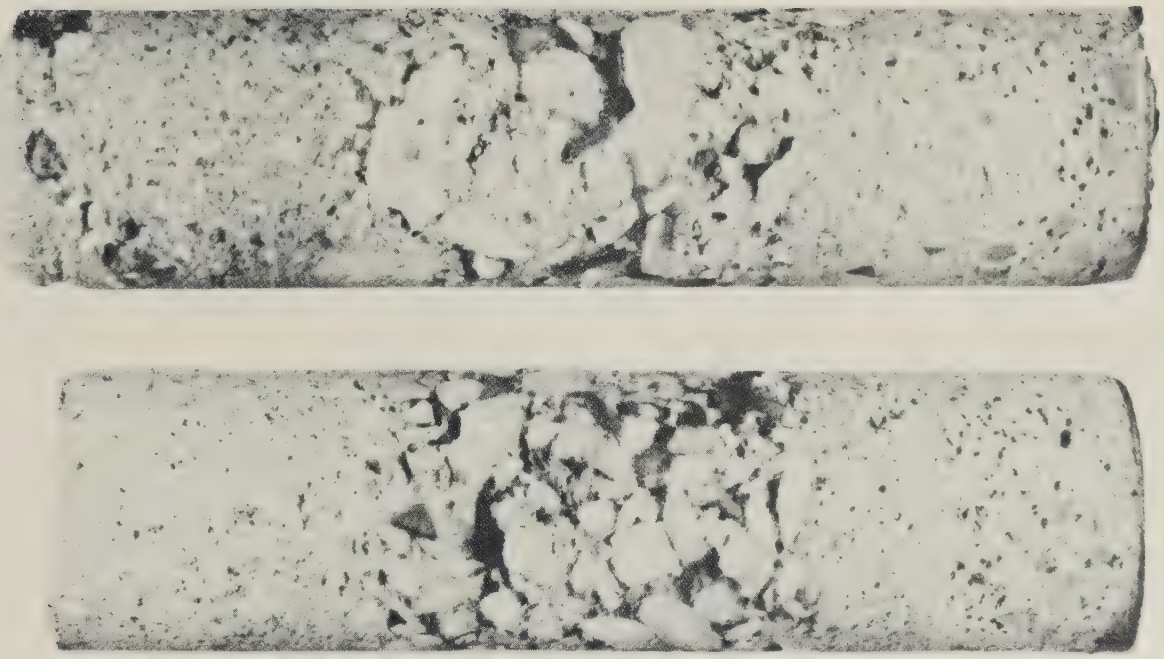

Figure 5.—Polymer rebonded concrete cores from New York Department of Transportation bridge repair trial.

various problems. However, final selection will be based on data accumulated from actual use and will be made by the operating engineer.

On a national scale, the National Experimental Evaluation Program (NEEP), operated by the FHWA's Office of Highway Operations, provides opportunities for prompt and thorough evaluations of new concepts. This program should be fully utilized for experimental application of new materials and techniques developed by research, and should be used as the method to identify the most effective solutions for any particular problem under consideration.

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Road Roughness Measurement and Its Applications

by Glenn G. Balmer

Noncontact Profiling System.

—courtesy, Illinois Institute of Technology Research Institute

Severe road roughness endangers vehicle control, results in passenger discomfort, accelerates roadway deterioration, and degrades the pavement's performance. A thorough knowledge of how roughness affects highways will encourage better construction, more efficient maintenance, and planned reconstruction.

This article discusses road roughness by describing measurement systems and applications of roughness technology. It is a condensation of a report, "Road Roughness Technology, State of the Art," FHWA–RD–73–54. (*1*) [1]

[1] Italic numbers in parentheses identify the references on page 153.

Introduction

Road roughness—an uneven, impaired, or bumpy roadway—affects:

- Highway safety.
- Riding quality of the roadway.
- Pavement loading, especially from heavy vehicles.
- Life of the pavement.

The relationship of road roughness measurement to these factors is illustrated in figure 1. Highway accidents or loss of vehicle control may result from roadway conditions. If roadway characteristics can be measured and analyzed, systematic maintenance or reconstruction programs will provide safer transportation facilities.

Most roughness measurement equipment relates to the longitudinal profile of the highway pavement. (*1*) However, a rut depth gage and other devices are available to measure the transverse roughness.

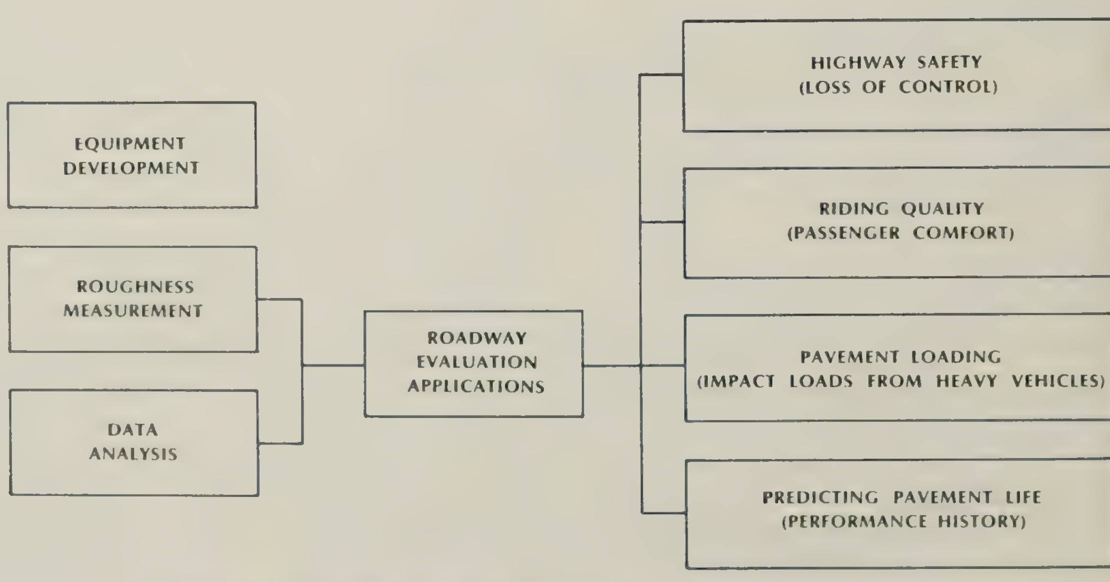

Figure 1.—The uses of road roughness technology.

Vehicle response and riding quality depend on the speed of travel, driver behavior, and vehicle characteristics as well as on the roughness of the pavement.

Measurement of Pavement Roughness

Pavement profile measuring equipment varies from a 10-ft (3 m) straight edge to electronically instrumented vehicles and includes rolling straight edges, single and multiple wheel profilometers, road meters, and roughometers. (2) They are used for construction controls, as indicators of road roughness, and for predicting vehicle response and riding comfort.

BPR roughometer

The road roughness indicator (fig. 2), commonly known as the BPR roughometer, rates or measures pavements; but it does not define the nature of the roughness, such as the wavelength of the irregularities.

Modified BPR roughometer

The roughometer measurement system has been modified by Purdue Research Foundation. (3) Now, measurements of beam vibrations are conducted instead of cumulating the vertical, unidirectional, sprung movement of the towed roughometer wheel as in the BPR roughometer.

The beams are mounted on a platform above the roughometer wheel, and the vibration frequency of each beam determines a point on the road roughness spectrum (fig. 3). These values depend upon the speed of travel and the size of the beam. Additional points can be obtained by repeating the test at a different velocity.

The tests are usually conducted for velocities between 20 and 40 mph (32 and 64 km/h). The equipment is instrumented to measure simultaneous vibrations from four beams.

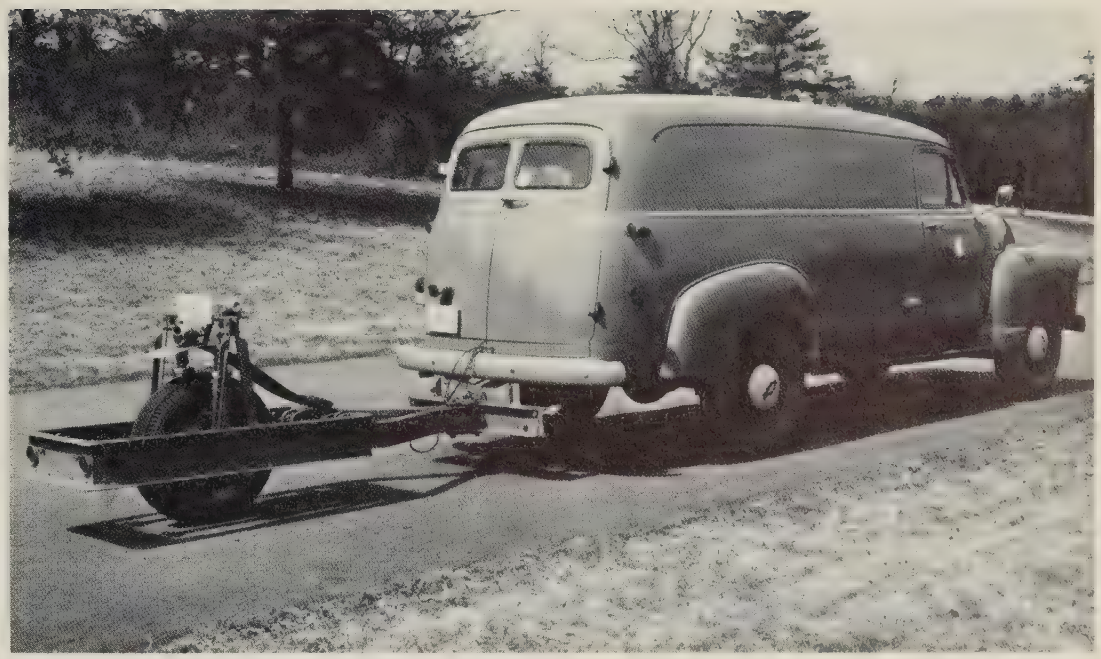

Figure 2.—The BPR road roughness indicator.

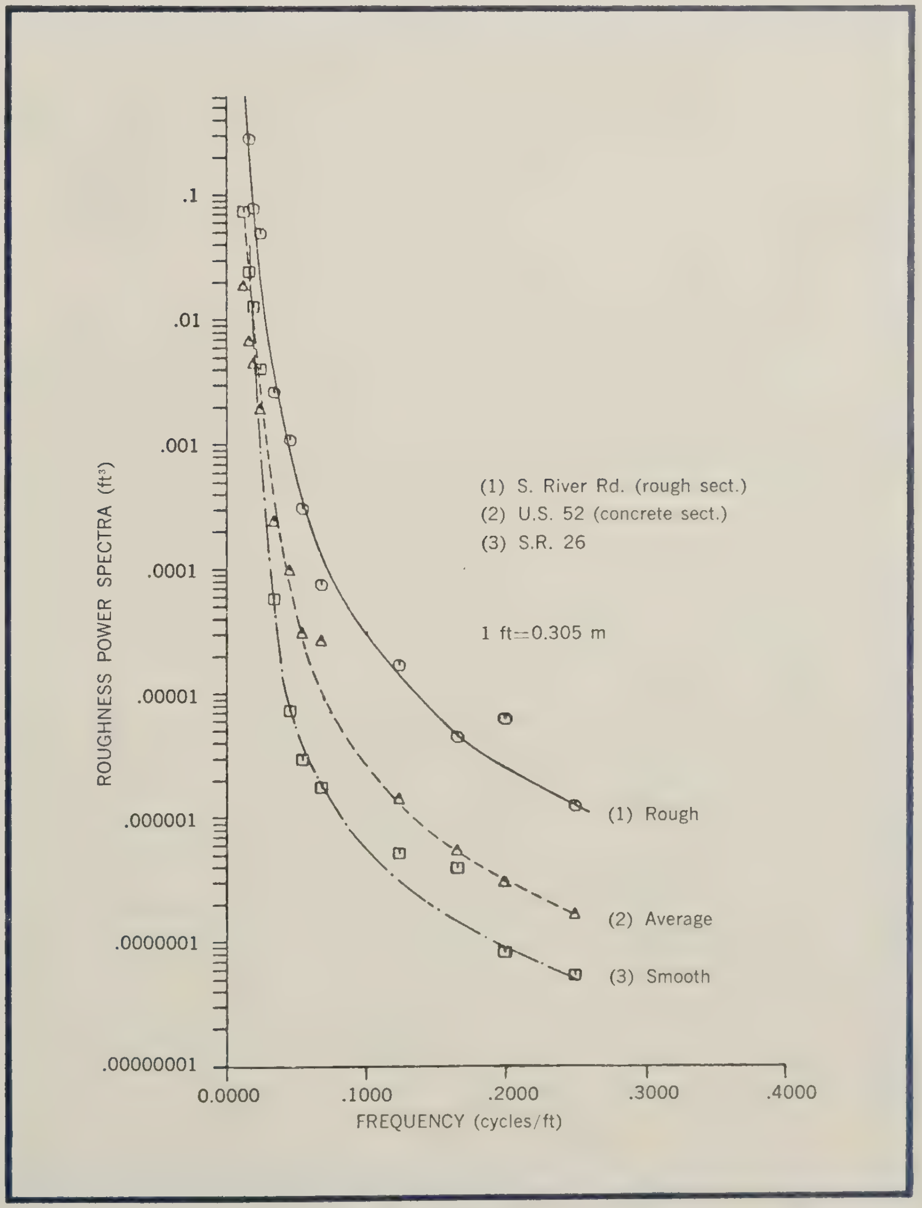

Figure 3.—Pavement roughness spectra (8).

GMR road profilometer

The General Motors Research (GMR) road profilometer, also called the rapid travel profilometer (RTP), evaluates pavement surface profiles at traffic speeds. (*4*) The equipment is instrumented to sense road roughness by a potentiometer connected to a spring-loaded, road-following wheel mounted below the chassis of a vehicle. Data are processed electronically during the testing or recorded on magnetic tape and analyzed later.

The profilometer can appraise many miles of highway at a rapid rate with a minimum of interference to vehicular traffic. However, the road-following wheel bounces from the pavement occasionally and deteriorates rapidly from rigorous wear. Thus, the cost of wheel replacement becomes a factor.

Noncontact profiling system

An acoustic probe, illustrated on page 148, was developed for the Federal Highway Administration (FHWA) by the Illinois Institute of Technology Research Institute (IITRI). (*5*) The sensor has fixed and variable sound length paths to determine the distance between the instrument and the pavement. A sound generator and receiver face the road surface so that sound transmitted by the generator reaches the receiver after reflection from the road surface. The time delay of the sound wave arriving at the receiver is a function of the probe height above the surface.

When completed, this noncontact profiling system will be used to evaluate longitudinal, pavement profiles. The sensor has already been laboratory and highway tested. Additional experiments will validate it at traffic speeds. Typical roughness measurements are given in figure 4.

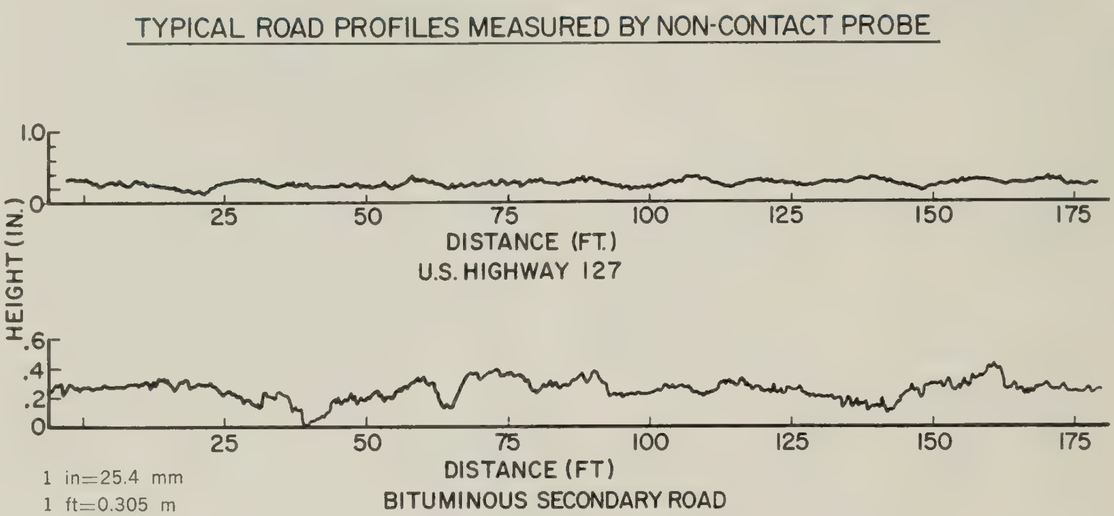

Figure 4.—Typical road profiles. —courtesy, Illinois Institute of Technology Research Institute

Road meters

Road meters are a low-cost, rapid method of measuring roadway roughness for inventory purposes. Tests can be conducted at 50 mph (80 km/h) or faster allowing an extensive road network to be evaluated in a short time. Roughness measurements are obtained from the vertical movement of the instrumented rear axle of an automobile.

The tests give comparative values of road roughness, and the road meters are usually correlated with other measurement systems. Correlation checks should be made when tires are replaced, when significant change is made in the vehicle, and at specified intervals.

Other measurement equipment

The CHLOE profilometer determines the slope variance of a pavement, the major variable in the present serviceability index (PSI) equations. (*1*)

The 10-ft (3 m) straight edge and modifications mounted on wheels are used as pavement construction controls and compliance tools. (*2*)

The multiple wheel profilometers serve a similar purpose and are used in other roughness measurements. (*2*)

The straight edge, CHLOE, profilograph, and other multiple wheel profilometers are usually operated statically or at a slow speed—a distinct limitation of these types of equipment.

Analysis of Road Roughness

Construction controls

Tolerances of pavement roughness have been included in construction specifications for decades. A specification may limit the variation of the surface profile to ⅛ in. in 10 ft (3 mm in 3 m), and compliance can be confirmed by a straight edge. A rolling straight edge, a roughometer, or a profilometer can also be used as construction controls. As measurement equipment and highway construction become more advanced, contract specifications will become more stringent.

Pavement serviceability-performance evaluation

The pavement serviceability-performance concept was conceived during the AASHO Road Test. It includes a scale with a high value of five and a low value of zero for the present serviceability rating (PSR) of a pavement—a condition appraisal of a road.

One subjective method of rating a roadway is to select a panel to evaluate its condition or riding quality by driving over it at traffic speeds. The PSR is a mean value obtained by averaging the panel members' evaluations.

Present serviceability index

In conjunction with the serviceability-performance concept, empirical equations were developed for the present serviceability index (PSI). Separate equations are available for flexible and rigid pavements, and the principal variable in the equations is the slope variance. (*1*) Also included are the magnitude of the rutting and the amount of pavement cracking and patching.

The slope variance can be obtained from measurements conducted with the CHLOE, a road meter, or a profilometer.

Road roughness rating values have been tabulated for pavement condition evaluation and as guidance for resurfacing. (*1*)

Power spectral density analysis

Through procedures described in references 6, 7, 8, and 9, road profile measurements such as figure 4 can be represented as roughness power spectra similar to figure 3 or tabulated as amplitude-frequency distributions. (*7*)

The power spectral density (PSD) graph portrays the frequency composition (inverse of the wavelength) of the profile in its mean-square amplitude values.

Each spectrum shows how various wavelengths in the pavement profile contribute to roadway roughness. The area bounded by the curve, the horizontal axis, and any two selected ordinates represent the total mean-square value of roughness for wavelengths lying between the two ordinates. The total area under a power spectrum curve gives the total mean-square roughness of the pavement.

Amplitude-frequency distribution

A tabular representation of road roughness, the amplitude-frequency distribution (AFD), summarizes profile data. (*7*) The tape recorded profile signals obtained from roughness measurements by the GMR profilometer, the modified BPR roughometer, or the noncontact profiling system can be reduced to tabular form by data processing procedures. Each entry in a table gives the equivalent number of cyclic "bumps" of a given height (volts) and wavelength from the measurements. The distribution of the values for a particular frequency band are shown in contrast to the power spectral density analysis which shows only a mean value for each frequency band.

Quarter-car simulator

Longitudinal road profile measurements, recorded on magnetic tape, can be used as inputs to a quarter-car simulator. The computer analyzes roughness data obtained at various speeds. The simulator is correlated with the BPR roughometer to interpret data with measurements conducted at 20 mph (32 km/h). It can also help determine readouts of jerk, acceleration, vertical displacement, or tire forces for a vehicle.

Applications of Roughness Technology

Highway safety

Steering, stability, directional control, braking, and skid resistance are highway safety factors influenced by pavement roughness.

The lateral friction force on a tire is a function of normal load, camber, and slip angle as well as of speed and pavement surface features. Roughness irregularities cause variations in the vertical tire load that result in variations in the lateral force and the slip angle. The driver compensates, if possible, for cornering friction loss by increasing the steering angle. The decrease in lateral friction due to roughness is critical when the driver must pass quickly to avoid collision with an approaching vehicle.

Similar losses occur in braking and traction from normal tire load fluctuations. Roughness also causes vibration and induces pitching, yawing, and rolling tendencies. Induced excitation near the "tire hop" resonant frequency causes the vehicle dynamic responses to be intensified, and "tire hop" or "freeway hop" may result. This has a bearing on directional control, braking, and traction.

Rumble strips and placement of bumps in the pavement are designed road roughnesses that alert drivers by noise, vibration, or appearance. (*10*) Intentional road bumps control speed. (*11*) However, they must be properly planned and used with discretion.

Riding quality

Vehicle response and riding comfort vary with the car because they are a function of speed, driver maneuvers, vehicle type, suspension system, and road roughness. Not only must the spectrum of road roughness be obtained, but vehicle characteristics must be determined to predict response.

One way to investigate these characteristics is to instrument the rear axle housing with strain gages, operate the equipment on several roadways with known roughness spectra, and conduct appropriate measurements. Similarly, vehicle characteristics can be determined from a vibrating platform in a laboratory. After the characteristics and road roughness spectrum have been obtained, they are used to determine vehicle response.

Pavement loading

Mathematical simulation and digital computation were used in a study to predict the magnitude and position of normal components of dynamic wheel loads. (*12*) A natural road profile, or a simulated roughness consisting of bumps with different sizes and arrangements in each wheel path, is used as an input. This model provides a tool to investigate the loading reactions of the pavement from heavy vehicles on a rough roadway. Simulation is a most efficient approach to the analysis of dynamic load effects on pavements.

Predicting pavement performance

The performance and service of a pavement are related to traffic, environment, and roadway roughness.

Nomographs estimate pavement life and serviceability. (*13*)

Road irregularities cause traffic impact loads that increase the stress on the pavement. (*12*) Heavy trucks are especially detrimental in accelerating the deterioration when the pavement is faulted, rough, or cracked.

Determination of cumulative damage and pavement serviceability has been researched, and a predictive structural subsystem (VESYS) was developed by the FHWA to be used in the design of flexible pavements. VESYS is described in the article, "A New Approach to Pavement Design," by William Kenis and George Tiller which begins on page 154.

Table 1.—Equipment measurement application

Equipment	Highway safety	Riding quality	Pavement loading [1]	Predicting pavement life [1]
Noncontact Profiling System	Not validated	Not validated	Not validated	Not validated.
GMR Road Profilometer	Applications not fully developed	Validated	Applications not fully developed	Applications not fully developed.
Modified BPR Roughometer	do	Applications not fully developed	do	Do.
BPR Roughometer	Not applicable	Validated	Not applicable	Of partial use.
CHLOE	do	do	do	Do.
Road Meter	do	do	do	Do.
Multiple Wheel Profilometer	do	do	do	Do.
Straight Edge	do	Of partial use	do	Not applicable.

[1] Measurements are used in conjunction with simulation studies or other supplemental analyses.

Cycles of wetting and drying, freezing and thawing, and spring break-up, along with pavement loading, affect the life of a roadway.

Subjective Equipment Application Evaluation

Table 1 shows subjective ratings of equipment use. Measurements from the first three devices can be analyzed to determine the longitudinal profile characteristics of a roadway for wavelengths that affect tire forces. Each can be applied to highway safety and pavement loading problems as technology is developed.

Most of the equipment is capable of measurements relating road roughness to vehicle response and riding comfort.

The road roughness spectrum is a chief input in analyzing dynamic load effects, and the first three devices determine this. The other equipment yields comparative roughness values.

An accurate road profile is required to predict remaining pavement life. Thus, the noncontact profiling system, the GMR road profilometer, and the modified BPR roughometer are candidates for providing information for the predictive techniques.

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(*12*) Nasser I. Al-Rashid, Clyde E. Lee, and William P. Dawkins, "A Theoretical and Experimental Study of Dynamic Highway Loading," Research Report No. 108–1F, *The University of Texas at Austin,* May 1972. PB 220373.

(*13*) Ivano E. Corvi and Bill G. Bullard, "A System for Estimating Present Surface Condition and Remaining Service Life of Existing Pavement Sections," *Public Roads,* vol. 36, No. 5, December 1970.

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[2] Reports with PB numbers are available in paper copies and microfiche from the National Technical Information Service, 5285 Port Royal Rd., Springfield, Va. 22161.

A New Approach to Pavement Design

by William Kenis and George Tiller

—courtesy, Washington State Highway Commission

Introduction

Current pavement design procedures are based on empirical relationships derived from experience and observation. These procedures are applicable to only a limited range of pavement materials, traffic loads, and environmental conditions. When it becomes necessary to determine the effects of conditions outside this range, the engineer must either perform very expensive accelerated testing or spend long periods observing the performance of actual construction. The Office of Research, Federal Highway Administration (FHWA), has developed a new pavement design procedure—based on a *mechanistic* structural subsystem—which may be used for any paving materials, axle loads, or environmental conditions.

This procedure is similar to those used to design bridges and buildings. A given design is evaluated by determining its structural response to expected loading and environmental conditions. In the design of a beam structure, for instance, the moment, shear, and deflection are calculated and compared with required specifications. The most economical section which meets all requirements is then chosen. Likewise, a designer can now evaluate a particular pavement design by using the new structural subsystem. The design procedure is shown in figure 1.

Because this procedure has a structural subsystem based on the fundamental principles governing the behavior of materials and the mechanics of layered media, it has definite advantages over empirical design procedures.

- It is applicable to all materials. New materials containing sulfur or waste products can be evaluated by predicting roadway service life.

- It is readily adaptable to all loading configurations such as tandem and variable spaced wheel loadings.

- It provides the engineer with a basis for relating stresses and deformations in the pavement-to-pavement distress.

- It can help the engineer learn more about how a pavement behaves, and thus better equip him to develop models for all modes of distress.

- It could also be used by State highway departments in scheduling maintenance activities by predicting future serviceability levels. This would help establish an economically sound basis for money and resource allocations.

VESYS

In the VESYS [1] structural subsystem, a set of mechanistic models has been integrated into a computer program for use in analyzing the structural integrity and performance of highway pavements. The concepts used have been formulated in studies funded through the State Highway Planning and Research Program, the National Cooperative Highway Research Program, FHWA Administrative Contracts, and in FHWA staff studies. The overall framework was developed at the Massachusetts Institute of Technology (MIT) under FHWA contract. VESYS, a modification of the MIT

[1] Originally, VESYS was to mean *Viscoelastic and Elastic Systems*; however, since then the structural subsystem framework has been completely modified to include a broad range of real-world pavement behavior and performance concepts.

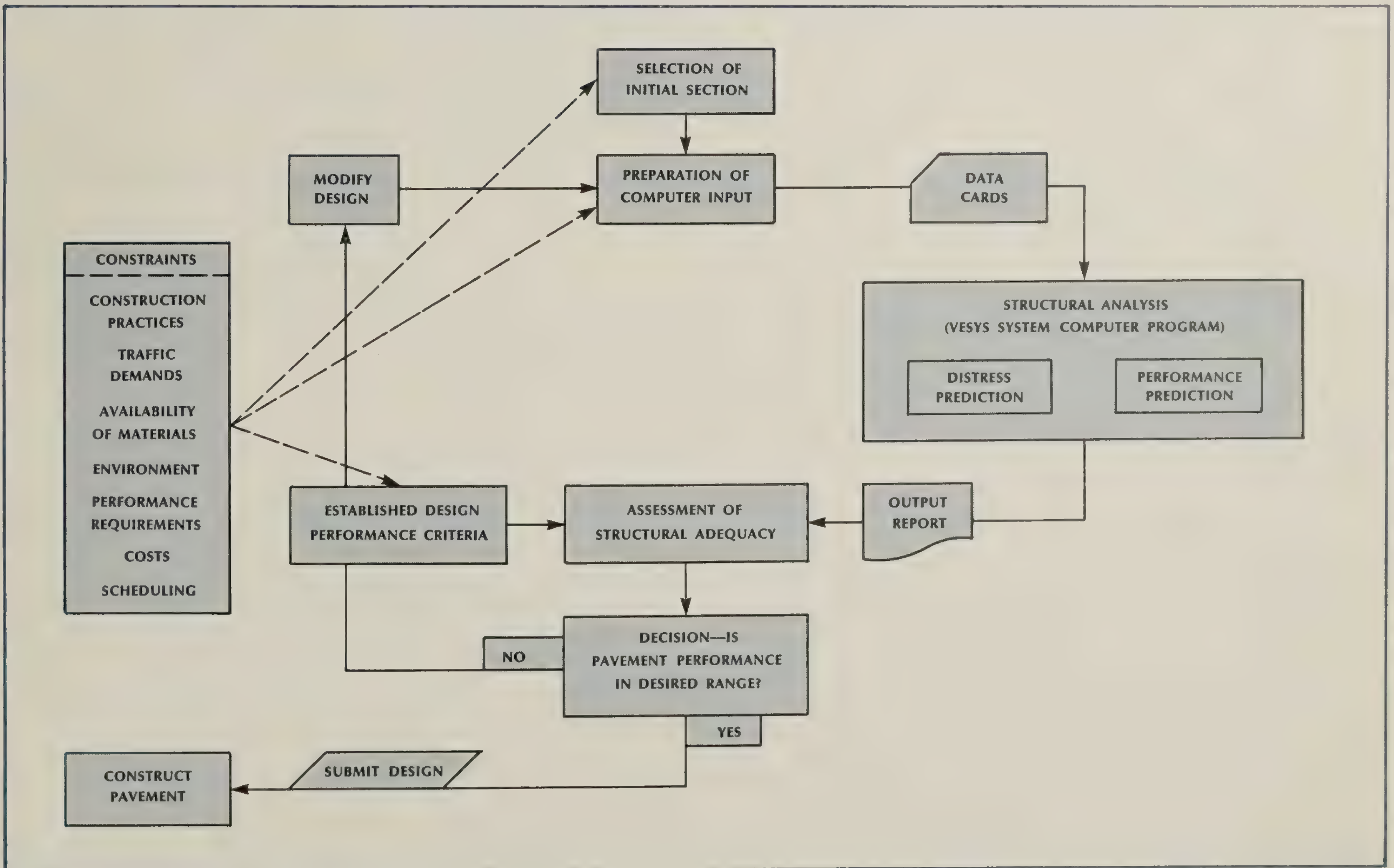

Figure 1.—Design procedure.

program, is now available on a limited basis for use by highway departments and other agencies cooperating with FHWA who are concerned with structural analysis and design of pavement systems.

The VESYS computer program measures the performance of a pavement in terms of its *present serviceability index* (PSI), derived from the American Association of State Highway and Transportation Officials (AASHTO) Road Test analysis. The PSI is a function of the structural integrity—continuity and deformation—of the pavement system. The program expresses it in the form of cracking, rutting, and roughness variables, using information on materials properties, geometry, traffic, and environment. The modular structure of VESYS, together with the inputs and outputs of the modules, is shown in figure 2.

Since factors which affect the real-world operation of a pavement system do not vary in a deterministic fashion, the VESYS models have been formulated in terms of closed-form probabilistic solutions. Inputs must be described as statistical distributions instead of single-valued estimates, and outputs are presented in terms of means and variances of the damage indicators—cracking, rutting, roughness—and serviceability.

Major Models in the Structural Subsystem

The *primary response model* represents the pavement as a three-layer, semi-infinite continuum with the upper two layers having finite thickness and the bottom layer having infinite depth. Each layer may be described by its elastic or viscoelastic properties, and the materials in each layer are assumed isotropic and locally homogeneous. The model performs a closed-form probabilistic solution to the three-layer viscoelastic boundary value problem. It assumes a single stationary circular loading at the pavement surface, complete shear at the interfaces, and incompressibility of the layer materials.

The *damage model* consists of three closed-form probabilistic models for the prediction of cracking, rutting, and wheel path roughness. The load associated

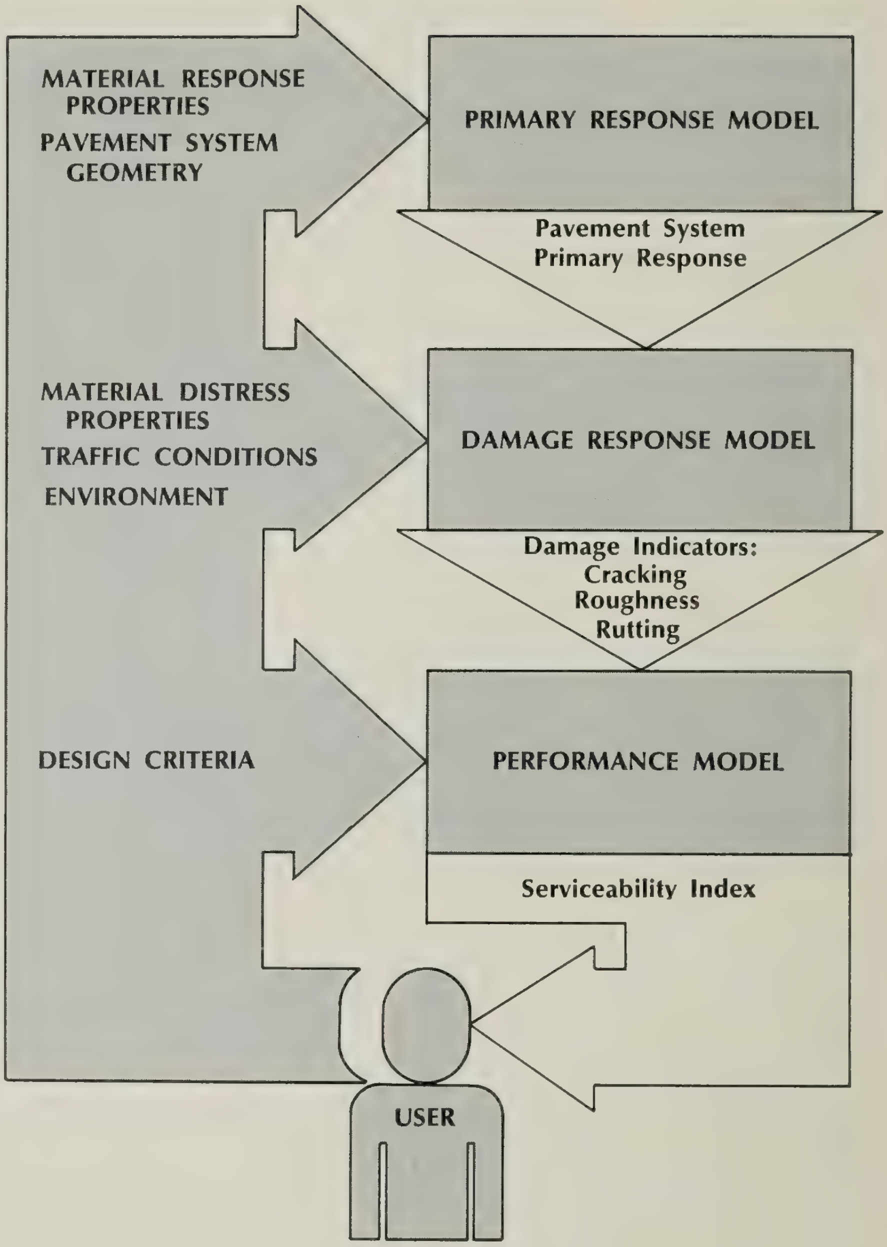

Figure 2.—Modular structure of VESYS.

fatigue cracking model assumes Miner's law for the prediction of the first crack. This law uses a set of fatigue characteristics derived from laboratory tests of beam specimens. The *rutting model* applies a repeated loading deformation law with a built-in decay factor in order to determine the accumulation of permanent strain. The pavement system's primary deformation response and the permanent strain characteristics of each layer are used. The *roughness model* assumes that longitudinal roughness occurs in wheel paths due to variations in material properties. An autocorrelation factor is used to express roughness in terms of slope variance as defined by AASHTO.

In the *performance model,* the AASHTO PSI equation uses the damage indicators to predict the mean and variance of the PSI at selected points in time. This provides the highway engineer with an objective measure of pavement serviceability over service life.

Features

VESYS is a user-oriented program with the following features:

- Simplicity. The user punches certain verbal *commands* on the input cards, followed by the appropriate data. VESYS scans the input deck using these commands to identify each piece of data. It can thus check for missing information and automatically substitute default values where needed. The program also performs extensive error checking and prints messages to help locate the source of any errors it finds.

- Flexibility. By specifying the appropriate commands and input data, the user can select the range and level of analysis he desires. This flexibility allows the execution of the entire program as a unit, or of any of the main modules independently.

- Modularity. The arrangement of the various analytical portions of VESYS into well-defined modules makes any future modification a fairly simple task. The modular framework can be kept intact while components are modified, replaced, or added. This technique was used during the development of the program when a deterministic primary response model was replaced by the current probabilistic solution.

Planned Improvements

The FHWA Office of Research plans several major improvements and additions to the VESYS program. Among the more important changes will be:

- Extension of the present three-layer analysis capability to include a variable number of layers of different materials.

- Extension of the primary response model to include additional wheel loads and variable wheel load spacing.

- Addition of advanced models recently developed for damage response.

- Incorporation of the VESYS program into an overall system which will design an optimized pavement section as a function of cost, service life, and maintenance.

Users

The VESYS structural subsystem, in the form of the VESYS II–M Computer Program, is currently being implemented by the Utah and Florida highway departments. They are applying the VESYS Program to actual pavement design problems, using different environmental conditions, materials properties, and performance requirements, in typical management situations. These States are also evaluating simplified test procedures that determine the elastic or viscoelastic properties of the pavement layers. This implementation effort will demonstrate the practicality of the program from a user's standpoint. The program has also been examined by Austin Research Engineers, Inc., in order to determine its sensitivity to broad ranges of realistic input values. In addition, it is currently being used by Pennsylvania State University under Highway Planning and Research (HP&R) Program activity to examine the performance of various pavement test sections on the Pennsylvania Department of Transportation test track facility in State College, Pa.

Additional information on the design procedure and the VESYS program is available from the U.S. Department of Transportation, Federal Highway Administration, HRS–14, Washington, D.C. 20590.

Does Voltage Measurement Detect Salt Corrosion of Concrete Reinforcing Steel?

by Horace A. Berman and Bernard Chaiken

The question is often raised whether the presence of dissolved salt causes erroneous interpretations in the technique of measuring electrical half-cell potentials to detect the existence of corrosion in the steel reinforcement of chloride-containing concrete. This article describes the results of experiments designed to assess the validity of electrical half-cell potential measurement as a technique for detecting the existence of corrosion of the steel reinforcement of chloride-containing concrete.

The research showed that the voltage measured is not directly affected by the presence of sodium chloride except insofar as the chloride ion is a factor in initiating corrosion. Consequently, the electrical half-cell potential measurement is a valid technique for detecting the existence of corrosion of the steel reinforcement of chloride-containing concrete. Corrosion in saturated calcium hydroxide solution exposed to air occurred in these tests at very low sodium chloride concentrations, as low as 0.03 molar (1.8 grams of sodium chloride per liter of solution). This threshold concentration was raised to 1.0 molar (58.4 grams of sodium chloride per liter of solution) when oxygen was excluded.

To determine whether pH change might be a factor in corrosion, measurements were made in a carbon dioxide-free atmosphere on the pH change produced by addition of sodium chloride to saturated calcium hydroxide solution. Except for very low concentrations of sodium chloride, the pH of saturated calcium hydroxide decreased with increasing sodium chloride concentration and increased with decreasing sodium chloride concentration. Small additions of sodium chloride up to a concentration of 0.008 molar (0.5 g of NaCl/liter) actually produced a pH increase.

The results indicate that pH reduction may contribute to steel corrosion in concrete, but do not conclusively prove that it does. Nevertheless, they suggest the desirability of investigating the addition of alkaline material to concrete containing, or exposed to, chloride ions above the critical concentration, as a means of restoring a suitable pH and thereby preventing steel corrosion.

This article is a condensation of an interim report, "Effect of Sodium Chloride on the Corrosion of Concrete Reinforcing Steel and on the pH of Calcium Hydroxide Solution." (*1*) [1]

Introduction

When chloride-containing deicing salts are applied to reinforced concrete pavements and bridge decks, they may cause corrosion of the reinforcing steel and subsequent damage to the concrete. Chloride ion breaks down the normal passivity of the steel in its alkaline environment when the chloride ion concentration reaches a certain threshold level. Bridges exposed to salt water experience similar salt penetration and steel corrosion.

Highway engineers use an electrical potential measurement technique to determine where corrosion is taking place on a bridge deck. A copper-copper sulfate half-cell is placed on the deck and connected to one terminal of a voltmeter. The other terminal is connected to the steel. It is assumed that when the negative voltage measured is greater than 0.35 V, corrosion is occurring. (*2*)

[1] Italic numbers in parentheses identify the references on page 162.

Several questions have been raised about this measurement system. Does the observed potential indicate only corrosion, or does it to a certain degree measure chloride ion concentration as well? Can high chloride ion concentrations in concrete cause high potentials even when there is no corrosion, or do the chloride ions first cause corrosion which in turn produces the high potentials?

To resolve these questions, we made direct observations of steel corrosion and accompanying electrical potentials as affected by sodium chloride (NaCl) concentration in saturated calcium hydroxide ($Ca(OH)_2$) solutions designed to simulate the environment in the cement paste binder.

Also of interest is the mechanism which causes a chloride salt to make the environment corrosive. If, as some investigators have suggested, the cause is a decrease in pH of the calcium hydroxide solution in the mortar, it is possible that corrosion could be prevented by introducing highly alkaline substances like sodium or barium hydroxides.

Certainly, calcium chloride additions should decrease the pH of calcium hydroxide solutions because the common-ion effect decreases the solubility of hydroxyl ion (OH^-). With NaCl additions, however, there is no obvious chemical explanation for a decreased pH. On the contrary, Johnson and Grove reported that sodium chloride increased OH^- solubility in calcium hydroxide solutions. (*3*) Nevertheless, the increased ionic strength of the solution containing NaCl might decrease the activity coefficient of the OH^- ion enough to bring about a net decrease in OH^- activity.

Chloride-contaminated concrete can contain from 0.9 to 8.3 kg Cl/m^3 (*4, 5*) corresponding to concentrations of from 0.4 molar to a saturated solution of NaCl. Forbes, Stewart, and Spellman (*6*) report a pH decrease from 12.5 to 11.6 for saturated $Ca(OH)_2$ solution when 1 percent NaCl is added (0.2 molar), and a further drop to 10.2 for 30 percent NaCl (probably 30 g NaCl added to 100 g calcium hydroxide solution).

These pH decreases could have been caused by exposure of the solutions to carbon dioxide (CO_2) rather than by the presence of NaCl if no precautions were taken to exclude CO_2. We therefore undertook to determine the pH change caused by adding NaCl to saturated $Ca(OH)_2$ solutions in an environment maintained free of CO_2. We were interested in observing whether the effects of NaCl on the pH and on corrosion could be correlated.

Effect of Sodium Chloride on Steel Corrosion

Two series of corrosion tests were made, both on steel drill rod. The first series was carried out in containers open to the air. The second series was carried out in closed containers under a nitrogen atmosphere. Figures 1 and 2 illustrate the testing apparatus. (1) Drill rod was used because corrosion was readily observable on its smooth surface. Earlier tests on mild steel deformed reinforcing bars gave results similar to those reported here.

In each series, one-half of a corrosion cell consisted of a reinforcing bar partially immersed in saturated calcium hydroxide ($Ca(OH)_2$) in one of two connecting containers. The $Ca(OH)_2$ solution extended into the other container where it made electrical contact with a copper-copper sulfate half-cell through a block of hardened cement paste. The cement paste separated the two solutions and simulated a concrete bridge deck and the type of physical contact made in the field between the half-cell and the deck.

The bar was immersed in saturated $Ca(OH)_2$ solution and voltage readings taken until constant, at least overnight. Then the chamber was emptied and filled with a second saturated $Ca(OH)_2$ solution containing sodium chloride (NaCl). Readings were again taken until the voltage was constant. The bar was observed for corrosion. Starting with a clean bar each time, the experiment was performed for concentrations of 0.01 molar to 1.0 molar NaCl in the air series, and 0.01 molar to 3.0 molar NaCl under nitrogen. Measurements with chloride-free saturated $Ca(OH)_2$ solution were interspersed with determinations on solutions containing NaCl.

Corrosion started in the air cell when the NaCl concentration was as low as 0.03 molar. This corrosion threshold was raised to 1.0 molar NaCl in the nitrogen cell. Thus, both oxygen and chloride ion are needed for corrosion, the threshold concentration of chloride ion depending on the quantity of oxygen available.

In general, whenever actively spreading corrosion took place, the negative electrical potential increased

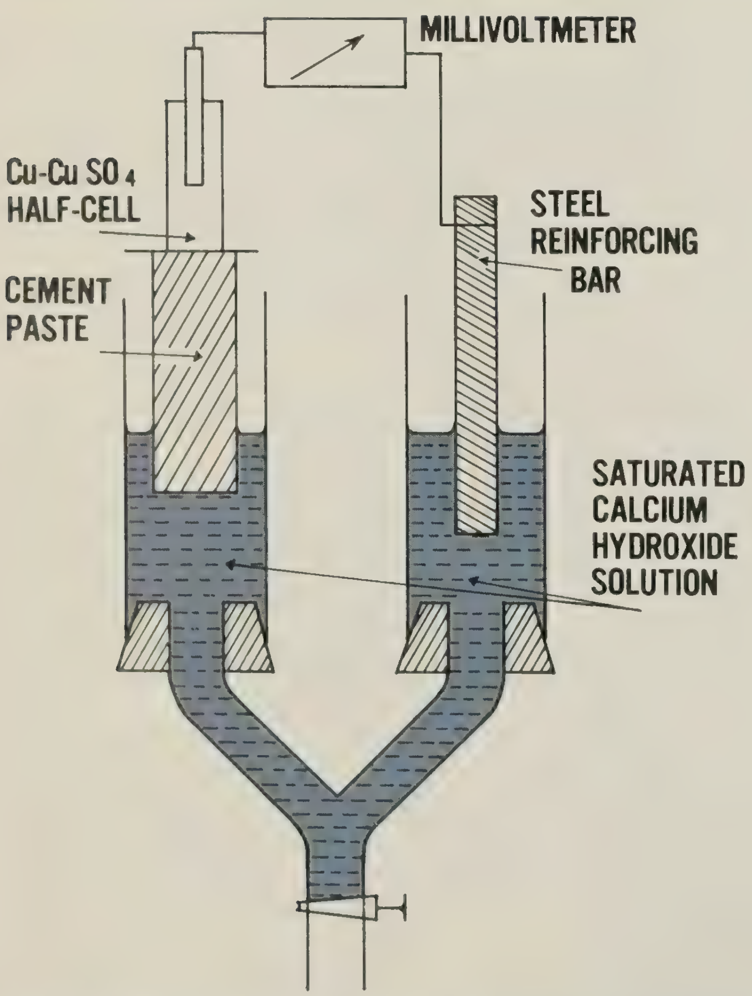

Figure 1.—Apparatus for corrosion experiments on steel reinforcing bar in saturated calcium hydroxide solutions containing sodium chloride (cell open to air).

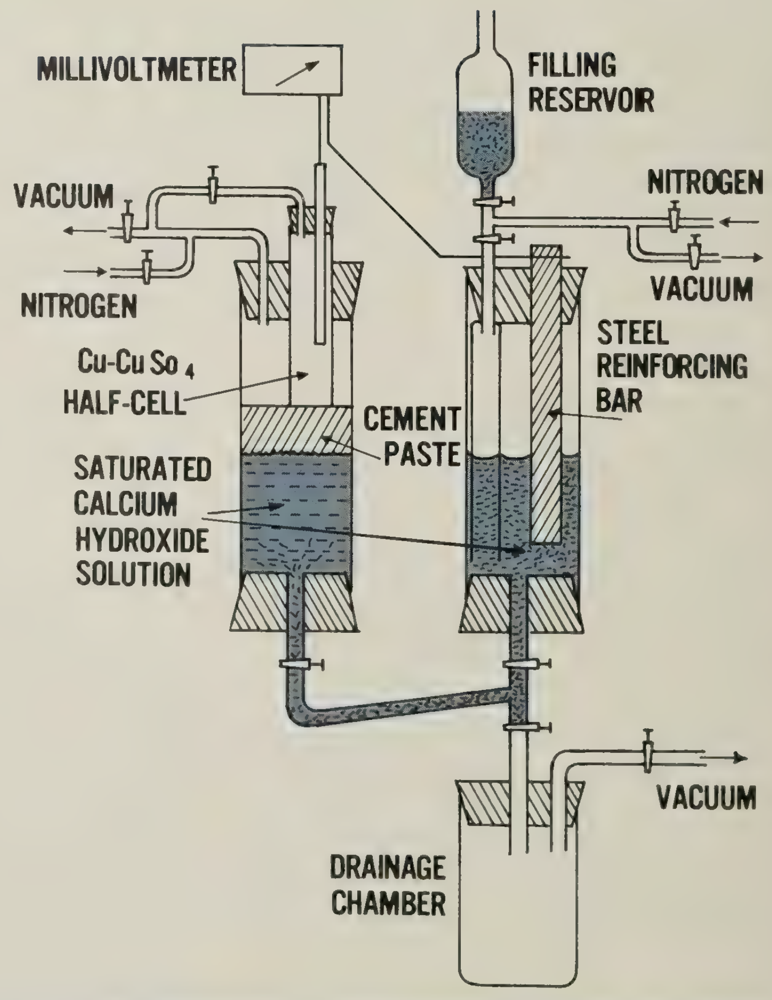

Figure 2.—Apparatus for corrosion experiments on steel reinforcing bar in saturated calcium hydroxide solutions containing sodium chloride (under nitrogen at 600 mm Hg or 0.08 MN/m² pressure).

from its initial value to a final value between 0.4 and 0.7 V. When no actively spreading corrosion was observed, the potential decreased from its initial value or was unchanged. Active corrosion was much more severe in air than in nitrogen, but in both atmospheres the tests could be divided into two groups: one in which there was no corrosion or only inactive corrosion; the other in which active corrosion occurred. The first group was accompanied by negative potentials between 0.15 and 0.28 V, the second group by potentials between 0.36 and 0.70 V. Since the boundary concentration of NaCl between the two groups differed in air and in nitrogen, the potential was unmistakably tied to the corrosion process and not to the chloride concentration per se.

Effect of Sodium Chloride on pH

Measurements of pH were made in a tightly stoppered flask. (See the full report (*1*) for illustrations of the testing apparatus.) The electrodes were supported tightly in the rubber stopper, their ends immersed and their leads outside the flask. The electrode-flask assembly was surrounded by a covered jar containing ascarite to absorb carbon dioxide. All solutions were prepared with boiled distilled water. All operations, including solution preparation, took place in a closed system with techniques described earlier. (*7*)

In one series of tests, the pH of chloride-free saturated calcium hydroxide ($Ca(OH)_2$) solution containing excess solid $Ca(OH)_2$ was measured. One day of equilibration was allowed. Then part of the solution was withdrawn and replaced with sodium chloride (NaCl) solution free from carbon dioxide (CO_2). The solution was mixed to obtain a uniform NaCl concentration and to resaturate with $Ca(OH)_2$ and pH measurements were taken for at least 24 hours. The NaCl concentration was increased in steps from 0.002 molar NaCl to 0.073 molar. Then the NaCl concentration was decreased by replacing half of the solution each time with saturated $Ca(OH)_2$ solution. The purpose of decreasing the NaCl concentration was to rule out the possibility that a pH decrease while adding NaCl might have been caused by ingress of CO_2. If the pH decreased while NaCl was being added and increased while NaCl was being removed, the change in pH could be attributed to the NaCl.

The results confirmed that NaCl additions decreased the pH of saturated $Ca(OH)_2$ solution after a NaCl concentration of 0.008 molar had been exceeded. However, as shown in figure 3, a plot of pH for the NaCl dilution series against NaCl concentration did not follow the corresponding plot for the NaCl addition series, but showed definite hysteresis. From this and other indications during the experiment, it was concluded that the equilibration time at a given concentration level had been insufficient. Therefore, a second NaCl addition series was carried out, in which pH measurements for each NaCl concentration step were continued until a constant reading was obtained, a 16-day process in some cases. The second addition series involved larger concentration increments than the first, to a final concentration of 2.4 molar. Figure 4 shows that the pH values in the two addition series were different at corresponding NaCl concentrations but that the trend of decreasing pH with increasing NaCl concentrations was common to both series.

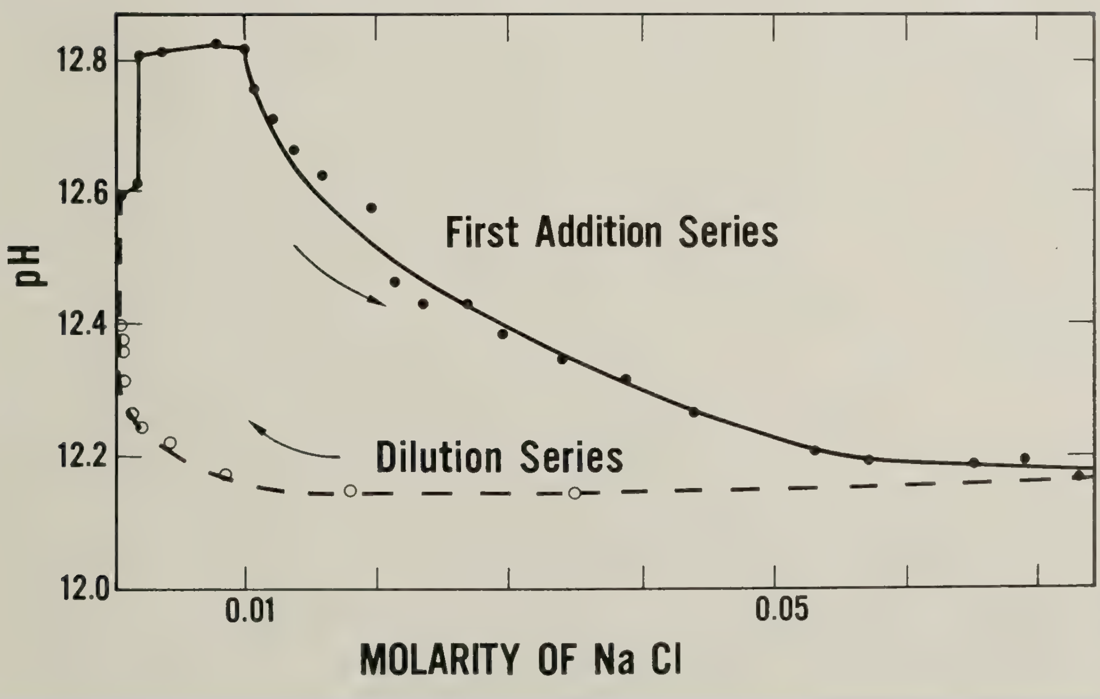

Figure 3.—pH of saturated calcium hydroxide solutions as a function of sodium chloride concentration (first sodium chloride addition series and sodium chloride dilution series).

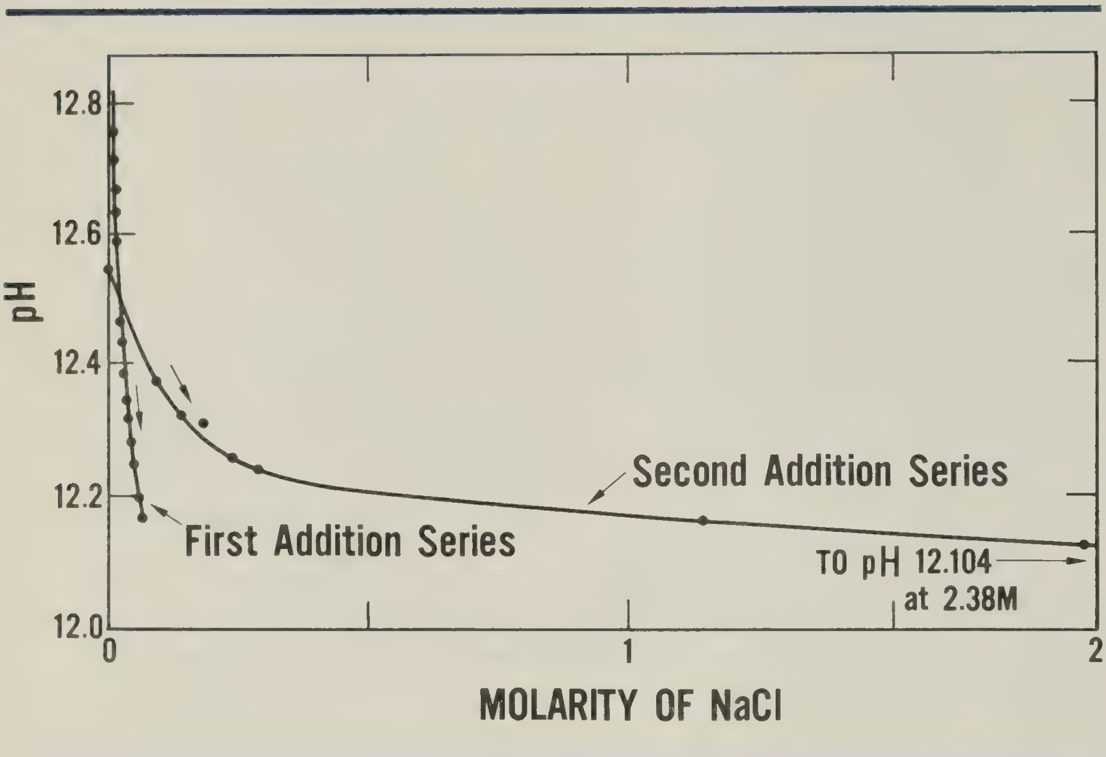

Figure 4.—pH of saturated calcium hydroxide solutions as a function of sodium chloride concentration (first and second sodium chloride addition series).

Conclusions

Electrical potential measurement is a valid indicator of active corrosion in concrete reinforcing steel. Voltage readings obtained by this method were not affected by sodium chloride (NaCl) concentration in the 0 to 3 molar range except insofar as the presence of chloride ion is a factor in initiating corrosion. With the steel used in these tests, a threshold concentration of 0.03 molar NaCl was necessary to produce active corrosion in air. Exclusion of oxygen raised the threshold to 1.0 molar NaCl, demonstrating the importance of oxygen to the corrosion process.

Electrical potential measurements do not necessarily separate sound from defective concrete. Areas with low-potential readings but high chloride ion contents may not be corroding because adjacent portions of the steel are more anodic. If the concrete in the anodic areas is removed and replaced with fresh concrete, the steel in the surrounding areas may then corrode actively. Thus, as pointed out by Clear and Hay (*4*), concrete should also be analyzed for its chloride ion content, if both corroded and corrodible steel areas are to be found.

Sodium chloride decreases the pH of saturated calcium hydroxide solutions. The pH of a chloride-containing concrete would therefore be lower than that of a chloride-free concrete. The pH decrease began at 0.01 molar NaCl and the threshold for corrosion was 0.03 molar, concentrations which are not far apart. Consequently, the effect of sodium chloride on pH may be one mechanism for steel corrosion in concrete, although these test results do not prove that pH is the cause. Work by Hausman (*8*) has demonstrated that the tendency for steel corrosion in air is greater the larger the ratio of chloride to hydroxyl ion concentration. Our results support this conclusion and suggest that it might be feasible to increase the pH of salt-contaminated cement paste or concrete with sodium or barium hydroxides, amines, or other alkaline agents and thus perhaps limit the corrosion process.

Acknowledgment

The authors wish to acknowledge the contributions of Joseph Zenewitz, who carried out much of the experimental work on the pH measurement, and Earnest Bailey, who performed the corrosion experiments.

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[2] Available from the National Technical Information Service, 5285 Port Royal Rd., Springfield, Va. 22161. Stock No. PB 228679.

Highway Design for Motor Vehicles—A Historical Review

Part 5: The Dynamics of Highway Curvature

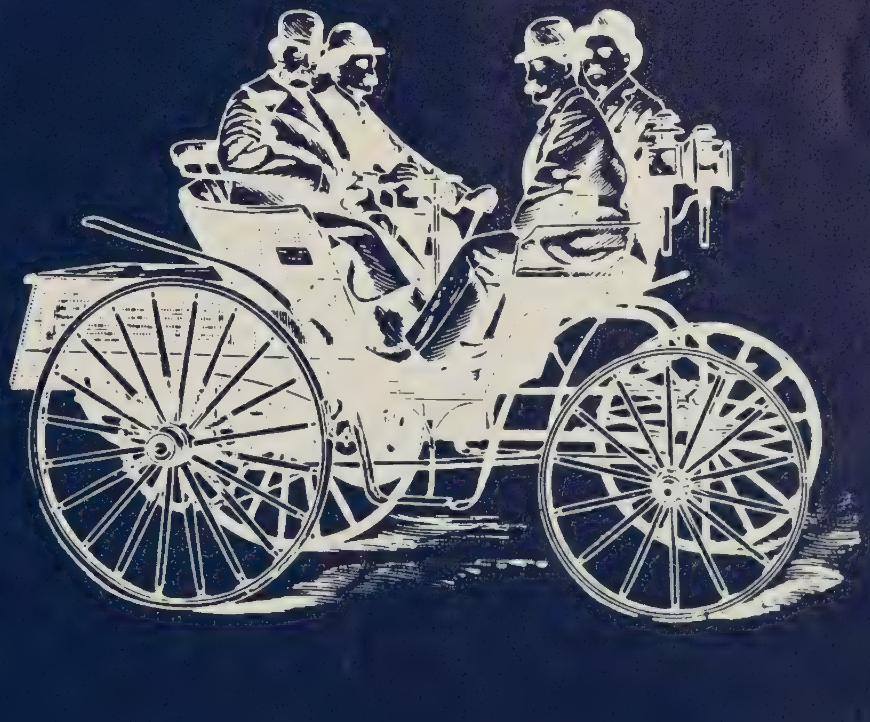
by[1] Frederick W. Cron

This is the fifth 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. Part 4: The Vehicle-Carrying Capacity of the Highway was published in vol. 39, No. 3, December 1975. The remaining parts, to be published in future issues, are 6: Development of a Rational System of Geometric Design; 7: The Evolution of Highway Grade Design; and 8: The Evolution of Highway Standards.

Before the appearance of bicycles and automobiles on the highway, vehicle speeds on the smoothest surfaces seldom exceeded 8 mph. At this speed the width of the road and the length of the vehicle were much more important than speed for determining road curvature. A four-horse team pulling a freight wagon was about 50 feet long. This rig would go around a curve of 105 feet radius without leaving the carriageway if the pavement were at least 12 feet wide. For an 18-foot pavement the radius could be only 77 feet. Of course, during part of the maneuver the rig would be occupying the entire roadway including the lane for opposing traffic, so roadbuilders tried to get longer radii where possible. In 1908 the Permanent International Association of Road Congresses (PIARC) recommended that the minimum radius be 50 meters (165 feet), and also that transition curves be placed between each end of the curve and the adjoining tangent to reduce the abruptness of the change from straight line to curve. *(1)*[2]

In the early 1900's the practice in France was to use a 50-meter minimum radius on national roads in fairly level country, but this was shortened to 30 meters in more difficult terrain. On district roads 15 meters was the minimum radius. In Austria the minimum radius varied from 24 to 49 meters on main roads, 20 to 30 meters on district roads, and as low as 10 meters on minor roads. *(1)* New York on the other hand strove for a minimum radius of 200 feet wherever possible. *(2)* For very small changes in direction—10° or less—some road engineers used no curve at all. *(3)*

Since the time of Trésaguet, and indeed back to the Roman era, engineers had cambered or crowned road pavements to shed water quickly. This crown was applied uniformly to the entire road, curves as well as straightaways. Animal-drawn traffic



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

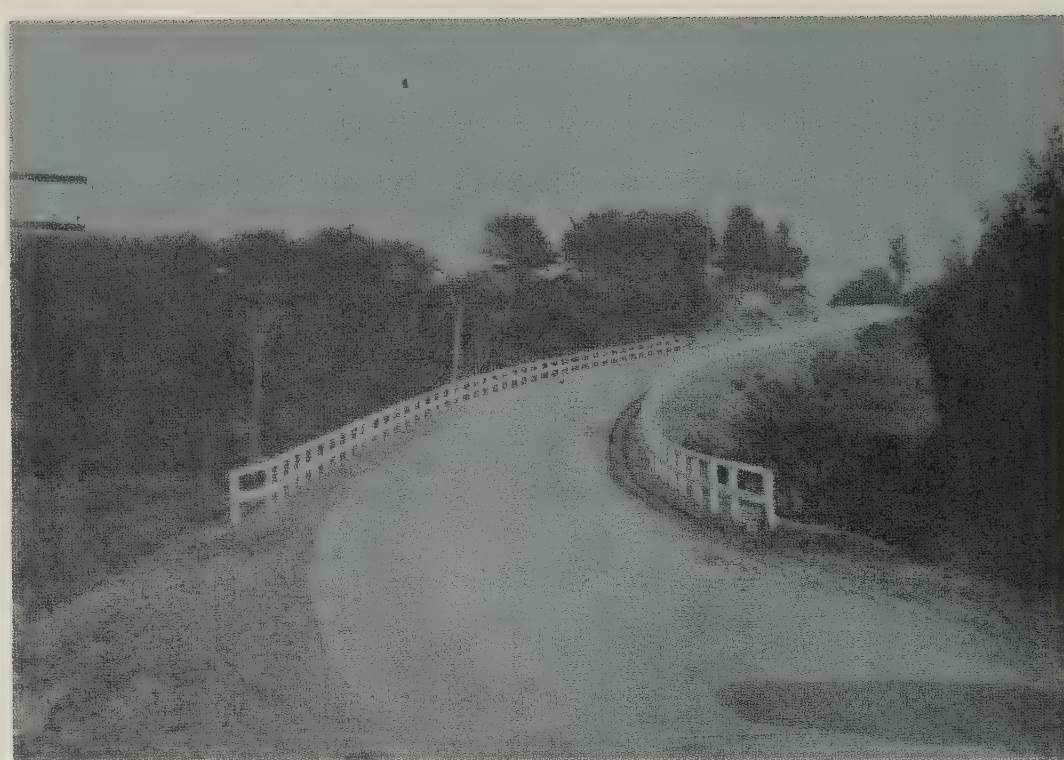
[2] Italic numbers in parentheses identify the references on page 171.

traveling only 2 to 3 mph had no difficulty rounding the curves, even though they were apt to be of short radius. Motorists, however, found the crowned curves irksome. They wanted to travel at 20 to 25 mph but were unable to take the curves at that speed without *cutting the curve* to utilize the banking afforded by the crown in the opposing lane.

Curves Banked to Equalize Wear

Aside from the danger involved, curve-cutting greatly increased the wear on macadam surfaces by concentrating the traffic on the inside lanes of curves. About 1912, some roadbuilders began to *superelevate* [3] or *bank* the sharper curves of new roads to encourage auto drivers to stay in their own lanes. Practice varied widely among highway organizations as to the amount of superelevation to use, or, indeed, whether to use it at all. In the United States, New York—a leader in the superelevation movement—used a straight two-way crown of one-half inch per foot, or 4 percent, on macadam roads and one-fourth inch on concrete pavements. This crown was carried around curves of radii longer than 500 feet, but sharper curves were superelevated 1 inch per foot for macadams and five-eighths inch per foot for rigid pavements. Apparently, these values were purely empirical, the transverse slope being regarded as a function of the nature of the pavement surface rather than the radius of the curve. In fact, a widely respected authority on road design from New York asserted that "Variation in superelevation for curves of different radii is a useless refinement and good practice rarely adopts superelevation for radii greater than 800 feet." (2) This empirical approach to superelevation on highways seems strange when one considers that every educated civil engineer of the period had a thorough understanding of the dynamic basis of superelevation as practiced by the railroads.

[3] The term *superelevate,* like others in highway engineering, comes from railroad practice. The railroads canted their tracks on curves by elevating the outside rail.



On widened curves which are improperly banked the traffic swings to the inside of the curve to take advantage of the crown, leaving an untraveled lane on the outer edge. (4)

At this time, 1912 to 1915, horse-drawn vehicles were still an appreciable part—approximately one-third—of the total traffic on all main roads in the United States; and there was a real danger that if a sharp curve were superelevated sufficiently to make it adequate for a speed of 30 or even 20 mph, the cross-slope would be so steep that slow-moving, horse-drawn vehicles would slide sideways when the surface was slippery. Furthermore, there was considerable public hostility to providing any superelevation due to the opinion that it encouraged high speeds and reckless driving on curves. Not until about 1920 had animal-drawn traffic become so negligible in the United States that it could be disregarded in highway design. Until then, superelevation rates were a compromise—an excellent example of how so-called standards evolve from a consensus, sometimes without scientific support.

Curve Widening

Concurrently with superelevating sharp curves, some States also began to widen them on the inside. This was partly a concession to curve-cutting and partly because the rear wheels of a vehicle do not track exactly in the path of the front wheels on a sharp curve. There was no consistency in the amount of widening among the States that practiced this innovation. West Virginia, for example, used only 3 feet of widening for curves of 75 feet radius, while New York used 3 feet for curves of 1,500 to 2,500 feet radius and went up to 8 feet on 300-foot-radius curves. Generally, however, the amount was scaled somewhat to the radius, and extended all around the curve. The transition from the normal pavement width on tangents to the widened curve section was accomplished in several ways: Michigan and New York used a circular curve of longer radius than the centerline for the inside edge of the pavement, while Pennsylvania and Washington used spiral transition curves such as those adopted by railroads for track easements. (*4*) This seems to have been the first use of spiral curves on highways in the United States, although PIARC had recommended the use of spirals on roads as early as 1908.

By 1920 animal-drawn vehicles had practically disappeared from the main roads of the United States; and engineers, for the first time, could design highways for motor traffic only. Of the earlier features of road design one of the first to go was the high crown. Tighter, smoother surfaces such as cement concrete, paving brick, asphaltic *carpets,* and bituminous macadam did not require a steep crown for transverse drainage. High crowns caused vehicles to veer to the right. Even more important, crossing and recrossing a steep crown during the overtaking maneuver was not only uncomfortable for drivers but hazardous. By 1925 crowns on concrete pavements were generally about one-fourth inch per foot, or 2 percent, and today one-eighth inch per foot, or 1 percent, is usual.

Relating Superelevation to Speed

Another product of the new motor-oriented thinking was the belief that one should be able to travel all parts of the highway—curves as well as tangents—at the legal speed limit, which was then 25 to 30 mph in most States. This belief prompted more thorough studies of the curvature-superelevation relationship, one of the earliest of which was in 1920 by Luedke and Harrison of the Bureau of Public Roads. (*4*) By mathematical analysis they showed that complete *superelevation* necessary to offset the centrifugal force generated by a vehicle traveling around a curve could be calculated by the formula:

$$e = \frac{V^2}{15R}$$

Where,

e=Superelevation in feet per foot.
V=Vehicle speed in miles per hour.
R=Curve radius in feet.

They then showed that for a speed of 25 mph a cross slope of 0.21 foot per foot or 21 percent would be needed to supply complete superelevation for a curve of 200-foot radius. This was five times the current practice, which was to bank curves of 150 to 500 feet radius at a rate of one-half inch per foot, providing a cross slope of only a little over 4 percent. And yet Luedke and Harrison knew from experience that an auto could easily negotiate a 200-foot radius curve with 4 percent superelevation at 25 mph. The difference, about 17 percent, could be accounted for only by ". . . the stability of the vehicle itself," or its ability to resist side skidding. Expressed another way, the ½-inch superelevation provided horizontal resistance to compensate for a speed of about 11 mph on a 200-foot radius, and the resistance required for higher speeds was provided by the side-friction of the vehicle's tires.

Luedke and Harrison were also concerned with the manner in which the transition from a crowned to a superelevated section was accomplished. Assuming a constant velocity in the formula $e = \frac{V^2}{15R}$, e should increase uniformly as the centrifugal force is developed, that is, as the radius decreases. If the cross slope is developed too rapidly, the driver will feel uncomfortable and will try to lengthen the transition distance by swinging toward the center of the road or even into the opposing lane in extreme cases. To remedy this, Luedke and Harrison recommended inserting a transition curve of variable radius between the tangent and the curve on which the driver could gradually adjust to the horizontal change in direction as the outer edge of the road was elevated smoothly to the required superelevation. Such *spiral curves* were commonly used on railroads to lessen the shock of the change from linear to curvilinear motion, but no highways in the United States at this time had spiraled centerlines.

Although they did not use centerline spirals, those States that used superelevation at all had their own transition methods, and generally they accomplished the transition in a distance of about 100 feet. New York, however, made the length of transition a function of the curve radius, varying from 35 feet for curves of 2,500 feet radius to 85 feet for curves of 300 feet radius.

The First Spiraled Centerline

The earliest fully spiraled road centerline was the high-speed test loop of the General Motors Proving Ground in Michigan, constructed in 1926, where spiral easements were applied to three 1,000-foot-radius curves. After 12 years of operation the director of the Proving Ground stated that it would have been a great mistake to have omitted the spirals. (5)

The first public highway to have a fully spiraled centerline was the Mount Vernon Memorial Highway in Virginia, designed by the Bureau of Public Roads in 1929. The BPR engineers first laid out the location on a large-scale map with a flexible spline, a new technique borrowed from New York's Westchester County Parkways. They then resolved this line, which was actually a *free form,* into circular and spiral curves so that it could be staked on the ground by current surveying methods. The resulting alinement consisted almost wholly of relatively flat curves none of which had a radius shorter than 1,200 feet. Curves of less than 2,000 feet radius were spiraled at each end. One spiral curve was 1,512 feet from end to end—possibly the longest ever to be incorporated in a highway. Of course, a spiral of this length went far beyond the requirements of transitioning and into a still-unexplored realm—that of esthetics and visual impact. This mighty spiral also refuted the arguments of those who claimed that spiral curves were dangerous because their constantly changing curvature kept the driver off-balance. Actually, after its completion in 1932, one could drive the 15-mile length of the Mount Vernon Memorial Highway in complete safety at 55 mph, and almost without hand steering.

The Beginnings of Access Control

The earliest access-controlled motor highway in the United States was the Long Island Motor Parkway, built originally on private right-of-way as a race course for the Vanderbilt Cup. Opened to traffic in 1908, this 40-mile road was paved with concrete and was one of the first roads in the world to have superelevated curves. When not used for racing, the parkway was opened to pleasure vehicles as a toll road. The European counterpart of the Long Island Motor Parkway was the *Avusbahn,* begun in 1913 but not completed until 1919. This German ancestor of the *autobahnen* ran in an absolutely straight line from Charlottenburg to Berlin with no direct access to the traffic lanes and no grade crossings.

In 1923 an Italian corporation began construction of a high-speed toll road from Milan to Lake Como for the exclusive use of motor vehicles. It was laid out as a series of long tangents joined by superelevated curves of 500 meters minimum radius, and there were no crossings at grade with other roads or railroads. The Milan-Lake Como *autostrada* was followed by six others—all built to the same high standards. Although financially unsuccessful as toll roads, these Italian *autostrade* were the first motor roads of any considerable length to be built with full access control—that vital principle of modern freeways.

We have seen that in the early days of the automobile, roads were narrow and crowns were steep. Consequently, most drivers ran in the middle, straddling the crown, and few considered this unusual. When two vehicles approached each other, both had to move to one side in order to pass. *Safe sight distance* was the distance required for a driver traveling at the ordinary touring speed of 20 to 30 mph to turn out and pass an approaching car without applying his brakes. (2) Inquiry among auto clubs as to what drivers felt this distance should be showed rather general agreement on distances of 200 to 300 feet.

According to road tests made in Erie County, N.Y., about 1912, a car traveling 20 mph could be brought to a safe stop in 40 feet, while one traveling 40 mph could be stopped in 140 feet with the emergency brake. For safe design the New York State Department of Highways at this time required 250 to 300 feet of sight distance on curves and a minimum curve radius of 200 feet. (2)

By the early 1920's, highway accidents had become a source of grave concern in the United States and abroad. Most of the serious accidents were attributed to recklessness and excessive speed, but skidding was

—courtesy, California Division of Highways.

In the early 1920's most drivers ran in the middle of the road, straddling the crown. They gave way to the right only for passing.

also blamed for a very significant share. This last was a subject that seemed amenable to solution by engineering research and design.

The Beginnings of Skid Research

As early as 1922 the Iowa State Experiment Station, under T. R. Agg, had made some experiments to determine the tractive resistance of automobiles on various types of road surfaces. (*6*) The primary purpose of these studies was to develop data on road economics in support of good roads programs. However, almost as an afterthought, the experiments also included studies of the sliding friction of rubber tires on various road surfaces. A test car with brakes only on the rear wheels was towed at a speed of 3 to 5 mph and the brakes were applied gradually until the rear wheels started to slide. The pull exerted on the tow line was measured with a Burr dynamometer and a Kohlbusch dynamometer. The researchers then calculated the coefficient of friction from the simple relation: The coefficient of friction equals the force required to cause the wheels to slide divided by the weight on the wheels.

The coefficients for uniform straight sliding as measured in these tests ranged from 0.179 on hard-packed snow to 0.517 on wet concrete and 0.715 on dry concrete. Coefficients about 10 percent higher were observed while the wheels were still turning, just before sliding began.

To measure side-skidding coefficients, the test vehicle was secured parallel to a very heavy truck with the tow line and dynamometer between them. They then drove off at the same speed in slightly diverging paths. The dynamometer was read when the wheels of the lighter test vehicle began to slide sideways. For safety reasons it was impossible to conduct this test at speeds faster than 3 mph. Coefficients thus measured ranged from 0.269 on natural sandy soil to 0.431 on dry wood block pavement, with dry concrete about 0.401.

In 1927 the Iowa researchers expanded the tractive resistance and braking tests. For the braking tests the test vehicle was a stripped-down touring car chassis equipped with four-wheel brakes and balloon tires and weighted to give a gross load of exactly 500 pounds per wheel. The vehicle was towed at a speed of 4 to 5 mph while the pulling force was measured with the Kohlbusch dynamometer. For side skidding measurements, two towing vehicles were used—one to pull the test vehicle forward and the other to pull it sideways in a skid. The coefficients for both straight and side skidding thus measured were substantially higher than those measured in the 1923 research. (*7*)

British, French, and American Skid Testers

Meantime, the British Ministry of Transport was developing a skid tester to measure the resistance to skidding of highway surfaces. This was a test wheel equipped with a standard pneumatic tire which was towed by a motorcycle from an outrigger. The wheel was attached to the outrigger through a vertical pintle so that it was free to swivel from side to side like a dolly, through an arc of about 20°. For running a test the wheel was set at an angle of 18° to the direction of travel, so that in effect, it was dragged over the road surface. The frictional force thus generated tended to push the wheel into a position parallel to the direction of travel and the force required to do this was measured by an oil-pressure dynamometer. Vehicle speed and dynamometer pressures were automatically recorded on a chart driven by clockwork carried in a sidecar mounted on the outrigger. Tests were usually run during rain when the coefficient of friction was lowest. (*8*)

Three skid testers based on the same principle as the British apparatus were developed in France about the same time. In 1932 Moyer at the Iowa Engineering Experiment Station, and Stinson and Roberts at the Ohio Engineering Experiment Station simultaneously developed trailer-type skid testers. The horizontal force required to pull these test trailers after the brakes were applied was measured by a dynamometer and automatically recorded along with the speed on clockwork-driven charts. Both trailers could be adjusted to measure either straight-line skidding or side skidding. The Iowa skid tester was pulled by a truck carrying a water tank and sprinkler with which the pavement could be flushed just ahead of the test wheels. The Ohio researchers made all their tests during appreciable rainfall, after the dust had been washed from the road surface. (*9, 10*)

The Three Types of Skidding

All these investigations showed that there were basically three types of skidding. The first was a locked-wheel slide, which occurred when the brakes were applied suddenly as in a panic stop. The coefficient of friction, that is, the ratio of the force causing the tires to skid to the load on the tires, for this *straight skid* condition was referred to as the *kinetic coefficient of friction*. Applying the brakes gradually to the point where the wheels were turning but skidding was imminent produced the *skid impending* condition at which the *static coefficient of friction* was measured. The third type of skidding occurred if the tires were skidded sideways as when rounding a curve with inadequate superelevation.

For paved road surfaces such as asphalt and concrete the *skid impending* condition gave the highest coefficient of friction, especially at high speeds; but, as Moyer pointed out, this coefficient had little practical application since few automobile braking systems were perfectly adjusted and even fewer drivers had the skill to bring their vehicles to a fast stop without locking at least one wheel. Most skid resistance measurements were therefore made for the skidding straight ahead or side skid conditions.

All observers found tremendous differences in skid resistance between different types of surfaces, between dry surfaces and the same surfaces when wet, between the same surfaces tested at low speed and at high speed, and between various tread patterns and inflation pressures of tires. In the Iowa tests new tires skidding straight ahead on wet asphaltic concrete surfaces generated coefficients of friction of 0.80 at 10 mph and 0.55 at 40 mph. For the same wet surfaces and tires the side skid coefficients were 1.0 at 10 mph dropping to 0.85 at 40 mph. For wet portland cement concrete and new tires the straight skid coefficients were 0.65 at 10 mph dropping to 0.40 at 40 mph while the side skid values were 0.80 at 10 mph and 0.60 at 40 mph. If there was mud on the concrete, the straight skid and side skid coefficients at all speeds might drop to 0.20 or 0.25; and if the surfaces were icy, they might be as little as 0.15 or even 0.05. The Iowa researchers concluded that to be reasonably free from the danger of skidding when wet, road surfaces should have a side skid coefficient of 0.50 or higher at 30 mph and a straight skid coefficient of at least 0.40 at 40 mph. (9)

Stopping the Vehicle—Driver Reaction Time

But Moyer did not stop there. He went on to show that if a driver requires one-half second to size up the situation and react by pressing the brake pedal, then it will take 250 feet to bring his vehicle to a stop from a speed of 56 mph on a road surface with a coefficient of friction of 0.50. For a speed of 81 mph this stopping distance would increase to 500 feet. Such a stop would impose a decelerative force of 16.1 feet per second per second—one-half the acceleration of gravity—on the occupants of the car, which Moyer thought would be a reasonable maximum for safety and comfort. To allow for more slippery surfaces, slower reaction times, and less effective braking systems, Moyer recommended that a minimum clear sight or stopping sight distance of 1,000 feet be adopted for main highways.

Moyer probably got his figure for driver reaction time from earlier research in which Moss and Allen in 1925 investigated the personal equation in driving. (*11*) These investigators mounted two revolvers under the running board of a car pointing down to the road. They then tested 57 drivers of different ages, sexes, and intelligence. The observer, who rode in the front seat beside the driver, fired one pistol as the signal for the driver to apply the brake. The first indication of pressure on the brake pedal fired the other gun automatically. Shells loaded with red lead were used so both shots left red spots on the pavement. Since the vehicle speed was known, the reaction time could be calculated by measuring the distance between the two spots; thus if the speed was 44 feet per second and the distance between spots was 22 feet, the reaction time was 0.5 second.

Moss and Allen found that reaction times varied from 0.31 second to 1.02 seconds, with an average of 0.54 second. Reaction time varied little with the age and sex of drivers or with vehicle speed, but tended to be shorter for persons of high intelligence and for practiced drivers. They thought it likely that in a randomly selected group of drivers many could be found with reaction times as high as 1.5 or even 2 seconds.

How Side Friction Is Developed

Moyer went even further than recommending safe stopping distances. Using three standard automobiles as test vehicles, he ran a series of tests on actual highway curves to determine how the balancing frictional force which counteracts the centrifugal force is developed. When a vehicle is steered around a curve at very low speed, the front wheels are turned at an angle to the axis of the vehicle. This *theoretical steering angle* depends on the radius of the

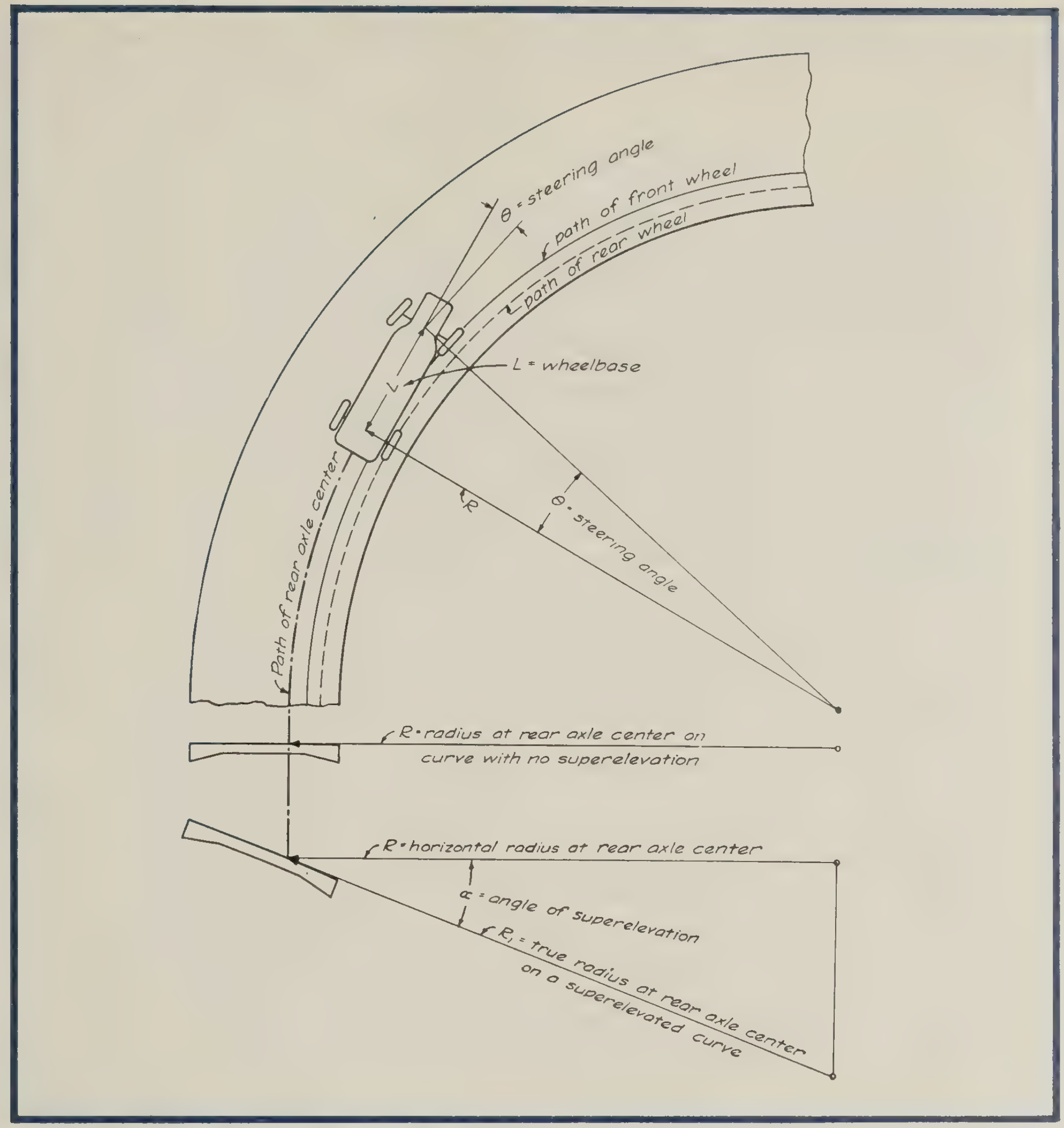
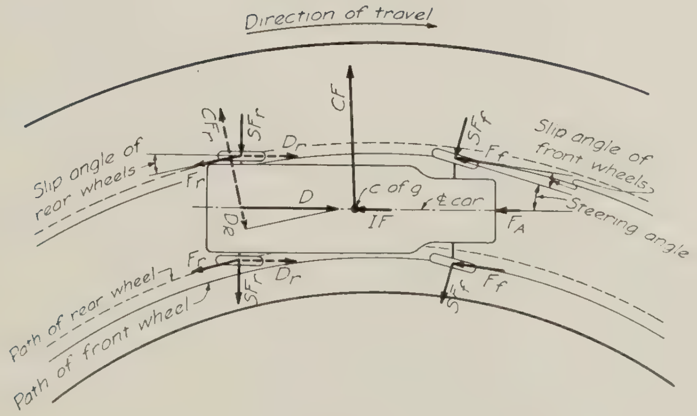


Figure 1.—Vehicle rounding curve at very low speed. (9)



Legend

CF	Total centrifugal force
CF_r	Centrifugal force on rear wheels
D	Total driving force
D_R	Radial component of driving force
D_r	Driving force on rear wheels
F_A	Air resistance
F_f, F_r	Rolling resistance, front and rear wheels
IF	Inertia force
SF_f, SF_r	Side skid force, front and rear wheels

Figure 2.—Vehicle rounding curve at constant speed. (9)

curve and the wheelbase of the vehicle (fig. 1). If the speed of the vehicle is increased, some centrifugal force will be developed which must be resisted by side friction between the tires and the road. To develop this side force the driver must turn his front wheels a little more than the theoretical steering angle, thus in effect dragging or scuffing the tires a little. The additional angle causing this slippage is the *slip angle*. On a level curve this slip angle will vary with the speed, the coefficient of friction between the tires and the road, and the design of the vehicle's front wheel suspension. It may vary from only a few minutes for very flat curves or low speeds to several degrees for high speeds and sharp curves.

In his tests of side skidding with the Iowa trailer, Moyer showed that the coefficient of side friction increases uniformly from zero at zero slip angle up to a maximum at 8° slip angle which depends on the tire and the road surface. Further increase in the slip angle beyond 8° produces practically no increase in friction.

The development of friction at the rear wheels is somewhat different because they cannot be steered. At very low speeds the rear wheels normally track inside the front wheels, the offset depending on the curve radius (fig. 1). As centrifugal force is developed by higher speeds, the rear end of the vehicle swings outward until its axis is no longer tangent to the circular path and the rear wheels are slightly angled to the direction of movement thus developing side friction (fig. 2).

Now suppose the pavement is tilted or superelevated by raising the outer edge. This introduces a centripetal force due to gravity which opposes the certifugal force; and if the curve is fully superelevated, all of the centrifugal force will be neutralized by the superelevation and there will be no need to develop side friction. When this condition is achieved, the slip angles can be zero.

Practical Limits to Superelevation

There are, however, practical limits to superelevating curves on public highways, for if the tilt is steep and the surface is slippery or icy, slow-moving vehicles may not generate enough centrifugal force to overcome the gravity force, and may slide down the tilted road surface toward the center of the curve. Because of this, most countries hold the maximum cross slope below 10 percent. Thus, even on superelevated curves, some side friction must be developed between the tires and the road surface. Although coefficients for side skidding on wet pavements of 0.50 or even 0.60 were easily developed on most pavement surfaces by the Iowa skid trailer, Moyer thought that such values could not be consistently relied on under average driving conditions, and he recommended using a value of no more than 0.30 for the useful coefficient of friction to counteract centrifugal force. (*12*)

To confirm this arbitrary figure based on judgment, Moyer observed blindfolded passengers in vehicles traveling on curves. When driven at speeds such that a coefficient of 0.10 was required to counteract centrifugal force, the passengers could not sense clearly whether they were on a curve or a tangent. At faster speeds such that the coefficient was increased to 0.20, the passengers could clearly sense that they were on a curve; and when the coefficient was increased to 0.30 by further speed increase, they felt distinctly uncomfortable. At this speed the passengers and drivers felt a decided side pitch and some of the cars developed tire squeal on dry pavements. The skill of the drivers was taxed to hold the front wheels on the curve. Moyer therefore concluded that ". . . the maximum permissible speed on curves should not exceed that for which a useful coefficient of 0.3 to counteract centrifugal force is required." To be sure of developing this coefficient over a wide range of speeds, curvature, and driving practice, he stated that road surfaces should be constructed to provide a side skid coefficient of at least 0.60 at 30 mph, as measured by the Iowa test trailer. (*9*)

Dynamic Basis for Transition Curves

We have seen that as early as 1920, Luedke and Harrison had recommended inserting a transition curve of variable radius between the tangent and the circular curve to enable the driver to gradually adjust to the horizontal change in direction and the superelevated road surface. In 1932, F. G. Royal-Dawson enlarged on this idea by proposing a dynamic basis for the design of transition curves. (*13*) As was well-known, a vehicle traveling on a curve at constant speed accelerates toward the center of the curve at the rate of $\frac{v^2}{R}$, where v is the velocity in feet per second and R the radius in feet. On the other hand, when traveling on a tangent at uniform speed, there is no acceleration at all. The problem therefore is to achieve the change in acceleration at a uniform rate that is comfortable and safe for the driver and passengers.

The acceleration, $\frac{v^2}{R}$ on a 1,000-foot radius curve at a speed of 50 mph is 5 1/3 feet per second per second. If the rate of change is held to 1 foot per second per second, it would take 5 1/3 seconds to make the transition, which at a speed of 50 mph (73.3 feet per second) would require a transition curve 470 feet long. Common experience told Royal-Dawson that this was much more than was actually needed by the average driver at this speed, so he suggested using a greater rate of change for normal design, say 2 or even 3 feet per second per second.

In 1934 Moyer observed that a rate of change of acceleration of 2 feet per second per second was adequate and comfortable for the drivers of test cars on curves where side skid coefficients of 0.2 or more were necessary to keep the car turning in its proper lane. (*9*) With this rate of change Royal-Dawson's expression for transition length became:

$$L=\frac{1.58V^3}{R}$$

Where,

L=Length of transition curve in feet.

V=Speed in miles per hour.

R=Radius of curve in feet.

This equation, Moyer observed, was practically the same as that for the American Railway Engineering Association's spiral easement curve (originally proposed by A. N. Talbot). (9)

He went on to demonstrate the value of spiral transitions to the automobile driver traveling at high speeds by an example: According to the above formula the length required to transition from a tangent to a curve of 1,000 feet radius would be 43 feet for 30 mph, 340 feet for 60 mph, and 825 feet for 80 mph. For these spiral curves the shift of the central portion of the curve toward the center, or the *easement,* would be 0.1 feet for 30 mph, 4.8 feet for 60 mph, and 28.4 feet for 80 mph. (This shift, known to road engineers as the offset, *p,* increases as the sixth power of the speed.)

At 30 mph it would be relatively easy for the driver to form his own spiral by shifting 0.1 foot on an unspiraled curve. However, at 60 mph, shifting his path 4.8 feet would be quite another matter, for the driver would have to start his maneuver outside his own lane to stay on the road. The shift of 28.4 feet for the 80 mph transition would be quite impossible on a two-lane road, even assuming the driver was willing to drive a 1,000-foot-radius curve that fast.

Not everyone agreed with Moyer on his recommended rate of 2 feet per second per second of change in acceleration on spirals. The Oregon Highway Commission, for example, was using 3 feet per second per second for figuring spiral lengths on main trunk highways about the time Moyer was making his tests. (*14, 15*)

The studies of driver reaction and skidding we have just examined provided the necessary groundwork for the logical development of the *balanced design* concept that has dominated all subsequent geometric design practice. We will examine this development in Part 6.

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(*5*) A. J. Schamehorn, "What About Spiraling?" *Engineering News-Record,* vol. 115, Sept. 8, 1938, p. 293.

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(*13*) F. G. Royal-Dawson, "Elements of Curve Design for Road, Railway, and Racing Track on Natural Transition Principles," *Spon and Chamberlain,* London, 1932.

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(*15*) Thomas F. Hickerson, "Highway Surveying and Planning," 2d ed., *McGraw-Hill,* New York, 1936, p. 190.

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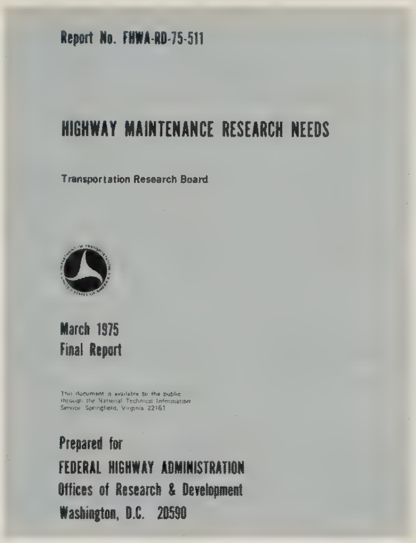
Implementation/User Items "how-to-do-it"

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

Highway Maintenance Research Needs

by Transportation Research Board for the FHWA Implementation Division



Report No. FHWA-RD-75-511

HIGHWAY MAINTENANCE RESEARCH NEEDS

Transportation Research Board

March 1975
Final Report

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D.C. 20590

This report describes the planning and results of an FHWA-contracted study by the Transportation Research Board for the development of a recommended highway maintenance program. The study included regional meetings held in Illinois, Georgia, and Texas. They were followed by a national workshop session attended by nearly 60 maintenance experts from across the country. At this session, 28 major problems in nine maintenance areas were identified.

After performing an analysis of the cost, length, and benefits of research projects for each problem area, a priority list of research projects to solve each problem was formulated. Among the top subjects on this list were improved procedures to optimize the expenditure of maintenance funds, better procedures to manage the use of deicing chemicals, the development of equipment to recycle used highway materials, studies to more accurately determine the effects of increased vehicle weights and dimensions, and better integration of maintenance needs into preconstruction procedures.

The report includes a discussion of the workshop, a discussion of the analysis and its results, and numerous tables and figures presenting the procedures, results, and recommendations of the workshop.

This report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Stock No. PB 247125).

The Use of Polymer Concrete for Bridge Deck Repairs on the Major Deegan Expressway

by Brookhaven National Laboratory for the FHWA Implementation Division

The rapid deterioration of concrete bridge decks is a major problem facing the highway industry. Repairing deteriorated structures with polymer concrete is one solution presently being tested. Because of its quick cure time and superior structural and durability properties, polymer concrete was used in the project described in this manual—the repair of two large holes on the Third and Lincoln Avenues viaduct of the Major Deegan Expressway in New York City. The expressway has a high volume of traffic and the repairs had to be done quickly without closing the entire roadway. This project demonstrated the practicality of using polymer concrete in such situations. The manual includes descriptions of the materials and procedures used, the method of traffic control, and a cost analysis.

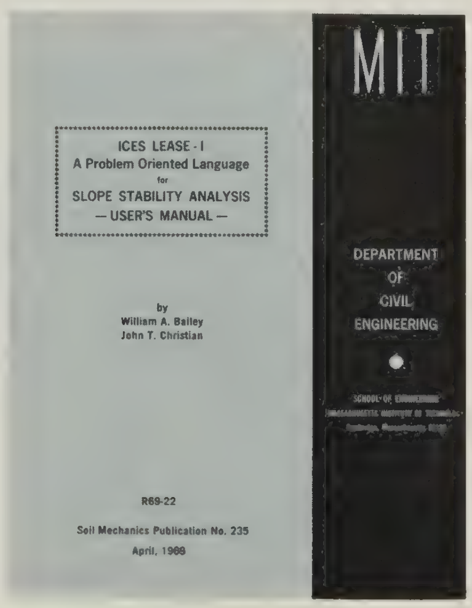
This report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22161 (Stock No. PB 246048).

Breakaway Barricade

by Nevada Department of Highways and FHWA Implementation Division

The Type III Barricade (Special) is used to control and channel traffic and is constructed of polyvinyl chloride (PVC) conduit. Reflective panels and anchor devices use wood, aluminum, and steel where necessary to insure functional operation of the barricade. The barricade breaks away instantly on impact because it relies on pipe joint friction rather than cemented joints. The various parts of the barricade will fly clear of the frame and the impacting vehicle resulting in minor damage to the vehicle, little loss of control, and no injury to the driver or occupants of the vehicle. The modular design of the barricade allows for easy and low-cost replacement of any damaged components. The barricade can be moved by one person without assistance and assembly and disassembly take only a few minutes. This allows the barricade to function effectively, consistent with its design and functional intent.

A user manual detailing the development and testing of this barricade is available through the Implementation Division and a film can be obtained through the FHWA regional offices (see page 179).



ICES LEASE-I A Problem Oriented Language for Slope Stability Analysis—User's Manual

by Massachusetts Institute of Technology

The LEASE I (Limiting Equilibrium Analysis in Soil Engineering) computer program, a subsystem of ICES (Integrated Civil Engineering System), is designed to perform stability analysis of arbitrary slopes by the method of slices. The failure surfaces are assumed to be arcs of circles. Analyses can be performed by either the total or effective stress method, depending on the input of appropriate soil strength properties and piezometric conditions. In addition, the program will locate the radius having a minimum factor of safety at each center in a specified grid of trial centers. Alternatively, a search routine is provided that can be useful in locating the center and radius of the critical trial failure surface.

This program is one of the best presently available for performing circular arc analysis. It has several advantages: It is completely user-oriented as it was developed for practical use by geotechnical engineers; input is clear, simple, and logical; and the program can be modified easily by inserting data cards specifying the desired changes at the end of the primary data deck. The program is written in standard FORTRAN IV computer language.

The LEASE program is available from ICES Distribution Agency, P.O. Box 3956, San Francisco, Calif. 94119, and the user's manual can be obtained from Massachusetts Institute of Technology, Civil Engineering Systems Laboratory, Room 1–139, Cambridge, Mass. 02139.

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 1A: Traffic Engineering Improvements for Safety

Title: Vehicle Detector Placement for High-Speed, Isolated Traffic Actuated Intersection Control. (FCP No. 31A2514)
Objective: Develop criteria for vehicle detector placement at traffic actuated signals including optimal loop configurations. Design, configuration, and location of detector systems and their interaction with various types of signal controllers including semi-actuated, full-actuated, volume density, and advanced controllers using minicomputers and microprocessors.
Performing Organization: Urban Interface Group, Laguna Beach, Calif. 92651
Expected Completion Date: March 1977
Estimated Cost: $186,000 (FHWA Administrative Contract)

FCP Project 1D: Improved Traffic Safety and Capacity on Two-Lane Rural Roads Through Speed and Hazard-Warning Displays

Title: Maine Facility—Traffic Research Field Laboratory Development, Operation, and Maintenance. (FCP No. 31D1613)
Objective: Continue development and manage the Maine Facility including utilization and maintenance for experimental research and analysis of problems on two-lane highways. Implementable solutions to problems of traffic safety, operations, and capacity will be developed.
Performing Organization: Transportation Systems Center, Cambridge, Mass. 02142
Expected Completion Date: October 1976
Estimated Cost: $464,000 (FHWA Administrative Contract)

FCP Project 1H: Skid Accident Reduction

Title: Seasonal Skid Resistance Variations. (FCP No. 41H3352)
Objective: Develop a methodology for predicting from a skid measurement made at any time during the year the lowest value a well-established pavement will attain during the same year.
Performing Organization: Pennsylvania Transportation Institute, University Park, Pa. 16802
Funding Agency: Pennsylvania Department of Transportation
Expected Completion Date: October 1978
Estimated Cost: $167,000 (HP&R)

Title: Sprinkle Mixes for Skid Resistance Surfaces. (FCP No. 31H8424)
Objective: Conduction of an in-depth analysis of all the elements used for sprinkle mix in a roadway pavement. Based on this analysis the various aspects and problems relating to all phases of sprinkle mix application, from basic design through final construction and maintenance on bituminous and concrete pavement, will be presented in a format usable by all highway agencies.
Performing Organization: Texas State Highway Department, Austin, Tex. 78701
Expected Completion Date: September 1976
Estimated Cost: $60,000 (FHWA Administrative Contract)

FCP Project 1J: Improved Geometric Design

Title: Design Criteria for Median Turn Lanes. (FCP No. 41J2132)
Objective: Survey current geometric design and traffic engineering practices for noncontrolled-access urban arterial and collector streets in a representative sample of cities. Develop documentation and guidelines for design and operational decisions

for median treatment for these facilities.
Performing Organization: Center for Highway Research, Austin, Tex. 78712
Funding Agency: Texas Highway Department
Expected Completion Date: August 1977
Estimated Cost: $51,000 (HP&R)

FCP Project 1O: Aids to Surveillance and Control

Title: Railroad-Highway Grade Crossing Safety. (FCP No. 31O1064)
Objective: Evaluate new candidate passive grade crossing warning systems at about 70 railroad-highway grade crossings in the 25 participating States. If a new signing and marking system is determined to be more effective than the existing cross-buck system, a change to the MUTCD will be recommended.
Performing Organization: Transportation Systems Center, Cambridge, Mass. 02142
Expected Completion Date: October 1976
Estimated Cost: $208,000 (FHWA Administrative Contract)

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

FCP Project 2C: Requirements for Alternate Routing to Distribute Traffic Between and Around Cities

Title: Integrated Motorist Information System Feasibility and Design Study. (FCP No. 32C3012)
Objective: Phase I—Alternative preliminary designs and feasibility analysis (based on benefit-cost ratios) of an Integrated Motorist Information System for the Northern Long Island (N.Y.) Corridor. Phase II—Development of a generalized feasibility methodology for such a system applicable to any specific site. Phase III—PS&E for selected design from Phase I (planned follow-on).
Performing Organization: Sperry Systems Management, Great Neck, N.Y. 11020
Expected Completion Date: May 1977
Estimated Cost: $624,000 (FHWA Administrative Contract)

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: Effects of Highway Construction on Blockhouse Creek and Stream Valley Run. (FCP No. 43E2212)
Objective: Sediment concentrations, sediment discharges, turbidity, and changes in the two streams will be monitored during and after construction. This data will be used with other similar data being developed in Pennsylvania to help develop and refine an equation for predicting sediment loads caused by construction.
Performing Organization: U.S. Geological Survey, Harrisburg, Pa. 17120
Expected Completion Date: September 1978
Estimated Cost: $98,000 (FHWA Administrative Contract)

FCP Category 4—Improved Materials Utilization and Durability

FCP Project 4B: Eliminate Premature Deterioration of Portland Cement Concrete

Title: Investigation of Bridge Deck Protective Systems. (FCP No. 44B1474)
Objective: Determine the effectiveness of various protective systems that may be applied to the surface of concrete bridge decks to eliminate or retard the corrosion process. Systems include cathodic protection, Iowa method low-slump concrete, Dow latex modified concrete, and several membrane systems.
Performing Organization: Missouri State Highway Commission, Jefferson City, Mo. 65101

Expected Completion Date: September 1980
Estimated Cost: $138,000 (HP&R)

Title: Cracked Structural Concrete Repair Through Epoxy Injection and Rebar Insertion. (FCP No. 44B2253)
Objective: Develop a method for epoxy bonding of bridge girder cracks larger than those which can be effectively treated by present techniques. It is intended that the new method will allow distribution of injection epoxy from the center of the failed girder radially outward to the surface while at the same time allowing for emplacement of one or more No. 5 or smaller rebars across the fracture being repaired.
Performing Organization: Kansas State Highway Commission, Topeka, Kans. 66612
Expected Completion Date: June 1978
Estimated Cost: $50,000 (HP&R)

Title: Improvement of Non-Durable Aggregates in Portland Cement Concrete. (FCP No. 44B3101)
Objective: Investigate pore size distribution of aggregates and its relation to field and laboratory freezing and thawing performance.
Performing Organization: Purdue University, West Lafayette, Ind. 47907
Funding Agency: Indiana State Highway Commission
Expected Completion Date: October 1977
Estimated Cost: $51,000 (HP&R)

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

Title: Freeze-Thaw Properties of Portland Cement Concretes Made With Natural Pozzolans and Fly Ash. (FCP No. 24C2074)
Objective: Pozzolans from three sources will be studied. Concrete mixes will be made with varying percentages of each pozzolan. Testing will be initiated at constant age and constant maturity. Tests will include freeze-thaw, scaling resistance, chloride permeability, skid resistance, compressive and tensile strength and modulus of elasticity, drying shrinkage, and abrasion resistance.
Performing Organization: Federal Highway Administration, Washington, D.C. 20590
Expected Completion Date: December 1976
Estimated Cost: $51,000 (FHWA Staff Research)

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

Title: The Investigation of Present Aggregate Gradation Control Practices and the Development of Shortcut or Alternative Test Methods. (FCP No. 34F7024)
Objective: Survey current gradation control practices to determine any shortcut or alternative methods in use. Investigate and evaluate these shortcut methods. Analyze available statistical data on gradation testing in order to make recommendations for new sampling and testing frequencies.
Performing Organization: Federal Highway Administration, Vancouver, Wash. 98661
Expected Completion Date: April 1977
Estimated Cost: $96,000 (FHWA Administrative Contract)

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

FCP Project 5F: Structural Integrity and Life Expectancy of Bridges

Title: An Experimental Segmental Bridge. (FCP No. 45F3124)
Objective: Evaluate the design, construction, and structural behavior of an experimental segmental bridge, including laboratory testing of bridge segments and special specimens.
Performing Organization: Pennsylvania State University, State College, Pa. 16802
Funding Agency: Pennsylvania Department of Transportation
Expected Completion Date: March 1977
Estimated Cost: $659,000 (HP&R)

Instructions to Authors

All articles proposed for publication in Public Roads magazine are reviewed for suitability by the technical editors. Authors will be notified of acceptance or rejection as soon as possible.

Recent issues of the magazine should be reviewed for type of articles, style, illustrations, tables, references, and footnotes.

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Three copies of the manuscript should be submitted to the Managing Editor.

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However, authors outside of government employ, or in other government agencies (State, city, local), should submit manuscript copies through appropriate Federal Highway Administration regional offices (see page 179).

Manuscript Format

Manuscripts should be typewritten, double spaced, with at least 1-inch margins on 8- by 10½-inch paper. Approximately three manuscript pages should be allowed for one magazine page, excluding art. Paragraphs should be indented and each page should end with a completed paragraph. Main headings should be centered and typed in initial caps. Subheadings should be flush left and the first letter only capitalized. Metric (SI) equivalents should be included in parentheses after any English unit measure. The article title and the name of each author should be typed on a separate page. If the article has been presented at a meeting, that should be indicated in a footnote at bottom of title page. Each page of the text should be numbered in the upper right margin.

Biography

A brief biographical sketch of each author should be supplied. This should include the author's present position and responsibilities and previous positions relevant to the subject matter of the article. Biographies are limited to approximately 100 words.

Abstract

An abstract should be supplied with technical articles. In the *development report* it should tell: (1) What has been accomplished, (2) its outstanding features, and (3) its applications, if known. The abstract of a *research paper* should focus on: (1) What has been accomplished, (2) its most important facts and implications, and (3) logical next steps open to study.

Tables

Nonessential technical tables should not be included in the article. Each table should be typed on a separate page. It should be identified by an Arabic number and a caption. Position of the table in the text should be noted in the margin. The article should be planned so that a table will not be located on the first (title) page. Details of data already presented in tables or charts should not be repeated in the text.

Illustrations

Illustrations *referenced in the text* are called figures, and numbers and captions should be assigned to each. The text should be organized so that illustrations can be scattered throughout the article. The referencing of several illustrations in one page should be avoided, as this presents problems in the layout. Black and white, glossy photographs of good quality are preferred; however, color photographs and art are acceptable. Original art work should be sent to the editor when the author is notified that his article has been accepted for publication. Legible copies should be sent with the manuscript. All captions (numbered and unnumbered) should be typed underlined on a separate page.

References

References should be numbered consecutively in the body of the text, enclosed in parentheses, and underlined. When copyrighted material is referenced and quoted, copyright releases should be obtained. Unpublished material referenced in the text will be described in a footnote. Material cited should be typed on a separate page under the heading REFERENCES. References should be numbered in the same manner as in the text and listed in the same sequence.

Galley Proofs

Galley proofs will be sent to authors for their approval.

For further information, contact the editor: (703) 557–4301.

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

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

STRUCTURES

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PB 242168	Investigation of a Vibratory Electronic Device for Non-Destructive In-Place Measurement of Various Pavement and Soil Layers.
PB 244268	Field Testing of Horizontally Curved Steel Girder Bridges—Fourth Interim Report.
PB 244456	A Study of Field Performance of an Experimental Portland Cement Concrete Pavement.
PB 244461	Pavement Deflection Measurement—Dynamic. Phase IV—Final Report.
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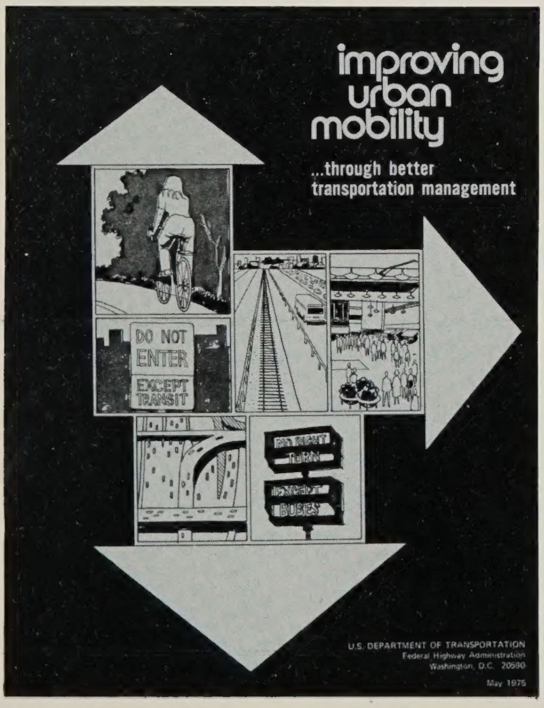
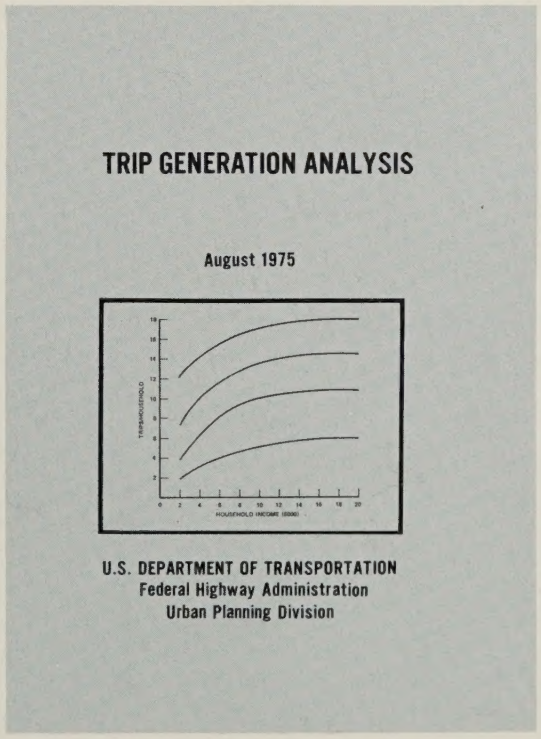
Improving Urban Mobility—Through Better Transportation Management provides suggestions for and illustrations of many transportation system management strategies to improve urban transportation. It shows a variety of techniques to improve the efficiency of existing roadways. Included are ways to facilitate bus movement and promote the use of high occupancy vehicles, such as carpools and vanpools. Alternative methods of transportation are also presented and discussed, as well as suggestions for adjusting the demand for transportation services. Throughout the brochure, problems of efficiency, environmental protection, and energy conservation are considered.

This brochure should be of interest to anyone involved with the planning and decisionmaking necessary for an efficient transportation system in an urban area. It may be purchased for $1.05 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Stock No. 5001–00098–9).



Trip Generation Analysis provides a step-by-step approach to trip generation analysis which should be pertinent in many current urban transportation studies. The approach presented is straightforward, based on logic and common sense, easily monitored, and can be updated with more efficient use of survey and secondary source data. It is easily understood by the administrator and the public and allows application to the various geographic units required for regional, corridor, and small area studies. The approach is based on dwelling unit cross classification for residential trip generation and on rates for non-residential generation.

The manual includes an evaluation of trip generation results, considerations to be made in trip forecasting, and monitoring and surveillance techniques for trip generation. It may be purchased for $2.30 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402 (Stock No. 050–001–00101–2).



Capacity Analysis Techniques for Design and Operation of Freeway Facilities is a sequel to the 1967 publication "Capacity Analysis Techniques for Design of Signalized Intersections." This manual presents a procedure for the graphic solution of the capacity of freeway facilities to simplify the work required by the computational procedures in the Highway Capacity Manual. Figures and nomographs have been developed to solve the capacity problems on through lanes, exit and entrance ramps, and ramp terminals. A full discussion of the principles and procedures in the application of the figures and nomographs in addition to sample problems are included in this publication.

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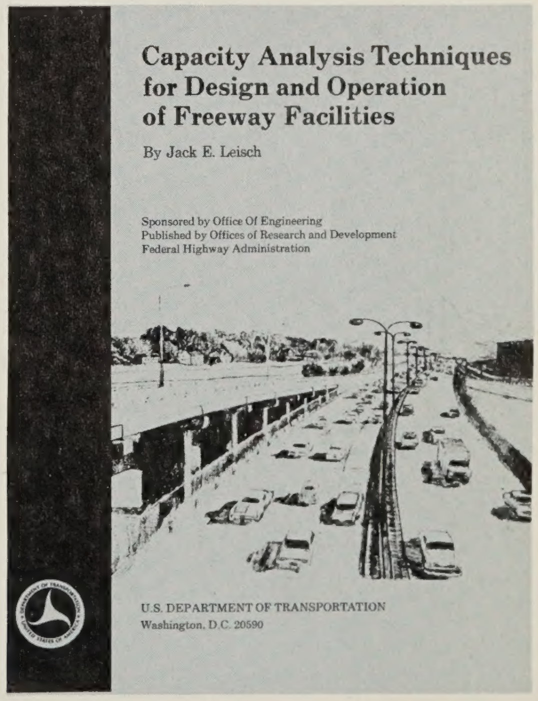

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