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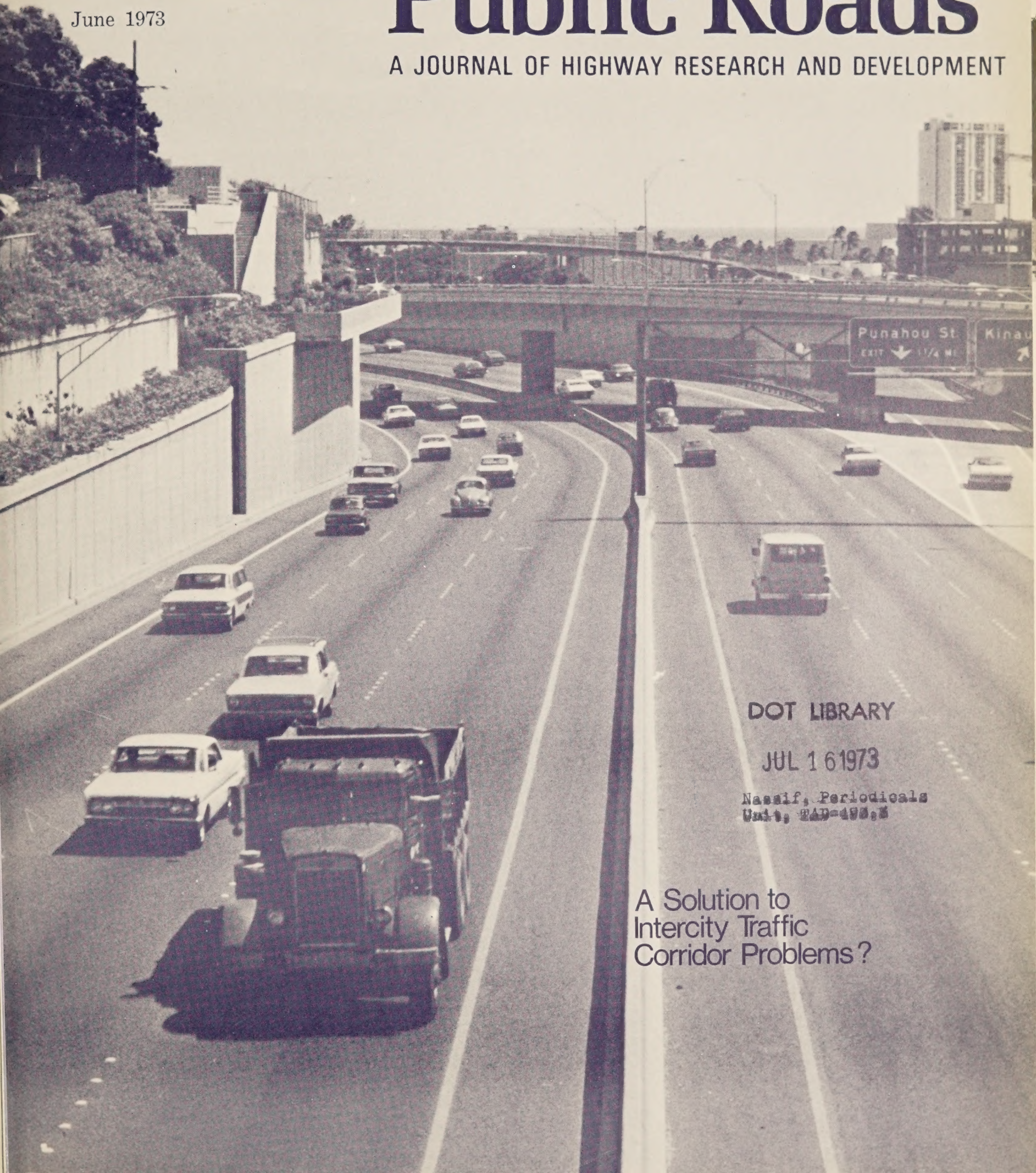

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COVER

Interstate H-1 near downtown Honolulu. (Photo courtesy of the Hawaii Department of Transportation.)

A SOLUTION TO INTERCITY TRAFFIC CORRIDOR PROBLEMS?

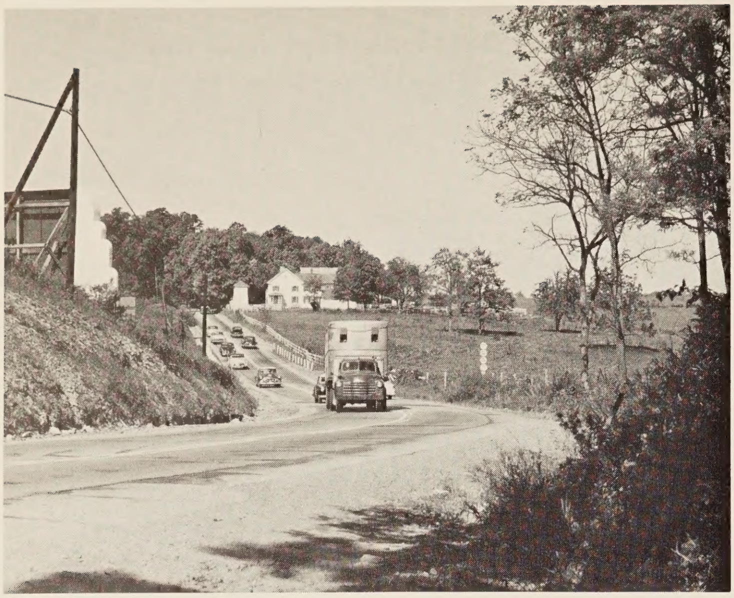
by M. F. Maloney, H. A. L. Lindberg, and G. W. Cleven

Introduction

THE approaching completion of the National System of Interstate and Defense Highways brings to conclusion an era of highway construction unprecedented in world history. In terms of added capacity, the gain has been tremendous; but in terms of added roadway mileage, the Interstate System accounts for just slightly over 1 percent of the Nation's total roadway mileage. It is interesting to note that in 1916, the country had nearly 3 million miles of roads and streets, whereas today, total mileage has increased by less than one-fourth to a total of 3.7 million miles. The population in 1916 was 102 million people who in turn possessed 3.6 million motor vehicles. Today, we are aware of the fact that while the population has doubled, the vehicle population has increased more than thirty-fold. Investment in the last half century has not been primarily for new roads, but for improving existing systems.

While the public's attention seems to be focused on the environmental impact of highway construction, highway departments have had to take a fresh look at the operation of the new system. It is the purpose of this paper to examine some critical aspects of contemporary traffic operations and to outline the role that modern control systems could play in alleviating problems, especially in regard to Interstate and other freeway type facilities including their adjacent parallel primary or even secondary routes. The paper's emphasis is placed on traffic corridors containing both through and local traffic and having a high type multilane freeway as the major backbone traffic carrier.

To understand the problems which have developed and which require new solutions, it is perhaps helpful to examine everyday traffic operations in the past, say 1940, with that of the present, and with that envisioned for 1979, which is the planned completon date of the Interstate System. In the good old days of 1940 (as we like to remember them), over 90 percent of the rural roadway system consisted of two-lane highways, many having narrower lane widths and poorer geometrics than we are accustomed to today. Some of the two-lane highways in rolling and mountainous terrain provided truck climbing lanes but many segments did not; thus, the low-powered trucks then prevalent were a constant source of aggravation to other drivers.



Typical 1940 traffic operations.

There were also some three-lane highways (now almost extinct) and four-lane to six-lane undivided highways in or approaching cities. Divided highways with partial access control, commonly called expressways or boulevards, were becoming more prominent. The first freeway featuring complete access control was the Pennsylvania Turnpike (called a folly when it was under construction in the late 1930's but later hailed, upon opening, as the Eighth Wonder of the World). This turnpike opened with no speed limits, and some of its first operational experience consisted of drivers burning up their engines through continuous high-speed motoring. Though their sustained running durability was less, the automobiles of this vintage were considerably less complex to maintain and repair when a problem occurred on the road.

The users of the highway system in 1940 were represented by 45 million licensed drivers of which 24 percent were women. Travel totaled 300 billion vehicle-miles, which is just a quarter of today's travel. In general, it can be said that yesterday's motoring public was more self-sufficient in dealing with car problems encountered on the road.

In terms of driving practices of the earlier period, the average speed for uncongested conditions in this earlier period was approximately 45 mph. National fatality rates were higher than present day, 11.1 per 100 million vehicle-miles compared to 4.7 per 100 million vehicle-miles today; and driving on the heavier traveled routes involved considerable tension and fatigue as might be expected where opposing traffic streams were not separated by a median strip and where numerous roadside access points were encountered. One of the most common and difficult driving maneuvers was that of passing other vehicles in the face of opposing traffic on roads having 10 to 11 foot lane widths. A summertime trip of 400 miles was a major dawn-to-dark undertaking and could even extend into the next day. In contrast, many people drove on weekends for the sheer pleasure of motoring. A 50-mile drive to visit relatives was an event of some importance and was often reserved for Sundays, thus, leading to the term "Sunday driver."

In retrospect, the 1940 highway system seems to have been hazardous but certain advantages did exist. When congestion developed on a route (perhaps because of truck traffic on grades or an accident), the motorist could usually get off at a service station, roadside restaurant, or on a side road to attempt to bypass, alleviate, or wait out the problem. The roadways were unfenced and a motorist could easily gain access to a private home to use a telephone, if necessary. There was not any widespread fear of violence or crime along the roadway. As a matter of fact, perhaps as a carryover of the depression, hitchhiking was an accepted way of getting around.

In contrasting today's highway operations with those of 1940, a major transition period must be recognized, that of the advent and construction of the Interstate Highway System. The planning of the Interstate System goes back before the war years, but it was not until legislation was passed in 1956 that the construction program commenced on the 42,500-mile network of highways connecting many of our cities of 50,000 or more population. Planned as a strategic network of highways for defense purposes, the system was also to serve a growing need for traffic-carrying capacity and for mobility of the traveling public. Vehicle ownership had increased from 32 million in 1940 to 65 million in 1956, and travel had doubled to 600 billion vehicle-miles. The safety and "protected investment" aspects of controlled access freeways had been established in the 1940–1956 period and except for a few rural sections of low projected volume, the Interstate System was planned as a multilane intercity network.

The utility and safety benefits of Interstate type highways hardly need reiteration. These high design roadways have greatly reduced much of the tension, fatigue, and danger inherent to driving on the 1940 era highway system. And while the Interstate System is expected to carry approximately 20 percent of the daily traffic, it constitutes but 1.1 percent of the Nation's roadway mileage. Now that the Interstate System is about 80 percent completed, the pattern of a whole new set of operational problems has evolved.

An appraisal of current drivers, vehicles, highways, and trip characteristics leads to an understanding of the series of problems which requires solutions. Looking at the driver first, there are now 117 million vehicles, a 360 percent increase over 1940. Licensed drivers, however, total 119 million (close to 1 vehicle/licensed driver) of which approximately 44 percent are women. The increasing role of women drivers can be ascertained in the statistic that 80 percent of women in the 26–29 year age group are licensed to drive. In addition to the increased role of women, the advent of two, three, and four car families and the increased percentage of foreign cars has generated a condition where there are a great many types of cars on the road and a great variety of drivers. Not only are people, both women and men, less able to cope with mechanical problems, but mechanical service itself has suffered because of the great number of models. Mechanical problems do account for 25–30 percent of the disabled vehicles found along our freeway system. In one California urban area the rate for disabled stops has been found to be one per 26,000 vehicle-miles. Some 30 percent of these disabled vehicles cannot be repaired along the roadside and must be towed to a service facility.

A 1940 "Sunday drive" scene.

Primary highway of the 1940's—before access control.

There is also more variation in the vehicle performance characteristics because of the extreme difference in weight/horsepower between some low-powered subcompact cars and high-performance sports cars and sedans. There is also a large number and wide variety of trucks, including some triple bottoms, though the ability of truck traffic to maintain speed has greatly increased.

Finally the recent emphasis on recreational travel has resulted in a bewildering array of campers, travel-trailers, and other special purpose vehicles on the highways. The average American travels about 130 times a year for recreational purposes and will usually drive a vehicle for at least part of the trips, accounting for approximately 18 percent of the total vehicle-miles of travel. About 87 percent of these recreational trips are to places 20 miles or less in traveling distance; for example, a visit to the local bowling alley. The disparity in driver experience and vehicular characteristics has a logical connection to traffic conflicts and turbulence. As a countering influence, the motoring public has compensated to some degree for these differences. Traffic authorities and visitors from abroad are outspoken in their admiration of the traffic stream discipline of American drivers. It is undoubtedly one of the reasons why our accident and fatality rate is much lower than that experienced in Europe.

The Interstate System is a human-engineered highway network designed to "forgive" driver mistakes and to make the driver's task simpler. For example, weaving sections which require a high degree of driver skill have largely been eliminated by use of grade separations and separate roadways. The high volumes and high speeds encountered on these freeway facilities pose other problems, however, especially in regard to signing, motorist aid, loss-of-control vehicles, and buildup of congestion. The latest average speeds are 65 mph for rural Interstate traffic and 56 mph for urban Interstate traffic. The average speed for main rural highways is 61 mph which is 16 mph higher than in 1940. The laws of physics tell us that collisions which involve higher kinetic energies predictably should be more lethal at higher speeds. There are, however, offsetting factors such as the availability of seat belts, improved vehicle designs, and the increasing use of crash cushions and breakaway designs for roadside structures.

The Interstate System contains numerous protective features such as access control, median barriers, widely spaced ramp access, fencing to keep animals and people off the rights-of-way as well as other control features all designed to make the motorist's trip as conflict-free as possible. Yet there are drawbacks to these very positive attributes because while there is protection, there is also a sense of confinement. The motorist is increasingly isolated from his everyday living environment. Every motorist experiences a sense of frustration when he runs into a traffic backup on a freeway type facility. Despite the abundance of company involved in the same predicament, the cause and extent of delay to be expected are usually unknown; and, moreover, nothing can be done about it except to inch forward. If an exit ramp is reached, a decision, probably more often wrong than right, can be made regarding possible alternate routes. In some instances, the trapped motorist is stymied on a long overhead structure or perhaps in a depressed section where vertical retaining walls are present. Perhaps in extreme cases, motorists may have to depend on authorities to provide ladders for escape should a major fire or flood develop, but the overriding motorist's need is for "information."

To date, the helicopter patrol and subsequent traffic condition radio forecasts, commonly found in the large urban areas, have been of limited effectiveness from the standpoint of both adequacy and timeliness. In one city only 48 percent of the freeway accidents were reported by all three radio stations. The average time elapsed in the reporting of an accident varied from 21 to 27 minutes depending on the station. There was no indication given as to whether an accident, previously reported, had been cleared and little information was given to motorists to indicate the length of freeway affected by an incident. Radio reports of traffic incidents were, however, generally correct as to location. Despite the aforementioned drawbacks, the helicopter patrol can be useful, if a systematic approach is taken, in surveying and reporting area wide traffic conditions.

The predictable recurring congestion caused by demand exceeding capacity is well known by the commuting motorist through his daily driving experience. Traffic operation engineers in urban areas, however, estimate that half the congestion found on freeways can be attributed to nonrecurring events known as "incidents." An incident is defined as a flow disruptive event that occurs unpredictably, often during peak periods when demand is high, which in turn reduces the capacity and level of service provided by the freeway. Examples of incident-causation include accidents, stalled vehicles, and debris dropped on the freeway. Incidents (nonaccident types) can lead to accidents because of the abrupt changes in flow and speed. In Detroit it was found that 33 percent of the incidents led to accidents. It has been estimated that the number of urban freeway accidents resulting from vehicles stopped on the roadway exceeds 40,000 per year. There is also an estimate of 750 million vehicle-hours of delay per year resulting from urban freeway incidents.

An investigation of a Houston freeway showed an average of 250 stopped vehicles per mile per year on traveled lanes and 2,250 other shoulder stops which in themselves cause some traffic disruption and endanger stranded motorists. It is the incident-caused congestion that most aggravates the motorist because of its unexpected occurrence and unexplained cause and magnitude. The magnitude of the effects can be great because of the large volume of traffic carried by urban freeways. Here again, the high capacity of the freeway can paradoxically be a detriment because of the large volume of traffic being carried toward and accumulated in the disturbance area.

As an illustration, consider an eight-lane freeway (four lanes one direction) carrying a typical peak period demand of 6,000 vehicles per hour (vph). Now suppose an accident occurs which blocks two lanes and restricts the flow to 1,200 vph/lane on the remaining two open lanes (the usual rate past an accident where the motorists slow down and gawk). Assuming the accident is cleared in 30 minutes and capacity flow commences, the magnitude of the incident is in the order of 3,000 person-hours of delay distributed over approximately 12,500 vehicles. The effects of the incident extend over a 2-hour period because of the accumulation of queued vehicles, the maximum number in queue for this illustration being 1,800 vehicles at the point in time when the incident is cleared.

While the example above is illustrative of a major problem that is vexing to drivers, it is particularly frustrating to those responsible for highway operations because often there are parallel routes which could be used by motorists if they were aware of the problem ahead and of the parallel route. In fact, much of the Interstate System, especially on the East Coast, parallels the primary routes which carried most of the traffic before construction of the Interstate System. The popularity of freeways is such that while constituting 2.3 percent of the urban miles of roads and streets, they carry approximately 24 percent of the urban travel. Therefore, the parallel arteries often have unused capacity available for diversion of traffic. In many cases in suburban and rural areas, the available unused capacity might be even higher.

In the past decade the Federal Highway Administration (FHWA), the highway departments, and the remaining research and development community have geared up to develop remedial techniques for these emergent problems. A number of projects have been completed or are underway in such cities as: Detroit, Chicago, Houston, Los Angeles, Dallas, New York, Seattle, Boston, and Cincinnati. Nearly all of these projects are geared toward implementation of one or more of the following functions:

- Motorist information.
- Route diversion.
- Freeway incident detection and management.
- Ramp metering.
- Motorist aid/emergency communication.

Scenario for Tomorrow

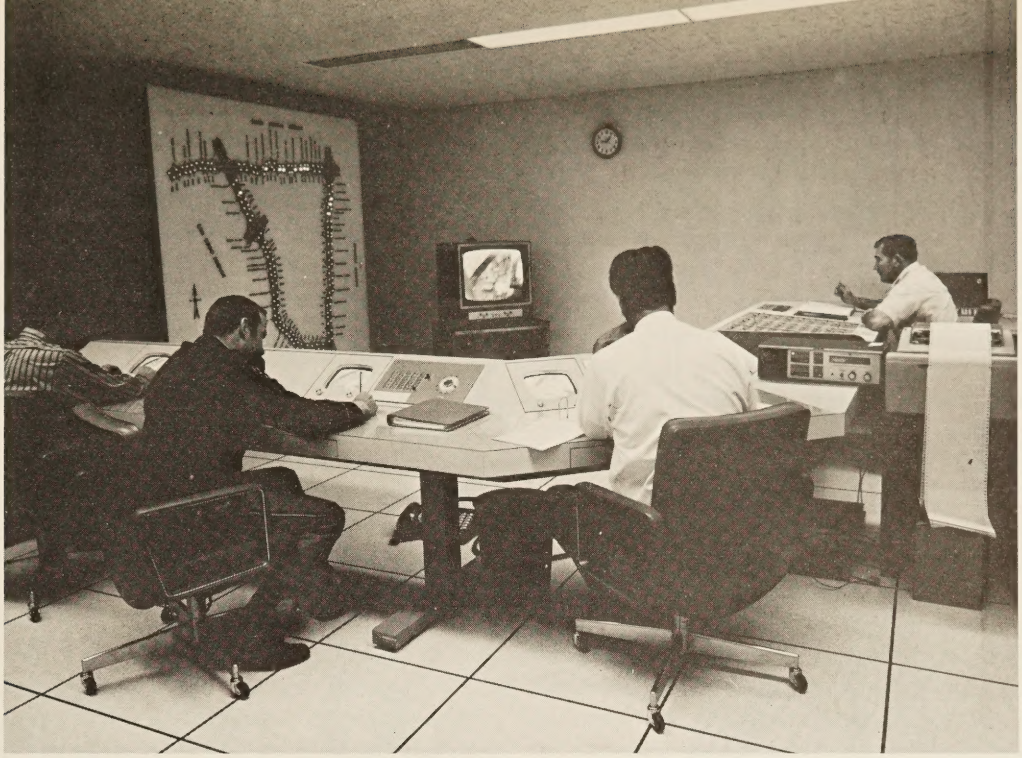
In order to illustrate the use of an "integrated motorist information system," which incorporates the functions described heretofore, let us see it in operation from the point of view of the driver. Specifically, let us follow Mr. Traveler and his family on an intercity trip some time in the late 1970's.

On the morning of their departure, while Mrs. Traveler prepares breakfast, Mr. Traveler looks over the newspaper, checks the stock market report, the area weather forecast, and the area and regional traffic forecasts. The traffic forecasts are based on previously-experienced patterns on this type of day (day of the week, season of the year, etc.), taking account of current conditions, such as construction and maintenance activities. Before deciding on a final routing, however, he desires more up-to-date information. Therefore, he uses his telephone to obtain the latest weather forecast and then dials for the latest traffic reports for the local area and for the region and direction in which he will be traveling. The telephone traffic reports are based on previous patterns updated by more current information on conditions; the local area report will also include current information on incidents affecting traffic flow. On the basis of these reports he selects his intended routing, but decides to postpone his departure by 30 minutes in order to avoid arriving at his destination city during a peak traffic time.

En route, Mr. Traveler intends to take the freeway out of town. As he approaches the entrance ramp he can see that, although there is relatively heavy traffic on the freeway, it is moving smoothly. This is due in part to the fact that the traffic input at the ramps is controlled in an attempt to maintain free flow on the freeway without imposing undue delays to traffic wishing to enter at the ramps. A sign situated in advance of the ramp entrance indicates the travel conditions on the ramp and freeway and advises proceeding on the service road or arterial street for local destinations within several miles. Since Mr. Traveler is on a longer trip, he joins the short queue waiting. After a short wait at the ramp signal, he is released at a time calculated to minimize any conflict in merging into an approaching acceptable gap in the freeway traffic stream.

Soon he encounters a variable-message sign which indicates that there is 1 mile of moderately-congested traffic beginning ½ mile ahead. Forewarned, he is not taken by surprise when the speed on the freeway drops drastically. He can remember that years ago, when such information on the extent of a disturbance had not been available, he would have experienced a great deal of uncertainty and some anxiety as to the length of the congested section and whether he should stay on or get off the freeway. Armed with the information, however, he is reassured and after a few minutes' slowdown due to a heavy exiting movement at the next interchange, he is on his way again and soon leaves the metropolitan area behind.

As he is still in familiar territory, Mr. Traveler sets his highway radio selector to receive emergency messages only. Later in his trip, when he is in less familiar territory, he can elect to receive more routine information as well. Such messages will be broadcast from the roadside on one of several frequencies which are reserved for highway communications. He can still listen to his favorite radio program or tape, because the roadside radio broadcasts will interrupt only for those types of messages he has selected.



A modern control center.

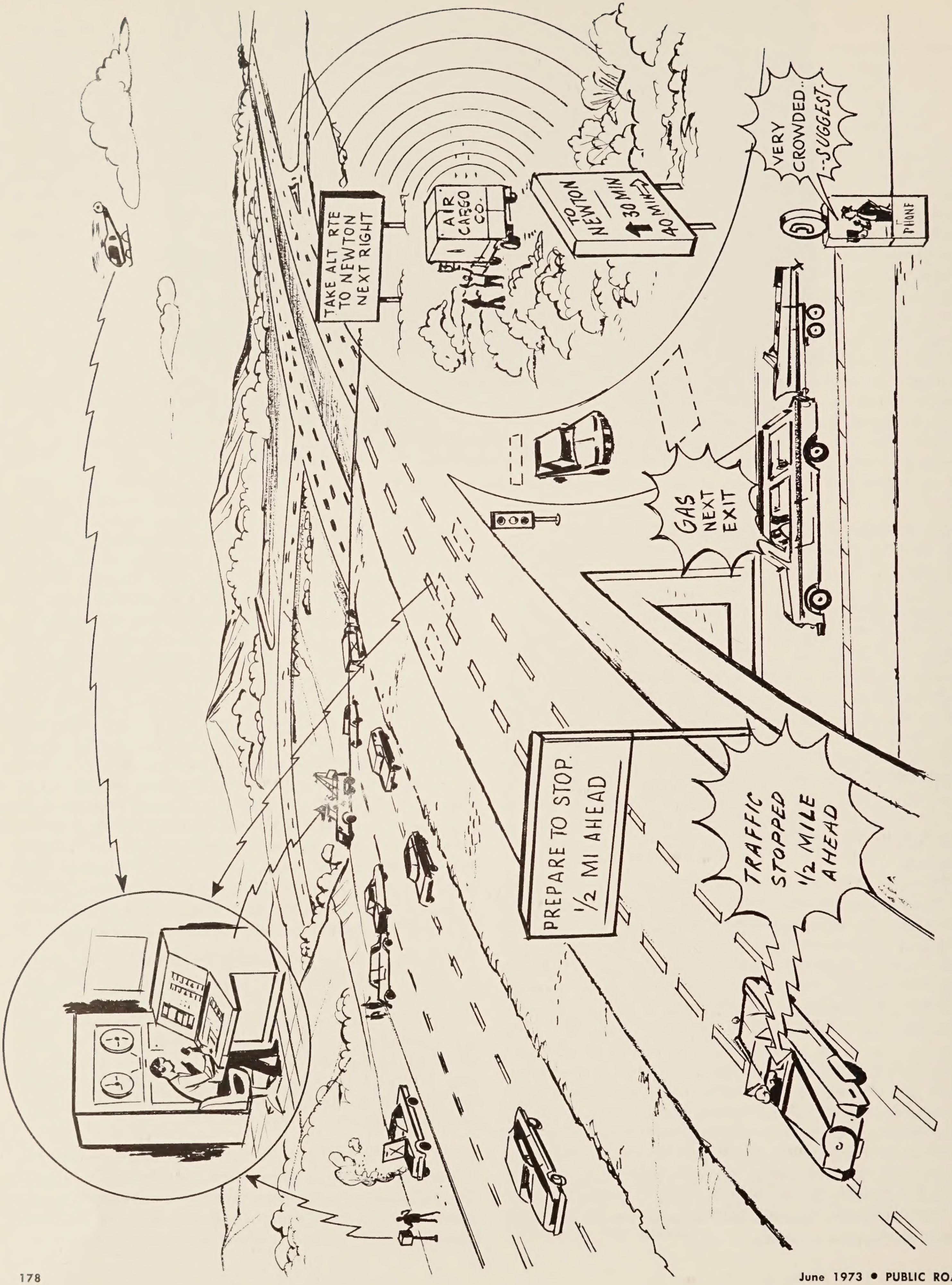
Mr. Traveler's previous car had a capability to receive roadside radio only, but his current model has the new two-way capability for transmitting (on a limited basis) as well as receiving. He feels secure in the knowledge that he has the capability for requesting aid and summoning help should it ever be required. Thinking along these lines, he notices that he is getting low on gas, so he sets his radio selector to receive services information as well. Soon he is advised of the availability of and directions to gas, food, and lodging in the vicinity. Shortly thereafter, however, the radio interrupts again to say that, because of a disturbance ahead, traffic is moving very slowly and he should be prepared to encounter stopped traffic within the next half-mile. The initial notice of the disturbance was received because it had been detected through an analysis of the in-lane traffic flow measurements which were continuously being fed to the regional control center and automatically processed.

The cause of the disturbance is diagnosed as an accident on the freeway and Mr. Traveler receives advice as to alternative routes to take, depending on his destination, to bypass the congested area. On the approach to the next interchange, variable message signs show the alternative routes to different major destinations. The control center, using the real-time data on traffic conditions in the corridor in relation to known capacities, has predicted what the travel conditions on the different links of the network would be. Based on previously determined driver criteria for route selection, such as minimum travel time with allowance for driving ease, the control center has automatically determined optimal routings through the corridor; messages which will encourage the required degree of diversion are being displayed to drivers via radio and variable-message signs at choice points. As traffic redistributes itself, the real-time measurements are being fed back to the control center so that the optimal routings and messages can be constantly revised in response to events.

Mr. Traveler elects to take an alternate route and is about to request services information again when he notices a car stopped on the shoulder with its hood raised and steam issuing from the radiator. The driver of this car apparently does not have two-way radio capability for he has walked to a roadside callbox where he is describing the exact nature of his problem to the control center. Mr. Traveler activates his transmitter, requesting voice transmission to report the incident, but his request is denied—the control center has already received digital transmissions from other drivers on the incident at this location. Suddenly, the radio breaks in to give notice of the approach of an emergency vehicle, and shortly thereafter, a police car passes him, lights flashing and siren wailing. Within a few minutes he sees a number of police cars around a truck at the side of the road and two men in handcuffs being put into the cars. This truck had been hijacked earlier, but the driver had secretly activated a silent radio alarm signal; and additional signals had been activated when the cargo was opened by the hijackers. These signals were detected by a special locator network which enabled the police to find the truck quickly.

Soon Mr. Traveler notices he is slowing down. He glances at his fuel gage, finds that it reads "empty," and remembers that he forgot to stop for gas. This time his request for voice transmission is granted; he describes the problem, his message is acknowledged, and he is told that a service truck will arrive within 10 minutes. Because the service needs for this area had been previously analyzed and provided for, it is only a short wait until the service truck arrives, thus Mr. Traveler's frustration is minimized.

The Traveler family arrives at its destination slightly later than anticipated but the trip has been fairly smooth considering the combination of events to which they were exposed. Years before, in 1973, such a trip could have been an unpleasant experience.



Integrated Motorist Information System.

The next morning, after glancing over the sports page in the morning newspaper, Mr. Traveler reads the traffic report, which describes a minor tieup due to an accident on the corridor freeway the previous day. Traffic is reported to have suffered delays of up to 15 minutes, but delays could have been longer had it not been for the traffic redistribution plan put into effect by the traffic operations control center and the rapid response by the traffic operations unit in clearing the roadway.

Mr. Traveler congratulates himself on having elected to divert to an alternate route and his faith in the highway transportation system is reinforced.

In addition to the described system which aided Mr. Traveler, there are other available technologies involving vehicle instrumentation which can be adapted to fill motorists' navigational needs. For example, before beginning his trip, Mr. Traveler could have had some assistance from his local auto club in planning a suitable route. They could prepare for him a special card (similar to an automatic telephone dialing card) which he would place in a slot on the radio console. Subsequent to that time, he would receive guidance instructions tailored to his special needs over his car radio as he passes through complex interchanges and other decision points. The appropriate audio message would be selected out of several being continuously transmitted in a specific order at each roadside transmitter location. This would be accomplished by comparing the next number on the card with existing route number designations and blanking out inappropriate information. When he does receive a message to leave the main route, he would first be advised as to movement to the proper lane. He would then receive more detailed instructions for his exit, keyed to existing and simple added visual signing and marker systems on the roadway itself. After completing his maneuvers through the interchange, he would receive a comforting confirmatory message to the effect that he is now on the next proper route and headed in the right direction, after which his dialing card would automatically advance to prepare for the next route change. In passing through interchanges where no exiting is required by his route plan, he would receive a message indicating assurance that all is well. If Mr. Traveler makes a mistake, this would be detected and he would be directed to the nearest roadside telephone. A telephone number would also be provided for routing assistance.

It should be mentioned that if he had not been rerouted by the previously described "scenario" system and was routinely using his route guidance equipment, Mr. Traveler, upon approaching his destination, would have received a message "You have entered the area indicated by your destination number. This is Progressive City which is equipped with Local Zone Control." The receiver would have automatically switched to a different frequency to receive the local guidance information, helping him exit at the proper location. After this point he would have to fall back on his own ability as a map reader, or ask directions. Throughout this period, during which he would have been receiving route guidance information, Mr. Traveler would have continued to receive emergency messages and traffic condition advisories.

Technology Available

The scenario depicting an advanced traffic control system has described five basic functions: (1) motorist advisory information, (2) route diversion, (3) freeway incident detection and management, (4) ramp metering, and (5) motorist aid/emergency communications. In addition, the system perhaps included a sixth specialized function, that of a cargo security system. The operational implementation of these five functions into a coordinated effort requires a system which operates in real time, is traffic responsive, is largely automated, and provides an integrated approach to the major subsystems of surveillance, trunkline communications, system control, and communications with the motorist. Mr. Traveler used the newspaper and telephone for pretrip information. While a telephone system has not yet been widely used for giving traffic information, there is an obvious parallel in the provision of telephone weather information to the general public and small aircraft pilots. As for showing traffic information in the newspaper, the predictable recurring peak period congestion, caused by demand exceeding capacity, can be shown graphically. Traffic engineers using aerial photographs or floating car methods have developed density and speed contour maps related to clock time to help determine when metering control should be applied. The motorist could use a simplified version of these maps to determine his expected speed and travel time over a given route.

Mr. Traveler's choice of the freeway as the way to leave town was the first major step in route selection. Experience in Chicago and Detroit has shown that drivers' adherence to sign messages at ramps describing freeway conditions was highly dependent upon the signs' accuracy in portraying the real traffic conditions. Signing and ramp metering has been effective in discouraging and redirecting motorists, on short trips, who can easily reach their destination by using the surface streets instead of overloading the freeway. Research in the 1960's was primarily aimed at solving the recurring congestion problem—keeping demand equal to or less than the capacity of individual freeway segments. Electronic surveillance and appropriate control of ramp inputs were extensively investigated.

Surveillance techniques have included the following: vehicle detectors mounted in the roadway, police and highway patrols, helicopters, and television cameras located at strategic locations. In addition, use has been made of information from State and local highway operations units (including, for example, Channel 9 Citizen Band REACT organizations) and the U.S. Weather Bureau. Information relevant to accidents, incidents, or disabled vehicles has been gathered from motorist aid callboxes, in-vehicular two-way radio, and motorists reporting events to toll booth collectors. Discrete vehicle detectors have included commercially available units mounted in the roadway at half-mile to 1-mile intervals and at critical locations. For the future, detector concepts currently under development will be used in selected locations to evaluate their advantages over presently available devices. One example is the Magnetic Gradient Detector, which requires less slotting of the pavement than standard loop detectors thereby reducing installation and road maintenance time. Also, a small cylindrical self-powered detector which does not require external power or signal leads is under development and will be employed when proven feasible.

The benefits, in terms of accident reduction and travel time savings derived from freeway surveillance and control systems in Atlanta, Minneapolis, Los Angeles, Detroit, Chicago, and Houston, have been well documented. A new system now in operation on the North Central Expressway in Dallas has also been successful in releasing ramp vehicles timed so that they can merge into approaching measured gaps in the right lane of the freeway. Another system, tested on a ramp to Route 128 at Woburn, Mass., provided guidance for ramp vehicles to merge into freeway gaps through use of a rampside moving green band. This system will be further tested in Tampa, Fla., at a more geometrically deficient site.

Once the traveler is on the freeway, he should receive advisory information designed to warn and advise him of traffic conditions, services, and possible route diversion actions. A response to incidents and general traffic congestion, now receiving FHWA program emphasis, is that of providing information to motorists to warn of congested or dangerous conditions that exist downstream. The motorist is thus forewarned in time to select an alternate route. If possible, the cause and magnitude of the congestion should be displayed to the driver so that meaningful decisions can be made on whether to continue or leave the freeway. Also, the driver should be forewarned if he is rapidly approaching a backed-up line of traffic. The message can be presented either through changeable message signs or through roadside radio wherein short range transmitters are used in conjunction with the standard AM car radio.

The Los Angeles 42-mile loop project (the triangle formed by sections of the Santa Monica, Harbor, San Diego freeways) is currently implementing 35 changeable message signs over one section of freeway and a roadside radio information system on another section of the loop. One very encouraging finding is that drivers have almost unanimously approved of the concept of advisory information. Human factors research has delineated the type of information best understood and desired by urban drivers. Driver preferences for types of information to be given were (in order): lane blockage, distance to blockage or problem, length of delay, reason for delay, and location of problem by ramp name.

In order to operate the signs and roadside radio systems, a backbone communications subsystem is needed. A variety of communication techniques can be employed depending on terrain, required bandwidth, and similar factors. These techniques include buried cable and pole-to-pole RF link repeaters. The RF communication link utilizes pole mounted antennas pointed in both directions along the highway. The signals are received, amplified, and retransmitted along the highway at half-mile intervals. A benefit of this technique is that any motorist traveling along the highway is in RF view of each antenna, or in other words, is able to communicate with the highway authorities for any need if his vehicle is appropriately equipped. Voice communication would be permitted only under control of the dispatcher. The half-mile spacing would also provide a convenient means for locating fixed callbox units and roadside radio AM transmitters.

Roadside radio was used following the California earthquake in March 1971 to inform motorists of the travel time delay through the detour areas. Signs were placed just before the radio zone area to notify motorists to tune to 830 on their AM radio. The experiment proved very effective. Similar systems are being used at Yellowstone National Park to inform motorists of scenic areas and parking availability. A specially developed buried cable is being used to broadcast radio announcements of airplane arrivals and departures and parking lot instructions at approaches to the Los Angeles International Airport. All of these systems require that the motorist manually tune his radio in order to receive these messages. Some motorists might be reluctant to do this; therefore, systems can be designed to permit automatic interruption of the standard receiver to allow such special messages to be heard. In addition, the motorist should have the option to preselect the type of messages of interest. For instance, if the late night traveler needs gas, food, or lodging, he may select to receive this category of messages. When he approaches an area that is broadcasting information of interest, his radio will automatically respond. Emergency messages or unique identifying sounds such as the approach of police, ambulance, or fire vehicles will always have priority over all other message types. Eventually, low cost two-way communication devices for motorists will provide a ready and safe means to summon aid in emergency situations. This unit could possibly evolve into an important part of the highway management system where direct access to the motorists is essential.

The control center would contain the data reduction, decisionmaking, and control functions of the system and would, of course, heavily utilize a digital computer system. Data would be received from the various sources and analyzed; on the basis of this analysis, traffic conditions would be defined and predicted, disturbances and incidents located, and remedial measures enacted. Optimal routings would be computed for those specific decision points which require diversion. Ramp control (metering) would be exercised when demands have to be limited to maintain free flow. All of the control center operations would be automated as much as possible to improve system efficiency and keep operating costs reasonable, but control center personnel would have the capability to interrupt the system, if emergencies so require.

The helicopter can be useful in surveillance of the overall road system if used in a systematic manner. In the large urban areas, the use of helicopters for patrol can be cost effective if an efficient surveillance patrol, reporting, and incident management program is formulated. In comparison with regular California Highway Patrol ground units, an evaluation of the California Highway Patrol helicopter in the Los Angeles basin showed:

- Reduction in delay to the motoring public due to early detection and reporting of incidents in the traveled way (savings of 3,469 vehicle-hours delay/month).
- Better onsite management.—The helicopter crew can make decisions at times regarding alternate routes for emergency equipment that the ground units, with their limited view of the area, are unable to make.
- Better service for the stranded motorist.

The principal advantages of the helicopter include its area-wide coverage, rapid response to and confirmation of incidents reported by others, and ability to report rapidly and accurately the magnitude of disturbances. To be effective, the helicopter crew's findings must be tied closely to radio traffic reports so that motorists can be alerted to take alternate routes or delay their trip starts. In all such systems, it is paramount that the information is timely and accurate. If not, the motorists soon lose faith in the system and do not respond. In the Los Angeles

42-mile loop surveillance and control project, a closed circuit TV system is mounted in the patrol helicopter so that a control center Incident Management Team (usually traffic engineers and a highway patrolman) can view incidents close up before making decisions to rectify the situation.

Incident detection and management have been viewed for several years by urban freeway operational engineers as the number one research priority. Needless to say, any techniques which can be developed to signal the occurrence of an incident within a few minutes of its occurrence could lead to substantial reduction in travel delay and in accident potential. The utility of such advanced information is that it can reduce the effects of incidents by reducing the traffic flowing into congested areas, thus bringing an earlier termination to incident effects. The trend is toward computerized detection of incident-caused traffic disturbances. Detectors, spaced ½ mile to 1 mile apart in several or all lanes, are sampled to determine occupancy, speed, flow, and other traffic parameters. Algorithms are used in the computer analysis to signal the onset of rapid congestion buildup. Some recent valuable findings resulted from the John C. Lodge Freeway surveillance and control project in Detroit. Eight incident detection algorithms were tested against 50 collected incidents (18 of which were accident caused). The general conclusion was that incidents can be detected within 2 minutes of the first incident-caused congestion as contrasted to a usual 5–10 minutes for detection where computerized incident detection is not employed. The most promising incident detection techniques will be field tested on the Los Angeles 42-mile loop project.

Now that the accident-caused incident has been detected by the computerized incident detection algorithm and remedial diagnosis completed, Mr. Traveler receives advisory information for bypassing the freeway congestion. In this case, Mr. Traveler is already on the freeway as contrasted to the earlier situation at the beginning of his trip where he received advisory information (through ramp and freeway condition signs) as he approached the access ramp to the freeway. The medium of transmission for the advisory information will be chosen on the basis of the nature of the information to be transmitted to the motorist, the physical configuration or characteristics of the site, and the local traffic conditions. One such medium might be fixed and changeable message signs, coupled with additional information on their AM radios, to advise motorists of highway hazards, emergency vehicles, alternate routes, off-road services, and possible scenic attractions. The standard AM radio is capable of receiving all of these messages on designated frequencies. In the future, it is proposed that vehicle radios be designed with the capability for selection (by the driver) of automatic reception of either all messages or "emergency only" messages. Low power, short range, roadside transmitters would be used to broadcast this information to vehicles at key locations along the highway. Control signals for the transmitters would be derived from the trunkline communication link.

The motorist communication system would also provide a means for motorists equipped with digital units (including controlled voice) to request aid. A motorist who becomes stranded usually becomes a pedestrian, seeking assistance. This becomes extremely dangerous on high speed freeways where pedestrians and hitchhikers are prohibited. As a result, motorist pedestrian fatalities make up a substantial portion of the freeway fatalities.

MOTORIST'S RADIO FOR AID/EMERGENCIES AND ADVISORY COMMUNICATIONS

The in-vehicle system provides distinct safety advantages and enables drivers, particularly women, to remain in the relative security of a locked vehicle until aid arrives. The motorist requesting aid would normally use one or a number of push buttons to describe the aid requested. Voice transmission from the motorist would be permitted, but under complete control of the dispatcher at all times. Digital aid request would be the primary means of exchanging information whenever possible, and its use would be encouraged in all but specific instances. Digital communications can accommodate a greater information density than voice, and when coupled with a computer for system control, offers the only viable means of handling the large information flow required in advanced traffic control systems.

Some research has been performed on the motorists' use of an alternate street route in lieu of a congested freeway (the John C. Lodge Expressway in Detroit) as part of the National Cooperative Highway Research Program. In this case, drivers were advised of the availability of an alternate route, marked by trailblazer signs, prior to their intended entry onto the freeway. In a rural intercity application in France, alternate routing proved to be very successful. An experiment was conducted on the Lyon–Grenoble roadway network in conjunction with the 1968 Winter Olympics. By routing drivers over alternate routes, the real-time system prevented congestion which would have resulted from a traffic forecast of 150 percent of capacity for the 60-mile main roadway. Another freeway rerouting experiment is getting underway north of Baltimore, Md., where southbound traffic will be provided information for rerouting around the Baltimore Beltway when the Baltimore Harbor tunnel facility (the most direct route) is overloaded. Despite the longer distance, a considerable savings in travel time is anticipated for motorists choosing to use the beltway.

Mr. Traveler in the scenario sees another driver in distress using a roadside telephone callbox. In the rural areas, the emphasis has been on improved design and operation of such motorist aid systems. A motorist aid system is geared to help the motorist who is stopped along the highway and requires external aid before his travel can be resumed. This stop rate appears to vary between 30,000 and 50,000 vehicle-miles between stops. The stop rate for urban freeways is even higher.

The provision for motorist aid can be met through several methods. For example, the use of visual methods utilizing frequent police patrols or service truck patrols is very effective. An equally effective method is a system where the stranded motorist initiates the request for aid by means of frequently spaced push button callboxes or telephones. Other electronic systems or combination of systems, such as television surveillance, incident detection, and FLASH (wherein the passing motorist reports the presence of a stranded motorist) can be used to alert authorities of a stranded motorist. From a cost-effectiveness standpoint, a frequently spaced (1 mile) wayside telephone is the most preferred system. Not all rural telephone systems are cost effective, however, especially if the Interstate route has relatively low average daily traffic volumes. The principal benefit is in delay reductions. Other benefits involve savings in accident potential and accident loss. Nonquantifiable benefits include: less fear of being stranded at night (especially women), increased confidence in the highway system, quicker aid for motorists or passengers who become ill, and more timely reporting of hazardous road conditions involving debris, ice, fog, animals, or traffic jams.

Motorist aid systems are used in urban areas as well, where an average spacing of ½ mile per telephone callbox appears most effective. In fact, two-way voice telephone systems seem to be the preferred system to date based on research findings. In the Los Angeles installation, the following percentage breakdown of calls on the Harbor Freeway was considered typical of the overall system: mechanical, 23; tire repair, 17; gas, oil, water, 13; stalled vehicle, 4; report on accident, 8; false alarms, 1; private police use, 6; and miscellaneous categories, 28. It was found that 39 percent of all calls required vehicle tows. Of special interest is that 8 percent of the calls were to report accidents.

After Mr. Traveler runs out of gas, he receives prompt aid through a service patrol truck. In response to incidents and stranded motorists on heavily used urban freeways, some States are providing service through dedicated patrol trucks. The State of Illinois, for example, keeps a fleet of 50 radio-equipped trucks to provide for patrol of 135 miles of freeways. This aid, provided around the clock, accounts for 60,000 assists a year. A pilot study using dedicated State motorist service patrols has been conducted in Los Angeles where this concept of patrol aid has been enthusiastically endorsed by motorists. It is rather interesting to note that in this pilot study, of the disabled motorists having to stop, 64 percent were able to move to the right shoulder before stopping, 11 percent stopped on the median, 10 percent stopped on the ramps, and 15 percent stopped in the traffic lanes, the latter being the most dangerous and congestion-causing situation. These figures were for eight-lane freeways and would undoubtedly differ for a four- or six-lane freeway. Here and elsewhere a consistent finding is that approximately 10 to 25 percent of vehicle disablements are caused by motorists running out of gas, an indication perhaps that one of our vehicle standards should include provision of a small auxiliary gas tank.

The basic integrated motorist aid system would initially include the trunkline communication links, the detector stations, fixed and variable message signs, the roadside motorist aid callbox units, and the control center. The communication system should be designed to accommodate all expected services, and as experimental systems are proven, they could be incorporated into the system. These include AM roadside radio, in-vehicular radio, and two-way motorist aid units. Fog, ice, and snow detectors would be added as required. An integrated system could also be expanded to include some means of automatic vehicle location which could be used by truck and bus companies for scheduling and fleet security, as depicted in the scenario by the apprehension of the truck hijackers. Currently, the U.S. Department of Transportation is involved in analyzing and selecting a systems approach for vehicle location which provides adequate accuracy at reasonable cost. Contenders, such as OMEGA or Loran C, if developed and implemented, appear to provide adequate performance for use as a vehicle locator where location accuracies are not deemed to be overly critical. Presumably, certain hardware and systems aspects of such a location system (passive and nonsaturable) could be eventually integrated into an overall highway communications system.

Course of Action

The foregoing has described a system which could be effectively implemented on heavily used intercity traffic corridors. While the emphasis of the past research has been to solve urban and suburban freeway problems, off-the-shelf technology can be adapted to high speed highway systems in general, including more rural highway sections.

To maintain the level of service intended by the designers, there must be a modus operandi for achieving a better balance of demand with available capacity on a real-time basis for traffic corridors between major cities. The Northeast Corridor (Boston–Richmond) has been the subject of special studies aimed at solving this growing transportation problem. There can and will be sufficient capacity in the various heavily used segments of this corridor, if alternate routes can be effectively utilized when traffic congestion occurs on the main route. Motorists will need to be advised when and where alternate routing would benefit them. As a result of the increasing interconnection of the intercity highway system in the Northeast Corridor (NEC), many intercity drivers should have the opportunity to make multiple route selection decisions. Between Boston and Washington, any given motorist could make as many as 10 consecutive route selection decisions. Without a real-time highway information system, the motorist has no alternative than to blindly select the route with which he is familiar or which appears the most favorable on the map. The intercity driver intermingled in commuter traffic differs from the commuter in two ways:

(1) He is basically unfamiliar with the road and its operational characteristics (e.g., congestion periods and geometric drawbacks).

(2) He really does not have to be there to the same extent as the commuter. He can often take another route or alter his schedule if he had advance information on the problem ahead.

A system such as suggested herein could be applied over one of the intercity corridor segments or links in the Northeast Corridor and be operational in the bicentennial year of 1976. There are, of course, other heavily used intercity corridors, such as, Detroit–Toledo and Chicago–Milwaukee, but the Northeast Corridor is highlighted because of its population/land ratio and emphasis on automobile travel of which there is a 65 percent projected increase by 1985. An original objective of the NEC study was to determine whether other modes of transportation might feasibly reduce this demand, but the findings were predominately negative. Presently, 74 percent of intercity travel in the NEC is automobile and 5 percent buses. Common carrier modes do not lend themselves to multipurpose trips, multistop trips, or reaching out-of-the-way places. Moreover, the cost of high-speed common carrier modes is substantially higher than the perceived cost of automobile travel. For these reasons, a realistic forecast of future travel largely boils down to "more of the same."

Nationwide, there are other sobering forecasts, such as, very little additional roadway mileage planned with which to carry the increased demand. Since 1960, vehicles and travel have increased at a much more rapid rate than the needed increase in mileage of freeway type facilities. Based on the past 20-year period, the nationwide average annual compound rate of travel increase on all roads has been about 4.6 percent. Travel in 1972 was up 5.4 percent from 1971. All indications are that highway departments will have to achieve maximum utilization of their facilities as never before. The past decade has demonstrated that real-time management of traffic facilities can produce substantially improved operations. The frequency of accidents, incidents, environmental disturbances, and other unpredictable events portends we can no longer afford the luxury of operating our highways on an "average good day" performance basis.

In recognition of the increasingly serious problems on intercity traffic corridors, the Federal Highway Administration, in its Federally Coordinated Program of Research and Development in Highway Transportation (FCP), has been funding the development and refinement of remedial techniques. To achieve uniformity, functional integration where possible, and viable standards and guidelines for integrated motorist information systems, the Federal Highway Administration has the goal of developing the necessary guidelines and standards for motorist information systems. A cost-effectiveness framework is under development so that transportation officials cannot only make an orderly and informed choice of the subsystem elements best able to accomplish the goals of their particular motorist information system but still provide the necessary (for the motorists) uniformity of message content, display characteristics, and service procedures.

To achieve credible national guidelines and standards, development thereof will be based on experience gained under real-world operational conditions. To this end, the Federal Highway Administration is proposing to develop an integrated operational link or corridor utilizing the state-of-the-art techniques in motorist information systems and real-time traffic management. A fully cooperative effort with local and State highway authorities is vital to the success of this endeavor.

Once a prototype system has been installed and placed in operation, the State(s) will be expected to operate and provide routine maintenance of the system. This will involve a major commitment of manpower and funds. The Federal Highway Administration is ready to provide leadership and consultative support for the operation of the system in addition to performing the systematic evaluation needed for development of the aforementioned guidelines and standards. Refined strategies and advanced technology should be evaluated as well. The operational characteristics of future systems would then be solidly based on specifications originating from a real-world 1976 operational demonstration.

The dominant form of transportation in this country is highways. To date, technology has not offered a realistic replacement nor does such appear to be in the offing for the foreseeable future. Highway transportation currently accounts for 80 percent of the Nation's total transportation investment, or about $160 billion. It is obvious that the level of investment that has already been placed in highways leaves us with no other course of action than to optimize the existing highway network to be the most effective and efficient mode of transportation available. The integrated motorist information system discussed herein is an important step in this direction.

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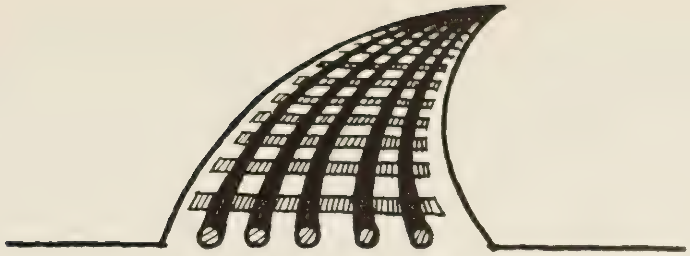

NONMETALLIC COATINGS FOR CONCRETE REINFORCING BARS

by Robert G. Pike,[1] Richard E. Hay,[1] James R. Clifton,[2] Hugh F. Beeghly,[2] and Robert G. Mathey [2]

The study reported here was conducted to determine the feasibility of using organic coatings, especially epoxies, to protect steel reinforcing bars embedded in concrete from corrosion accelerated by chloride ions.

Coatings were evaluated on the basis of their chemical and physical durabilities as well as their protective qualities. In this study, attention was also directed to the application methods and surface preparation of the steel reinforcing bars. Four different materials appear to be suitable for such coatings.

Introduction

THE premature deterioration of concrete bridge decks has become a major problem during the past decade (*1*).[3] Chloride ions from de-icing materials are considered responsible for this early deterioration by accelerating corrosion of the steel reinforcing bars. Use of the two more commonly applied de-icing materials—sodium chloride and calcium chloride—has increased substantially during the past decade. Normally, steel is passive towards corrosion when in an environment of high basicity (pH of about 13) inherent in portland cement concretes (*2*); chloride ions, however, are able to depassivate steel and thereby promote its active corrosion (*3*). The increased volume of the bars because of this corrosion results in spalling and cracking of concrete, necessitating extensive and expensive repairs.

One practical method for preventing the rapid corrosion of steel reinforcing bars may be to coat them with protective materials. Galvanization has been used as a coating process (*4,5*). Cadmium (*6*), nickel (*7*), and organic types of barrier coatings (*8,9*) have also been used for protecting reinforcing bars. Tripler and coworkers evaluated a few nonmetallic coatings and suggested that an epoxy—coal-tar-type coating—could have potential as protective coating for reinforcing steel (*7*).

The study reported in this article was conducted to ascertain the feasibility of using organic coatings, especially epoxy systems, to protect steel reinforcing bars.

Specific objectives of the study were as follows:

- Investigate the feasibility of using nonmetallic coatings to protect reinforcing steel.
- Select the most promising materials based on physicochemical testing, considering the economics involved in coating and fabricating the reinforcement.
- Determine the most practical method of testing such coatings.
- Prepare sample specifications which might be used to obtain such coated bars.

[1] Federal Highway Administration (FHWA)
[2] National Bureau of Standards (NBS)
[3] Italic numbers in parentheses identify the references on page 196.

Although the testing program is not yet complete, the results so far obtained indicate that certain coating materials may satisfactorily protect reinforcing steel from corrosion.

Materials

Selection of coating materials

Coating materials to be evaluated were selected on a generic basis and were restricted essentially to organic formulations. Important criteria for selection included (1) inertness towards the constituents of cement paste and to chloride ions, (2) creep characteristics, (3) film integrity and protective qualities, and (4) cost considerations.

Coatings selected for evaluation (table 1) are of commercial origin. Code numbers were assigned to identify the materials—the sequence indicates the chronological order in which the materials were received.

Polyurethanes and epoxies consist of two components and are classified as thermosetting materials because their cure is accelerated by heat. Once cured they normally retain their shape up to their decomposition temperatures. The other coatings in table 1 are classified as thermoplastics as they soften and change shape when heated.

The emphasis has been on thermosetting materials, especially epoxies, because these materials seem to best satisfy the chosen criteria. Altogether, 36 epoxy coatings—both powder and liquid systems—have been evaluated to some extent.

Some materials, especially powders, were submitted only in the form of cured films on steel reinforcing bars.

Curing methods and specimen preparation

Two-component liquid systems.—The epoxy liquid systems consisted of two components—an epoxy resin and a curing component. The curing of epoxies is attributed to chemical reactions between the resin and curing agents which lead to polymerization of the mixture.

Two other two-component liquid systems—a urethane and a zinc-zinc silicate—were also tested.

In these tests, the ratios of the two components and the mixing and curing times were closely controlled and were the same as those specified by the manufacturer's accompanying instructions. These systems were mixed at room temperature, ca. 24° C., relative humidity ca. 50 percent, using an electric stirrer for solventless systems and a metal spatula for solvent-containing systems.

Test specimens of the pure materials were cast and steel plates and steel reinforcing bars were coated with thin films. Specimen discs 2¼ in.[4] diameter by ca. ⅜ in. thick (thicknesses of solvent-containing systems were reduced to 3/16 in.) were cast using aluminum-weighing dishes as molds. The molds were stripped after the mixture had cured for 7 days. Wet films 3–7 mils[5] thick were formed immediately after mixing by applying the coatings with a Baker film roller applicator to the gel side of photographic paper or to sheets of Teflon.[6] After being immersed in water at room temperature for 16 hours, the cured films were stripped from the photographic paper. Cured films were easily stripped from Teflon sheets by using a thin-bladed spatula. Coating materials were applied with a paint brush to 4 by 4 by 0.050 in. cold-rolled steel plates and to No. 6 steel reinforcing bars.[7] Steel plates had been degreased with mineral spirits, and reinforcing bars had been sandblasted to a white surface (*10*) before coating.

One-component liquid systems.—The two one-component liquid systems, a polyvinyl chloride (PVC) and a phenolic nitrile, were hardened by the evaporation of solvents. Test specimens were formed as described previously for the two-component systems.

Powder system.—Mixing of the epoxy powders was unnecessary since the two components are contained within each powder particle. The powders were applied to steel and Teflon substrates preheated to ca. 200° C. in an electric oven by immersing the substrates into a fluidized bed (*11*) of the powders. The coatings were then cured in the electric oven under the conditions specified by the manufacturers. When allowed to cool to room temperature, the cured epoxy films were easily removed from the Teflon substrate by using a thin-bladed spatula. No. 6 steel reinforcing bars and 4 by 4 by 0.050 in. cold-rolled steel plates were also coated with the powders.

Discs for the liquid systems, described earlier, were not fabricated from epoxy powders because when masses sufficient to make 3/16 in. thick discs were heated to their specified curing temperatures, porous solids that had expanded over 100 percent were produced. Even four-fold reduction of the masses did not yield satisfactory specimens. Only one powder epoxy, No. 31, did not exhibit this expansion phenomenon. Possibly, some curing components are vaporized at curing temperatures causing the formation of porous structures in thick castings. When films less than 20 mils thick were formed from the powder epoxies, similar difficulties were not encountered.

Reinforcing bars coated by applicators.—After preliminary screening tests for resistance to chemicals, cure time, and integrity and brittleness of film, those coatings judged to have the most promise as protective coatings were subjected to further evaluation. No. 6 steel reinforcing bars 4 ft long having two different deformation patterns were supplied to an applicator or manufacturer handling the respective coatings. The surfaces of the bars were cleaned—usually by sandblasting—the coatings applied, and the bars returned to the National Bureau of Standards for evaluation.

Testing procedures and results

Given in this section are descriptions and results of the test methods used to evaluate the various coating materials.

Not all of the 47 coating materials were subjected to the same degree of testing since some were quickly judged unacceptable for the following reasons:

Nos. 5 and 13, extremely brittle.

No. 8, loss greater than 3 g in the immersion test.

Nos. 10 and 11, gel times longer than 8 hours.

Nos. 12 and 13, poor film integrity and excessive entrapped air in the cured state.

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[4] One inch equals 0.0254 meter, exactly.

[5] One mil equals 0.001 inch, exactly.

[6] All instruments and materials are identified in this report only to adequately specify the experimental conditions. In no case does such identification imply recommendation or endorsement by the NBS or the FHWA, nor does it imply that the material or instruments are necessarily the best available for the purpose.

[7] No. 6 steel reinforcing bars have nominal diameters of ¾ in.

Table 1.—Description of coating materials

Code No.	Type	Color	Uncured state	Comments
1	Epoxy	Red	Liquid	
2	do	Amber transparent	do	
3	do	Light green	do	
4	do	Orange	do	Undercoat
5	do	Brown	do	Polysulfide
6	do	Gray	do	Topcoat
7	do	Iron oxide	do	
8	do	Black	do	
9	do	Red	do	Primer
10	do	White	do	
11	do	Orange	do	
12	do	Yellow buff	do	Ketamine
13	do	Light green	do	Do.
14	do	Red	do	
15	do	Light buff	do	
16	do	White	do	
17	do	Gray	do	
18	do	Black	do	Coal tar
19	do	Brownish-red	do	
20	do	Green	Powder	
21	do	Light green	do	
22	do	do	do	
23	PVC	Dark olive green	do	
24	PVC	Dark purple	do	
25	Epoxy	Blue	do	
26	PVC	Transparent	Primer	
27	Epoxy	Black	Powder	
28	do	do	do	
29	do	Yellow	do	
30	PVC	Pale green	do	
31	Epoxy	Light green	do	
32	do	White	do	
33	Urethane	Dull orange	Liquid	Unsolicited
34	Phenolic-nitrile	Red	do	
35	Urethane	Black	do	100 percent solids
36	do	do	do	Do.
37	Epoxy	do	do	Adhesive
38	do	Gray	Powder	
39	do	Brown	do	
40	do	Red	do	
41	do	Red	do	Only coated rebars submitted
42	do	Red		Same as 41; different coating procedure
43	do	Red	do	
44	Zinc-zinc silicate	Gray	Liquid	
45	Coal tar-epoxy	Black	do	Coal tar from England
46	Epoxy	Red	do	Polysulfide
47	Polypropylene	Clear	Powder	

Nos. 14 and 47, the tendency of some thermoplastics to soften at 60° C.

No. 15, same material as No. 16.

Nos. 20 and 21, not enough material was furnished for tests.

No. 34, too much solvent (solid content too low) and poor corrosion resistance.

Nos. 35 and 36, rubber-like expansion qualities, 500 to 600 percent elongation (obviously these two coatings would not pass the pull out and creep requirements).

No. 37, an adhesive too viscous to work with.

No. 44, very brittle, gave off H_2 gas in $Ca(OH)_2$.

No. 45, heavy film, high creep.

No. 46, softened and decomposed at 100° F.

Immersion testing

Epoxy disc specimens.—Disc-shaped castings of cured epoxy specimens were immersed in water, aqueous solution of 3M $CaCl_2$, aqueous solution of 3M NaOH, and a solution saturated with $Ca(OH)_2$ and $CaSO_4 \cdot 2H_2O$ and containing 0.5M $CaCl_2$. These test solutions are perhaps as aggressive as those found in concrete, if not more so. Therefore, materials performing well in the immersion tests will probably not be degraded by long-term embedment in concrete. Before determining the original weights and prior to the immersion studies, the specimens were immersed in water for 1 or 2 minutes and wiped dry. Original weights of discs varied from ca. 20 g for solvent-containing systems to ca. 50 g for the solventless epoxy systems. The temperatures of the test solutions were 24± 1° C.

The immersion data are presented in table 2. In some cases two separate castings were made shown by different immersion times. The epoxies containing solvents in their uncured state generally lost weight and had greater weight changes than the solventless epoxies with the exception of No. 7, a solvent-containing epoxy, which had the largest weight increase. The surfaces of both No. 7 and No. 9 were converted from smooth to rough textures during the immersion period. These weight changes are in accord with results of other studies (*12*). With the exception of two solvent-containing epoxy systems, Nos. 8 and 9, the epoxy coatings performed well and probably will not be degraded by long-term embedment in concrete. The long-term durability of polyvinyl chlorides when embedded in concrete, however, is thought to be of major concern for if considerable hydrolysis should take place, sufficient amounts of chloride ions to induce corrosion of the rebars might be liberated.

Coatings on reinforcing bars.—The chemical resistances of the coated reinforcing bars supplied by applicators were evaluated in aqueous solutions of 3M NaOH and saturated $Ca(OH)_2$ and were also visually inspected for evidences of softening, color changes, disbonding, and changes in film integrity. The data are presented in table 3, which includes results from three polyvinyl chloride coatings (Nos. 23, 24, and 30) as well as one one-component liquid epoxy (No. 19) and 10 powder epoxy coatings.

The rusting of some coated reinforcing bars in saturated $Ca(OH)_2$ solutions during the first 2 weeks of the immersion study is an interesting phenomenon, especially since the uncoated rebars were passive towards corrosion in a similar solution. Furthermore, the corrosion was observed only in the less alkaline solu-

Table 2.—Epoxy discs immersed in aqueous solutions

Code No.	Immersion time	Weight change: Water	Weight change: 3M $CaCl_2$	Weight change: 3M NaOH	Weight change: Saturated $Ca(OH)_2$, $CaSO_4 \cdot 2H_2O$ and 0.5M $CaCl_2$
	Weeks	*Percent*	*Percent*	*Percent*	*Percent*
1	31	2.3	1.3	1.9	2.4
	18	3.5	0.4	2.4	3.0
2	31	3.1	1.8	1.9	3.7
	18	2.4	1.6	1.8	2.3
3	31	−1.9	−2.1	2.1	−2.0
	18	−2.3	−2.6	1.9	−2.3
4	31	2.3	1.6	1.6	1.9
	18	1.5	0.7	1.3	1.6
5	31	1.2	1.1	1.6	1.8
	18	1.1	0.5	0.9	1.2
6	31	2.7	1.5	2.1	2.7
	18	1.7	0.7	1.0	2.1
7	31	17.0	20.0	15.0	18.0
8	31	−4.8	−5.7	−2.7	−4.8
9	31	−6.8	−10.0	9.3	−14.0
12	29	1.2	0	1.3	1.5
13	29	1.3	1.2	1.8	2.5
16	22	−0.8	−1.7	−0.7	−1.7
	18	−3.1	−3.1	−0.5	−3.4
17	24	2.1	0.7	1.6	2.4
	18	1.5	0.7	2.0	1.7
18	24	0.6	0	0.1	0.8
	18	0.9	0.4	0.7	0.8

tions; i.e., saturated $Ca(OH)_2$ (pH of 12.6) rather than 3M NaOH (pH of 14.5). The pH of saturated $Ca(OH)_2$, however, is sufficient to passivate steel. It is not obvious at this date why the same rusting phenomenon was not observed when the reinforcing steel was immersed in 3M NaOH. The cause of the corrosion apparently lies in either the surface preparation or the composition of the coating.

Phosphatizing the surface of metal substrates has been considered advantageous to inhibition of corrosion (*13*). In the present study, however, the coated bars with phosphatized steel surfaces, Nos. 38, 39, and 40, prematurely rusted when immersed in saturated $Ca(OH)_2$. This corrosion terminated after about 2 weeks of exposure. No rusting took place with reinforcing bars coated with the same epoxies applied to sandblasted surfaces.

Chloride permeability

The relative effectiveness of barrier organic coatings in protecting reinforcing bars from accelerated corrosion attributed to chloride ions can be associated with the following: physical and chemical durabilities of the coating (discussed in the previous section), intrinsic chloride ion permeability rates, film integrity, film thickness, and corrosion inhibitors added to coating formulations (*12, 13*).

The results of the study reported in this article confirm the results of others (*14*) that epoxies absorb measurable amounts of water and, therefore, thin epoxy films, ca. 2–10 mils, are not entirely impervious to moisture. However, chloride ion permeability rates may be much lower than those of pure water. Little if any data on the permeability rates of chloride ions through epoxy films have been previously reported.

The chloride permeability characteristics of thin films of cured epoxies were measured using permeability cells of the type shown in figure 1. The films selected for the permeability determinations were carefully handled and examined for any defects before installation in the cell. A cell consists of two glass compartments separated by the epoxy film sandwiched between two glass plates, each having centered 1-in-diameter holes. One compartment contains 175 ml of 3M NaC1 and the other 115 ml of distilled water. The activities of chloride ions passing through an epoxy membrane were measured using an Orion Specific Ion Meter Model 401, an Orion Chloride Electrode Model 94-17, and an Orion Double Junction Reference Electrode Model 90-02. Activity readings have been converted into concentration values of moles per liter by using a conversion diagram, constructed by plotting measured chloride ion activities versus known chloride ion concentrations.

The permeability data (calculated at listed exposure times) are presented in table 4 in the form of both permeability units and concentrations. Diagrams of the accumulative permeating chloride ion concentrations versus time are reproduced in figure 2 for four epoxy films. These plots are representative of the varying degrees of impermeabilities. The permeability rates were largest during the first 6 weeks of testing; afterwards the values were lower and more constant. Films of Nos. 1, 3, 17, 19, 31, 38, and 39, were

Table 3.—Immersion testing of coatings on reinforcing bars [1]
[Immersion time 45 days]

Code No.	3M NaOH	Saturated $Ca(OH)_2$
19	No change	*A.* Rusted [2,4]
		B. No change [2]
22	do	No change
23	do	Do.
24	do	Do.
27	do	Do.
28	do	Do.
29	do	Do.
30	do	Do.
31	do	Do.
32	do	Do.
38	do	*S.* Rusted [3,4]
		P. Do.[3,4]
39	do	*S.* No change [3]
		P. Rusted [3,4]
40	do	*S.* No change [3]
		P. Rusted [3,4]
41	do	No change
Uncoated rebar	do	Do.

[1] No. 6 reinforcing coated by firms handling the respective coatings.

[2] *A* and *B* are specimens from companion bars.

[3] *S* denotes bars that were only sandblasted prior to application of the coating, while *P* indicates that their surfaces were also phosphatized prior to being coated.

[4] Rusting took place during the first 15 days of immersion, afterward no changes observed.

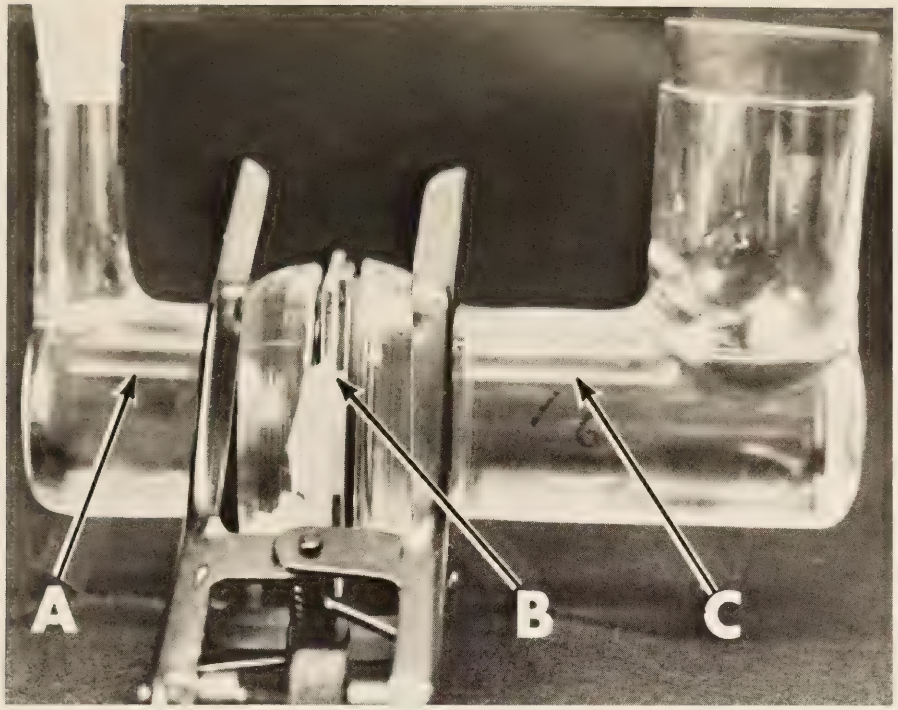

Figure 1.—Permeability cell. A. Compartment containing distilled water. B. Epoxy film sandwiched between two glass plates—each having centered 1-inch-diameter holes. C. Compartment containing 3M NaCl.

essentially impervious to chloride ions during the listed exposure periods. Films of Nos. 12 and 13 permitted the accumulation of chloride ions in the originally distilled water compartment of the cell (fig. 1) to approach, or reach, the chloride ion threshold concentration of 0.02M; i.e., the chloride concentration reported (*15*) to induce corrosion of steel embedded in concretes. Unequivocal interpretations of the chloride permeability values are not possible; however, epoxy films with low values would probably provide the best protection for reinforcing bars.

Electrochemical tests

Electrochemical tests were undertaken to quantitatively rate the relative performance of coatings exposed to solutions corrosive to steel.

Applied voltage studies.—The effects of electrical and electrochemical stresses on the bond of barrier coatings to steel were assessed by modifying the disbonding test, ASTM Designation G8-69T (*16*). These stresses can be induced by cathodic protection devices, stray currents, or by corrosion processes. The cathode and anode were No. 6 reinforcing bars, 6 in. long, both coated with the same materials. The electrolyte was an aqueous solution of 7 percent NaCl. A potential of 2 volts was applied and the electrodes were visually observed periodically for evolution of hydrogen gas at the cathode and for evidence of corrosion products of iron at the anode. Before immersion, any bare ends or obvious mechanically-damaged areas on the electrodes were covered with a film of silicone rubber and no intentional holidays [8] induced so that the sources of any corrosion were holidays in the films themselves. Therefore, the applied voltage method serves as a sensitive holiday detector and can be used to ascertain if holidays are developing in a film because of degradation of the coating.

The results of the impressed voltage studies are listed in table 5. It is felt that coatings which permitted the evolution of hydrogen gas within 15 minutes are of doubtful value (when applied in the indicated thicknesses).

Electrical potential and resistance measurements.—Alternate means of assessing the protective qualities of barrier coatings are electrical potential measurements on coated reinforcing steel immersed in a corrosive solution and the simultaneous measurements of the resistance of the coating films. Such measurements were taken from coated reinforcing bars partially immersed in 3½ percent aqueous solutions of NaCl. The

[8] Holidays are defined in this report as pinholes not normally visually discernible.

Table 4.—Permeability of chloride ions through epoxy films

Code No.	Film thickness	Exposure time	Concentration [1]	Permeability units [2]
	Mils	*Weeks*	*Moles per liter*	
1	3	16	[3] $<1 \times 10^{-5}$	$<1.7 \times 10^{-6}$
2	3	23	1×10^{-4}	9.7×10^{-6}
3	3	16	[3] $<1 \times 10^{-5}$	$<1.7 \times 10^{-6}$
4	3	23	1×10^{-4}	9.7×10^{-6}
6	3	23	1×10^{-4}	9.7×10^{-6}
11	3	12	4×10^{-3}	7.5×10^{-4}
13	3	21	1×10^{-2}	5.0×10^{-4}
16	7	23	2×10^{-3}	6.2×10^{-4}
16	3	10	8×10^{-1}	2.3×10^{-1}
17	3	16	$<1 \times 10^{-5}$	$<1.7 \times 10^{-6}$
19	7	6	No change	....
29	10	6	1×10^{-5}	3.5×10^{-6}
31	10	6	No change	....
38	2	6	..........do..........	....
39	2	6	..........do..........	....
40	2	6	1×10^{-5}	3.5×10^{-6}

[1] Concentration of chloride ions in the chamber originally containing only distilled water.
[2] Permeability units are: (grams per day)/exposed area (in^2)/film thickness (mils); i.e., theoretically the number of grams of chloride ion passing per day through a film having an exposed area of 1 square inch and a thickness of 1 mil.
[3] Multivolt readings were near the region of distilled water and the lower limit of the chloride ion concentration was estimated.

Table 5.—Measured resistance and effect of impressed voltage on coated rebars

Code No.	Film thickness	Application method	Production of H_2 (g)[1]	Partial immersion in 3½ percent NaCl				Rating[2]
				Resistance		Voltage		
				After 1 hour	1000 hours	After 1 hour	1000 hours	
	Mils		*Hours*	*Ohms*	*Ohms*	*Millivolts*	*Millivolts*	
1	4–5	Brush	<¼	537	200	−340	−570	3
2	5–15	do.	<¼	250	190	−588	−576	3
3	2–5	do.	<¼	400	180	−615	−604	3
4	20–30	do.	½	700	260	−470	−555	3
5	40–50	do.	<¼	1.1×10^3	[3] 425	−513	[3] −617	3
10	10	do.	<¼	....	....	....	....	3
11	10–12	do.	<¼	9.6×10^3	800	−497	−560	3
16	8	do.	1	400	250	−516	−593	2
17	4	do.	<¼	1.5×10^3	700	−430	−545	3
18	4	do.	<¼	98	240	−516	−604	3
19	4	do.	24	435	225	−503	−568	2
22	25	Fluidized bed	[3] >648	[4] $>25 \times 10^5$	[4] $>25 \times 10^5$	No reading [5]	No reading [5]	1
23	25	do.	[3] >120	[4] $>25 \times 10^5$	[4] $>25 \times 10^5$	do. [5]	do. [5]	1
24	35	do.	[3] >480	13×10^5	[4] $>25 \times 10^5$	do. [5]	do. [5]	1
25	6–11	Electrostatic spray gun	6	2×10^5	[4] $>25 \times 10^5$	−613	−541	1
26	2–3	do.	<¼	....	....	....	....	3
27	8	do.	<¼	....	....	....	....	3
28	1–2	do.	<¼	250	240	−600	−606	3
29	3–4	do.	<¼	475	300	−518	−565	2
30	15–18	Fluidized bed	[3] >168	[4] $>25 \times 10^5$	[4] $>25 \times 10^5$	No reading [5]	No reading [5]	1
31	8–9	Electrostatic spray gun	[3] >96	$>25 \times 10^5$	1500	−532	−588	1
32	4–6	do.	<¼	800	540	−617	−573	3
33	2–4	Brush	<¼	550	400	−516	−565	3
[6] 38	2–4	Electrostatic spray gun	<¼	[8] 360	[9] 210	[9] −514	[9] −589	3
[7] 38	2–4	do.	<¼	[8] 380	[9] 220	[9] −481	[9] −606	3
[6] 39	2–4	do.	<¼	[8] 380	[9] 240	[9] −557	[9] −610	2
[7] 39	2–4	do.	3	[8] 410	[9] 230	[9] −557	[9] −643	2
[6] 40	2–4	do.	<¼	[8] 280	[9] 200	[9] −513	[9] −608	3
[7] 40	2–4	do.	½	[8] 290	[9] 240	[9] −481	[9] −606	2
41	3–7	do.	½	3.8×10^5	3.0×10^3	−451	−570	2
[10] 42	3–4	do.	<¼	400	370	−526	−579	3
Uncoated bar		....	Immediate	200	370	−648	−634	4

[1] Coated bar anodically polarized with 1½ volts. Bars partially immersed in 7 percent NaCl.
[2] In order of decreasing corrosion protection: 1 2 3 4.
[3] Measured after 648 hours.
[4] Resistance values beyond capacity of measuring device.
[5] No current flow because of holiday-free films.
[6] Sandblasted surfaces.
[7] Phosphatized surfaces.
[8] Measured after 120 hours.
[9] Measured after 696 hours.
[10] Same coating material as No. 41 applied to cold bars; in No. 41 coating applied to bars heated to 190° C.

electrode potentials of the coated reinforcing bars were measured using a Coleman Model 37A pH Meter with a standard calomel electrode (S.C.E.) as the reference electrode. Measurements of the resistance of the films on the coated reinforcing bars were made using a Yellow Springs Instrument Company Model 31 Conductivity Bridge along with a platinum electrode.

The electrical potential and resistance data are presented in table 5. Low resistance readings, below 500 ohms, are indicative of films which either have many holidays or are permeable towards water and chloride ions. Coated reinforcing bars which were visually observed to have several corrosion sites gave potential readings below —600 mV (the electrical potential of uncoated reinforcing bars was —634 mV vs. the S.C.E. after 1,000 hours). The thicker films, above 15 mils, were free of holidays and had resistances higher than 24×10^5 ohms, beyond the range of the measuring device. The same films did not permit the passage of any measurable current; therefore, the potential of these bars could not be measured.

Potential and resistance data for three sets of reinforcing bars, each set coated with a different epoxy, are reproduced in figures 3, 4, and 5. The wide variance in the initial millivolt and ohmic readings of duplicate and triplicate specimens decreased rapidly within the first 200 hours of testing so that after 1,000 hours of testing good agreements were obtained for companion specimens. A rapid decrease in the resistance of a coating probably can be attributed to the emergence of holidays, while an increase in resistance is probably indicative of some type of healing mechanism.

The ratings of coatings in table 5 are based on their overall protective qualities. The authors believe that adequate protection is provided by coatings with ratings of 1 or 2. The coatings with

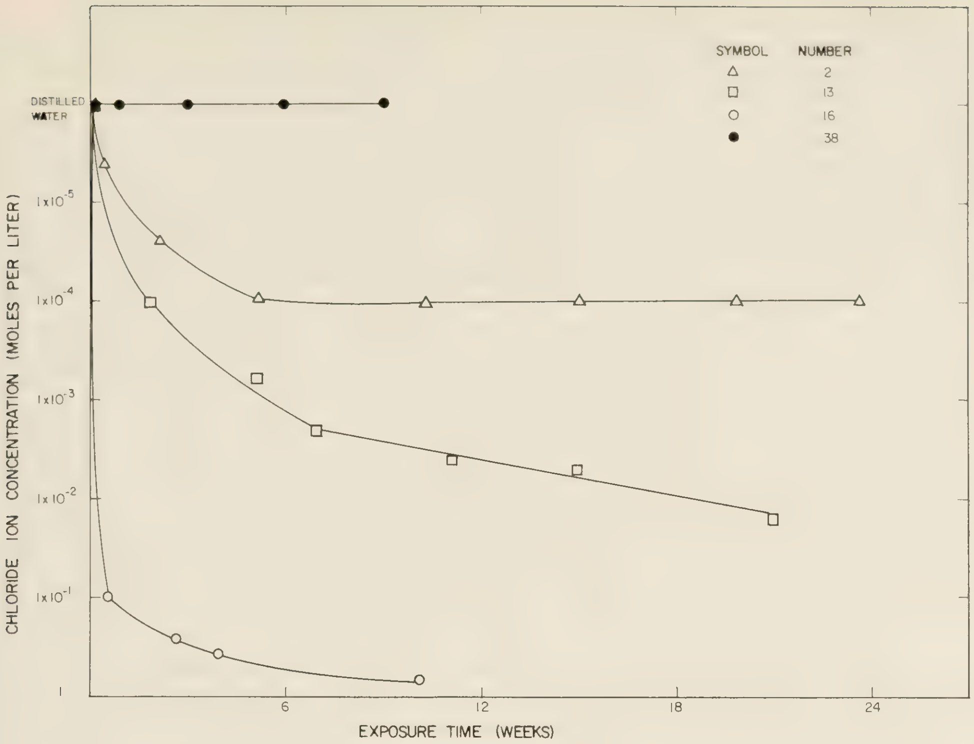

Figure 2.—Concentration of chloride ions passing through epoxy films—film thicknesses, 3 mils.

ratings of 3 may be inadequate because of poor application techniques, improper curing, or insufficient film thicknesses.

Physical properties

Tests were performed to measure the ability of coatings to resist rough handling. Before these physical tests were started the film thicknesses of the bars were measured, the number of holidays was determined, and the bars were examined for evidence of damage or faulty application.

Impact and abrasion resistances of epoxy coatings on steel plates.—Both direct and reverse impact resistances of cured epoxy coatings on 4 by 4 by 0.050 in. cold-rolled steel plates were determined in accordance with ASTM Designation G14-69T (*17*). A Gardner Laboratory Impact Tester with a 4-pound hammer was used in the test in which a weight is dropped from increasing heights to determine the energy required to rup-

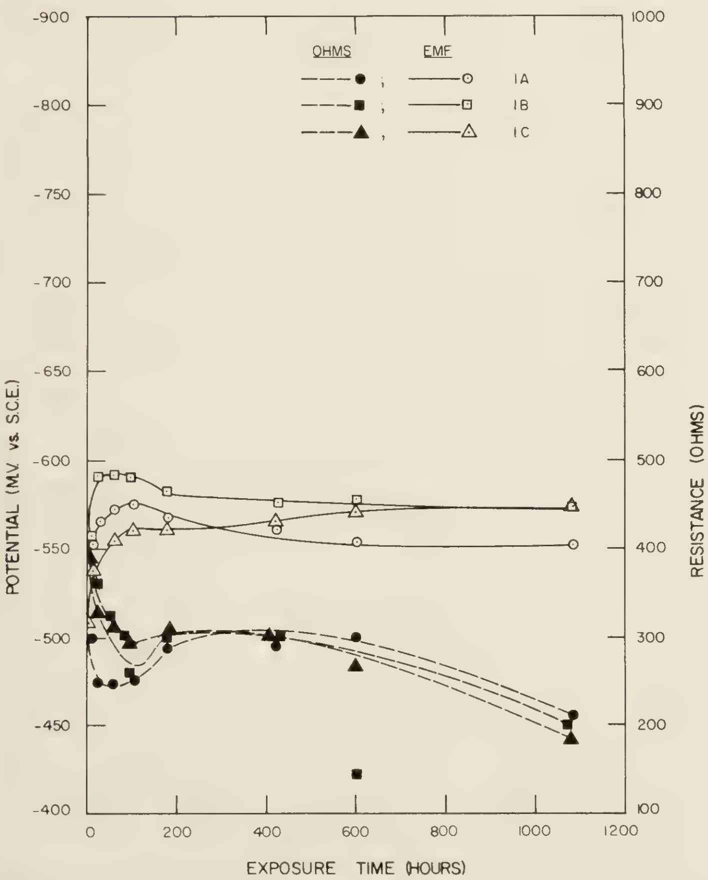

Figure 3.—Electrical potential and resistance measurements of coated reinforcing bars No. 1 immersed in 3½ percent NaCl.

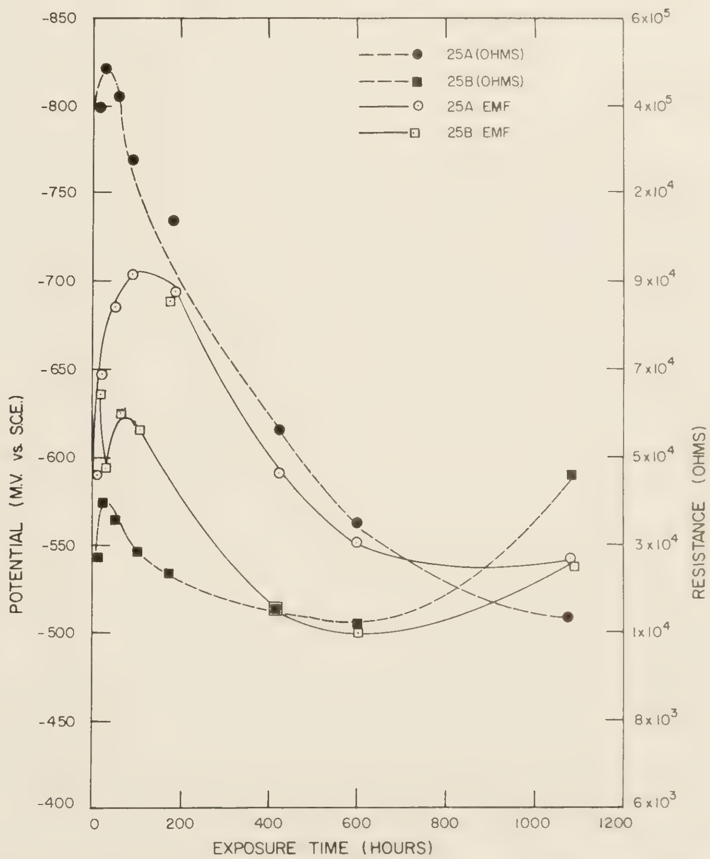

Figure 4.—Electrical potential and resistance measurements of coated reinforcing bars No. 25 immersed in 3½ percent NaCl.

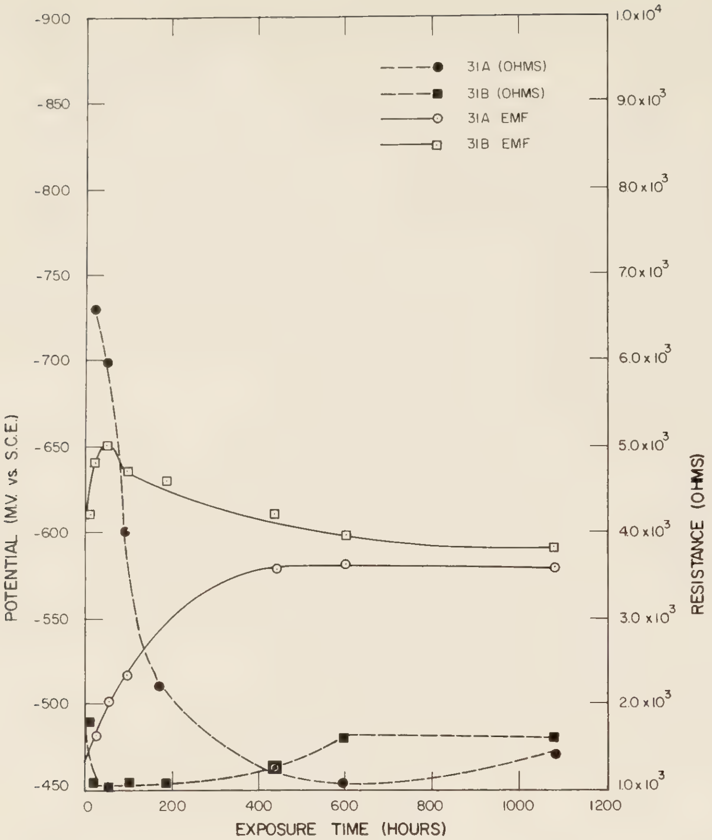

Figure 5.—Electrical potential and resistance measurements of coated reinforcing bars No. 31 immersed in 3½ percent NaCl.

Table 6.—Abrasion and impact resistance of epoxy-coated, cold-rolled steel panels 4 by 4 by .050 in.

		Impact resistance to 4 pound hammer		Abrasion resistance [1]
Code No.	Film thickness	Reverse impact	Direct impact	Weight loss
	mils	*in-lb*	*in-lb*	*mg*
1	7	20	90	71
2	7	4	[2] 120	56
3	8	40	160	107
4	5	4	40	70
5	7	8	20	58
6	6	4	20	71
11	6	—	—	89
16	5	8	50	148
17	6	7	50	58
18	7	12	110	52
19	1	>160	>160	51
19	4	160	160	—
25	7	4	60	—
28	8	40	60	88
29	8	50	60	57
31	6	20	80	—
38	7	20	80	—
39	8	20	40	—
40	11	20	([3])	—

[1] Tabor CS-10 wheels, with 1000g load per wheel, loss per 1000 cycles.
[2] Bond at the steel-epoxy interface severed at 10 in-lb.
[3] Coating shattered off of steel panel.

ture the coating (table 6). Reverse impact is more severe than direct impact and gives a better indication of the flexibility of a coating (low reverse impact values are indicative of brittle materials). However, in actual practice there would be little chance of reverse impact damage on a reinforcing bar. Furthermore, it is felt that the impact values for the powder materials (Nos. 25, 28, 29, 31, 38, 39, and 40) are too low and are not reliable indicators of expected service life. The bend testing of coated reinforcing bars, discussed later, is considered to yield more reliable results.

The abrasion resistances of epoxy coatings on similar steel panels were determined in accordance with ASTM Designation D1044-56 (*18*) by using a Taber Abraser and Taber CS-10 wheels with 1,000 g load per wheel. After each 200 cycles the wheels and specimens were gently cleaned with a soft-bristle brush. These abrasion data are also given in table 6 in units of weight loss in mg per 1,000 cycles. Two of the solvent-containing systems, Nos. 3 and 16, had weight losses over 100 mg indicating poor abrasion resistances.

Inspection of coated reinforcing bars.—The film thicknesses, the number of holidays per unit bar length (4 ft), and the visual evaluations of coated reinforcing bars, submitted by the respective firms handling the materials, are given in table 7. The film thicknesses were measured with a Mikrotest Model 800000 Magnetic Gage.

The following tentative conclusions concerning the integrity of the coating films are implicit in the results given in table 7.

- The effectiveness of the application methods in producing thin films free of defects decreases in the sequence: electrostatic spray gun greater than fluidized bed greater than dipping greater than brush.
- Powder coatings yield films of more uniform thickness than most liquid coatings.
- Good application practices, including proper surface preparation, are imperative if a coating material is to realize its fullest potential.

Bend tests of coated bars.—No. 6 bars coated by the various applicator companies were bent at a 120° angle with a radius of curvature of ca. 3 in. using a Green Lee Tool Company Model 770 Bar Bender. Portions of the bars in contact with the bending machine were protected with rubber tubing of 1½ in. o.d. and ¾ in. i.d. to avoid mechanical damage to the coating so that any cracking in a coating occurring during the bend test could be attributed to stress failure of the coating. The results of these tests are given in table 8.

Cracking and disbonding took place on the areas of some bars that were under tension during the bending. The four different polyvinyl chloride coated reinforcing bars (Nos. 23, 24, 26, and 30) gave excellent performances even though their film thicknesses ranged from 2 to 35 mils. A greater variation was ob-

Table 7.—Film thickness and integrity of coatings [1]

Code No.	Application method	Film thickness	No. of holidays per 4 foot bar	Visual evaluation and comments
		mils		
1	Brush	4–5	40	Deformations not well-coated and slightly exposed. Accumulation of epoxy in low-lying regions.
2	do	5–15	ca. 10	Deformations not well-covered. Long uncovered regions. Material brittle.
3	do	2–5	ca. 30–40	Deformations well-covered.
4	do	10–20	None	Deformations not well-defined. Epoxy concentrated in the low-lying regions between the deformations.
5	do	10–15	Too many to estimate	Longitudinal deformations not well-covered. Excess epoxy in regions between the deformations.
10	do	10	ca. 10	Susceptible to abrasion. Coating comes off easily. Rough texture. Epoxy accumulated between deformations.
11	do	10–12	None	Coating chips easily. Regions where deformations not well-covered. Evidence of epoxy dripping from bar.
16	Electrostatic spray gun	2–4	40	Deformation not well-covered. Accumulation of epoxy in low-lying areas.
17	Brush	4	Too many to estimate	Tops of deformations not well-covered. Brittle materials that easily chip off steel substrate.
18	do	4	do	Bad adhesion to steel.
19	Single dipping	1	40	Good coverage. Well-defined deformation pattern. No bad dipping regions.
22	Fluidized bed	25	Only at ends	Good even buildup film. Large thickness characteristic of application method.
23	do	25	do	Good even buildup film. Thermoplastic.
24	do	35	None	Deformation pattern not well-defined. Thermoplastic.
25	Electrostatic spray gun	6–11	do	Good coating material. Some bad spraying techniques. Bars sprayed from one direction giving only the underside of deformations a thin coating.
		mils		
26	Electrostatic spray gun	2–3	Too many to estimate	Top of deformations not covered. Coated rebars sticky when received. Thermoplastic.
27	do	8	ca. 1	High gloss coating. Even buildup. Very tough coating. Did not chip.
28	do	1–2	Cannot estimate	Either very high number of holidays or electrical conducting pigments. Rough texture.
29	do	3–4	do	Either very high number of holidays or electrical conducting pigment. Deformaitons not well-coated. Tough coating not susceptible to chipping.
30	Fluidized bed	15–18	None	Deformation pattern not well-defined possibly due to tendency of material to flow when cured at elevated temperatures. Thermoplastic.
31	Electrostatic spray gun	8–9	do	Good even buildup film. Deformations well-covered. Tough coating not susceptible to chipping.
32	do	4–6	40	Mill scale not removed. Coating chips easily. Disbonding between the scale and the steel rebar.
33	Brush	3–4	Too many to estimate	Coating easily damaged and chips.
38	Electrostatic spray gun	2–4	ca. 30–40	Deformation not well-covered. Some bars phosphatized.
39	do	2–4	ca. 30–40	Holidays located on deformations. Some bars phosphatized.
40	do	2–4	10	Tough coating not susceptible to chipping. Some bars phosphatized.
41	do	3–7	1	Good coverage. Bar heated prior to application of powder coating.
42	do	3–4	Too many to estimate	Same material as No. 41, but powder applied to cold rebars.
43	do	3–4	do	Abrades readily.

[1] No. 6 steel reinforcement bars coated by applicators or coatings producers. Unless otherwise stated, the mill scale was removed by sandblasting.

Table 8.—Physical testing of coated steel reinforcing bars[1]

Code No.	Film thickness	Results of 120-degree bend[2]	Impact rating[3]	Pencil hardness[4]
	mils			
1	4–5	Slight cracking near edge of deformation. Length of cracks ca. 1/8 in.	Good	>8H
2	5–15	Complete failure in bend area. Almost complete disbonding.	Poor	>8H
3	2–5	Few small cracks ca. 1/8 in. Good performance.	Good	>8H
4	20–30	Severe cracking at almost every transverse deformation in bend area. Cracks 1/2 to 3/4 in. in length.	Poor	
5	40–50	Severe cracking at deformations. Cracks ca. 1/8 in. wide. Undercutting disbondment between the films and steel.	do	>8H
10	10	Severe cracking which extended from longitudinal deformation. Disbonding between the coating and steel.	do	>8H
11	10–12	Same as No. 10.	do	>8H
16	2–4	Very fine cracks. Good performance.	Fair	>8H
17	4	Cracking started at 20-degree bend. Total disbondment in area under tension. Complete failure.	do	>8H
18	4	No cracking. Excellent performance.	do	>8H
19	4	do	do	>8H
22	25	Substantial cracking extending from longitudinal to longitudinal deformation. Some disbonding between the coating and steel.	Excellent	>8H
23	25	No cracks. Excellent performance.	do	8H
24	35	do	do	H
25	6–11	Many small (ca. 1/8 in. long) thin cracks—considered as moderate cracking.	Good	>8H
26	2–3	No cracks. Excellent performance.		
27	8	Substantial cracking extending from longitudinal to longitudinal deformation. Some disbonding.	Good	>8H
28	1–2	A. Slight cracking. Good performance. B. Substantial cracking and disbonding.[5]	Fair	>8H
29	3–4	No cracks. Excellent performance.	Good	>8H
30	15–18	do	Poor	H
31	8–9	do	Excellent	>8H
32	4–6	Complete failure. Total disbonding in bend area attributable to disbonding between mill scale and steel.[5]	Fair	>8H
33	3–4	No cracks. Excellent performance.	Good	8H
[6] 38	2–4	do	Excellent	>8H
[7] 38	2–4	Severe cracking on every deformation in area under tension during bending.		
[6] 39	2–4	No cracks. Excellent performance.	Excellent	>8H
[7] 39	2–4	Two or three small cracks. Good performance.		
[6] 40	2–4	Excellent performance. No cracking.	Excellent	>8H
[7] 40		Failure. Phosphate coating adhered poorly to the steel substrate. Cracking of epoxy coating in complete area under tension during bending.		
[8] 41	3–7	Excellent performance. No cracking.	Good	>8H
[9] 42	3–4	Substantial cracking.	do	>8H
43	3–4	Slight "popping off" of coating. Good performance.	do	>8H

[1] No. 6 steel reinforcement bars coated by applicators or coating producers. Unless otherwise stated, the mill scale was removed by sandblasting.
[2] Crack rating in order of decreasing performance: Excellent, Good, Moderate, Substantial, Severe, Complete failure.
[3] Relative rating: Excellent, Good, Fair, Poor.
[4] Lead hardness which imparts a scratch to the coating.
[5] Mill scale was not removed.
[6] Surface sandblasted prior to coating application.
[7] Surface sandblasted and phosphatized prior to coating application.
[8] Bars heated to 190° C. prior to applying powder coating.
[9] Same coating material as No. 41, but applied to cold reinforcing bars.

served for the epoxy coated reinforcing bars as some performed well while a few were classified as failing. Generally, the epoxy coatings which did not perform well were either the most brittle epoxies or they were applied in film thicknesses over 10 mils. The effect of the film thickness is well illustrated by comparing Nos. 22 and 31, which were both coated with the same materials but with different application methods. No. 22 had a film thickness of ca. 25 mils, while the film thickness of No. 31 was ca. 8–9 mils. When bent, substantial cracking was observed in the film of No. 22, while No. 31 was completely free of cracking.

Another factor affecting the bending characteristics of coated reinforcing bars is the type of surface preparation of the substrate prior to application of the coatings. In two series of coated reinforcing bars, Nos. 28B and 32, epoxy coatings were applied to unprepared surfaces which were still covered with mill scale. Almost total disbondment was observed when both series of bars were bent; while the epoxy adhered tenaciously to the mill scale, the mill scale was disbonded from the steel substrate. A portion of the coated reinforcing bars, Nos. 38, 39, and 40, were both sandblasted and phosphatized prior to being coated, while the remainder were just sandblasted. The sandblasted coated reinforcing bars gave no indications of coating failures when bent, while the phosphatized bars were susceptible to varying degrees of coating failures.

The temperature of the steel substrate, when being coated, can affect the flexibility of the cured epoxy coating. For example, Nos. 41 and 42 reinforcing bars were coated with the same material. However, No. 41 bars were heated to 191° C. and immediately coated, while No. 42 bars were at ambient temperature when coated. The epoxy coating was then cured at 177° C. on both sets of bars. Excellent flexibility was exhibited by No. 41, whereas No. 42 cracked badly when bent.

Impact on reinforcing bars.—The impact resistances of coatings were evaluated by dropping an 18 in. length of coated No. 6 reinforcing bar on a slab of concrete so that impact occurred lengthwise as follows:

1. A single bar was dropped 1 m from a horizontal position to the concrete.
2. The same bar was dropped from a height of 2 m.
3. A companion specimen was taped loosely between two bare No. 7 bars of the same length and the assembly was dropped from a height of 2 m to the concrete slab.
4. The bars were inspected after each drop for the following types of damages:
   a. Shattering of the coating to expose bare metal.
   b. Cutting of the coating to expose bare metal.
   c. Cracking of the coating.
   d. Disbonding of the coating from the steel substrate. The coatings were rated on a relative basis as shown in table 8. There is a fair correlation between the results of the bend tests and the impact tests.

Pencil hardness.—The pencil hardness values (table 8) were determined using a series of lead pencils covering the hardness ranges from H to 8H with steps of one-hardness increments. The hardness is designated as the softest lead that imparts a scratch in the coating. All of the epoxy coatings had ratings above 8H, while the polyvinyl chloride coatings were more variable with ratings of H for Nos. 24 and 30, and 8H for No. 23.

Pull out tests.—In order to determine if the bond between the coated reinforcing bar and the concrete would be sufficient to give the required tensile strength to reinforced concrete members, the "pull out strength" of coated bars was compared with that of uncoated bars according to procedures described by Mathey and Watstein (*19*). Tests of the uncoated bars themselves show a yield strength of 67,600 p.s.i. and a modulus of elasticity of 30.7×10^6 p.s.i. for the No. 6 diamond deformed bars, and 62,500 p.s.i. yield strength and 28.4×10^6 p.s.i. modulus of elasticity for the horizontally deformed bars. The "critical" bond stress indicates an impending failure and is defined as one of the following (*19*): the bond stress for a slip of 0.01 in. at the loaded end of the bar, or a slip of 0.002 in. at the free end of the bar, whichever occurs first. These critical bond stresses were used in developing the ACI Standard "Building Code Requirements for Reinforced Concrete," (ACI 318-63) (*20*). Although this code has been superseded by a code based on the principle of "development lengths," the critical bond stress levels remain essentially the same. These slip values are given in table 9. Also in table 9 are the average critical bond stresses of the uncoated bars. Twenty-one of the 29 coated bars tested exceeded 90 percent of the average value of the uncoated bars and some of the coated bars exceeded the value of the uncoated bars. Bond stress versus the slip at the loaded and free ends of the bars is shown in figure 6.

Creep tests.—It is known that cured epoxies will flow under sustained load; therefore, creep under tensile loads is being determined on No. 6 coated bars embedded in concrete, and the results will be reported as soon as available.

Conclusions

Based on the data obtained to date under this program, the following tentative conclusions appear warranted:

- Most epoxy coatings will not be degraded by long-term embedment in concrete.
- Sandblasting without subsequent phosphatizing is sufficient preparation of the steel before applying the coating.
- Only two coating materials allowed the passage of sufficient chloride ions to approach or reach dangerous concentrations of chlorides.
- Coatings which permit the evolution of hydrogen gas within 15 minutes under a potential of 2 volts are of doubtful value.
- Coatings with electrical resistances less than 500 ohms probably have many holidays or are permeable to water and chloride ions.
- Impact values on coated steel plates do not appear to give reliable indications of the serviceability of reinforcing bar coatings.
- The "bending test" gives a good indication of proper coating thickness, bar preparation, and curing of the epoxy coating.
- Pullout tests indicate that many epoxy coatings give bond strengths essentially equal to those of uncoated bars when their film thicknesses are less than 10 mils.

Recommendations

After consideration of the results of the tests described above, it appears that the four materials listed below should be

Table 9.—Pullout data

Code No.	Compressive strength of concrete	Maximum computed steel stress	Bond stress corresponding to Loaded end slip of 0.01 in.	Bond stress corresponding to Free end slip of 0.002 in.	Bond stress corresponding to Free end slip of 0.005 in.	½ Maximum computed bond stress	Mode of failure
	p.s.i.	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	*p.s.i.*	
U–H [5]	6,163	92,100	723	978	1,335	712	Reinforcement
U–H	6,613	87,600	641	889	1,211	629	Do.
U–H	5,724	87,600	712	1,157	1,327	727	Do.
U–D [6]	6,613	86,200	764	1,037	1,302	628	Do.
U–D	6,163	92,100	758	([1])	([1])	664	Do.
1–H	5,724	87,600	754	1,185	([2])	727	Do.
1–D	5,724	77,100	638	1,060	([2])	645	Do.
1–H–S [7]	5,724	87,600	609	925	1,103	727	Do.
3–H	5,724	87,600	712	1,210	1,391	727	Do.
3–D	5,724	77,100	745	1,199	([2])	646	Do.
18–H	6,163	87,600	766	1,352	([2])	675	Do.
18–D	6,163	86,200	656	1,197	([2])	673	Do.
19–H	5,724	87,600	676	1,089	([2])	727	Do.
19–D	5,724	86,200	759	1,277	([2])	726	Do.
22–H–1	6,613	69,200	444	413	782	497	Bond
22–H–2	6,613	([3])	368	231	455	—	([2])
23–H	6,613	62,400	107	25	67	477	([2])
23–D	6,613	54,500	167	50	114	395	([2])
24–H	6,613	18,500	18	5	11	133	([2])
24–D	6,613	22,700	18	1	5	165	([2])
25–D–1	6,613	87,600	655	1,050	([2])	629	Reinforcement
25–D–2	6,613	86,200	632	922	1,300	628	Do.
29–H–1	6,163	87,600	606	978	([2])	673	Do.
29–H–2	6,163	81,600	647	1,032	([2])	638	Do.
30–H	6,163	78,300	410	214	498	605	Bond
30–D	6,163	72,600	348	192	429	569	Do.
31–H	6,163	87,600	670	1,056	1,341	675	Reinforcement
31–D	6,163	86,200	646	956	1,200	673	Do.
38–H	5,724	92,100	701	1,128	1,335	766	Do.
38–D [4]	5,724	86,200	762	1,032	([2])	726	Do.
39–H	6,613	87,600	624	1,121	([2])	629	Do.
39–3	6,613	86,200	710	1,178	([2])	628	Do.
41–D	6,163	87,600	605	1,068	([2])	675	Do.
41–H	6,163	86,200	656	1,046	([2])	673	Do.

[1] No data acquired due to sticking gage.
[2] Failure took place before free end slip of 0.005 in. was reached.
[3] Test stopped at stress in the steel of 36,300 p.s.i with free end slip of 0.007.
[4] Phosphatized bar.
[5] U, uncoated bars; H, horizontal deformations.
[6] D, diamond deformations.
[7] S, coating mixed with sand.

further evaluated by experimental construction. These coatings, when applied by electrostatic spray gun in coats of 7±2 mil thickness on bars—cleaned to a white metal surface by sandblasting—and when properly cured and able to withstand the 120° bend test without cracking, should be satisfactory for the intended application.

Code No.

25 Miccron 650—Blue Epoxy—Republic Steel Corporation.

31 Scotchkote 202 — Minnesota Mining and Manufacturing Company.

39 Flintflex 531-6020—E. I. Du-Pont de Nemours and Company, Inc.

41 Ciba-Geigy Corporation, LSU 431, Formula 907-2-5.

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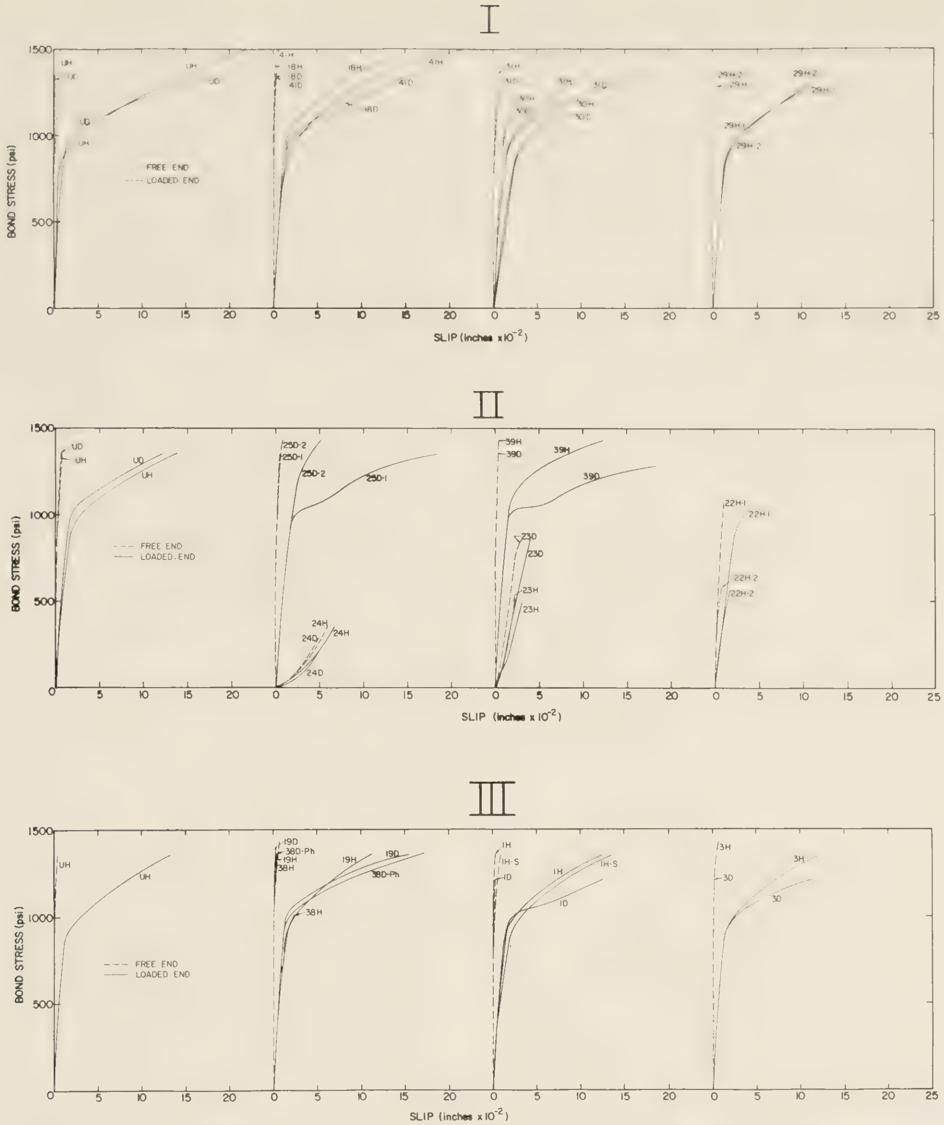

Figure 6.—Bond stress vs. slip at the loaded and free ends of coated and uncoated bars.

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(*15*) D. A. Hausmann, "Steel Corrosion in Concrete," *Materials Protection,* 6, 1967, p. 19.

(*16*) "Tentative Method of Test for Cathodic Disbonding of Pipeline Coatings," ASTM Designation G8-69T.

(*17*) "Tentative Method of Test for Impact Resistance of Pipeline Coatings," (Falling Weight Test), ASTM Designation G14-69T.

(*18*) "Standard Method of Test for Resistance of Transparent Plastics to Surface Abrasion," *ASTM Designation D1044-56.*

(*19*) Robert G. Mathey and David Watstein, "Investigation of Bond in Beam and Pull-Out Specimens with High-Yield Strength Deformed Bars," *Jour. Amer. Conc. Inst.,* March 1961, pp. 1071–1090.

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Status of New Inspection Instrumentation for Steel Structures

by the Implementation Division, Office of Development

As a result of the favorable response that has been received to date at initial demonstrations and field tests of the newly developed bridge inspection devices by the Southwest Research Institute, a concerted effort has been underway to fabricate 10 additional units for full field trial and evaluation beginning this summer.

With these new battery-powered highly portable devices, for the first time bridge inspectors will be provided with a practical means of locating and defining cracks in structural steel.

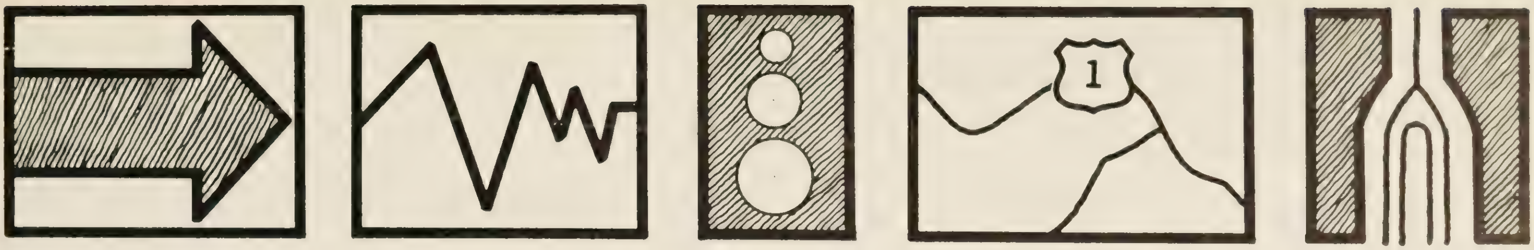
Features of the Acoustic Crack Detector (ACD), which is the primary unit for locating cracks, are as follows:

- One hand operation.
- Audible and visual crack indication.
- Digital readout on probe automatically indicates distance from probe to crack.
- Coupling indicator.
- Battery condition indicator on probe.
- Easily calibrated for various surface conditions.
- Can be worn as backpack or frontpack.
- Accessory belt for couplant, cleaning tools, position fixture, measuring tape, etc.
- No electrical shock hazard.
- Range: 3 to 10 feet probe to crack, typical on bridges, depending on surface conditions and preparation.
- Sensitivity: detects $\geqq$¾-inch crack with high reliability over operating range, shorter cracks at close range under some conditions.
- Discrimination: will not alarm on good welds without heavy undercut.
- Battery powered: ~8-hour operation—rechargeable using separate charger (furnished).
- Size: 10¼ inches by 12¼ inches by 2¼ inches.
- Weight: pack 8 pounds; probe 1.2 pounds.

Features of the Magnetic Crack Definer (MCD), which is the companion unit for defining precise location and length of crack, are as follows:

- One hand operation.
- Audible and visual crack indication.
- Lamp illuminates on probe indicating presence of and direction of crack.
- One channel detects open cracks and cracks along the toe of welds.
- One channel detects crack tip(s) in parent material.
- Both channels operate simultaneously.
- Complements ACD.
- Probe can be used to determine precise location and length of crack.
- Paint removal not required.
- Battery-condition indicator on probe.
- No electrical shock hazard.
- Crack definition: indicates crack length within ¼ inch.
- Battery powered: 1.2-hour operation—rechargeable using separate charger (furnished).
- Size: 10¼ inches by 12¼ inches by 3¼ inches.
- Weight: pack 14.6 pounds; probe 0.5 pound.

Delivery of the first instrument to the Federal Highway Administration is scheduled for August 1, 1973, with three additional devices to be delivered each succeeding month. Field testing will be initiated to coincide with delivery dates. When sufficient field evaluation has been completed, which indicates the instruments are in fact ready for full widespread field use, the plans and specifications suitable for manufacturing the device on a production basis will be made available by the Federal Highway Administration to industry and the States as rapidly as possible.



NEW RESEARCH IN PROGRESS

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

FCP Category 1—Improved Highway Design and Operation for Safety

FCP Project 1A: Traffic Engineering Improvements for Safety

Title: Advance Traffic Control Systems for Maintenance Operations. (FCP No. 41A2522)

Objective: To evaluate the effect of advance warning traffic control systems on traffic flow and driver alertness under various traffic and maintenance situations.

Performing Organization: Department of Highways, Baton Rouge, La. 70804

Expected Completion Date: June 1974

Estimated Cost: $31,000 (HP&R)

FCP Project 1G: Safer Traffic Guardrails and Bridge Railings

Title: Development of a New Energy Absorbing Bridge Railing. (FCP No. 31G2043)

Objective: To fabricate and test an energy absorbing bridge railing capable of redirecting a 25,000 pound vehicle.

Performing Organization: Southwest Research Institute, San Antonio, Tex. 78284

Expected Completion Date: February 1974

Estimated Cost: $75,000 (FHWA Administrative Contract)

FCP Project 1H: Skid Accident Reduction

Title: Skid Resistance——Pavement Surface Research. (FCP No. 41H1194)

Objective: To determine the skid resistance of various pavement surface types used in Kansas and to relate these findings to materials and construction, or maintenance practices for the purpose of identifying the best combinations for the Kansas environment.

Performing Organization: State Highway Commission, Topeka, Kans. 66612

Expected Completion Date: June 1975

Estimated Cost: $76,000 (HP&R)

Title: Bridge Deck Rideability. (FCP No. 41H2272)

Objective: To develop equipment to measure realistically riding surface profiles of newly constructed bridge decks; from this, make necessary changes in specifications to control rideability of bridge decks and approaches.

Performing Organization: Division of Highways, Sacramento, Calif. 95807

Expected Completion Date: June 1974

Estimated Cost: $50,000 (HP&R)

Title: Frictional Properties of Highway Surfaces. (FCP No. 41H2283)

Objective: Utilizing mu-meter and stopping distance car, determine the effects of differential wheelpath friction on vehicle control, accident analysis, average friction level, and driver behavior. Determine safe level of differential wheelpath friction for various vehicle speeds. Determine effects of grooving on vehicle control.

Performing Organization: State Highway Department, Phoenix, Ariz. 85007

Expected Completion Date: March 1974

Estimated Cost: $32,000 (HP&R)

Title: Locked Wheel Friction vs. Other Modes. (FCP No. 41H3152)

Objective: Modify PTTSC skid trailer to measure skid resistance using locked wheel, side force, and transient slip methods of test. Determine order in which each method ranks. Test pavements for different test speeds. Evaluate effects of water depth, test tire design, and yaw angle. Compare methods on a common basis to determine relative advantages for measuring the skid resistance of pavements.

Performing Organization: Pennsylvania State University, University Park, Pa. 16802

Expected Completion Date: December 1974

Estimated Cost: $80,000 (HP&R)

Title: Driver Awareness of Highway Sites with High Skid Accident Potential. (FCP No. 31H6752)

Objective: To define and measure quantitatively combinations of roadway characteristics and environmental conditions which create distinct degrees of skid risk.

Performing Organization: Biotechnology, Falls Church, Va. 22042

Expected Completion Date: January 1974

Estimated Cost: $85,000 (FHWA Administrative Contract)

Title: Field Test and Evaluation Center for Eastern States. (FCP No. 31H8263)

Objective: Establish, maintain, and operate a field test and evaluation center for standardizing the measurement of pavement skid resistance. Provide technical assistance and calibration services to State highway departments and other agencies in Eastern States.

Performing Organization: Ohio State University, East Liberty, Ohio 43319

Expected Completion Date: December 1974

Estimated Cost: $481,000 (FHWA Administrative Contract)

FCP Project 1N: Motorists' Direction and Information Systems

Title: Arrow Aiming in Traffic Guide Signs. (FCP No. 41N2792)

Objective: To determine the differential effects on driving behavior of arrow direction on guide and directional signs.

Performing Organization: Department of State Highways, Lansing, Mich. 48904

Expected Completion Date: May 1974

Estimated Cost: $50,000 (HP&R)

FCP Project 1O: Aids to Surveillance and Control

Title: Accident Analysis at Rail-Highway Grade Crossings. (FCP No. 21O1012)

Objective: Review existing grade crossing data base; analyze crossing accident and inventory data; edit-check data and update data base; analyze accident potential and accident severity of train involved and non train involved accidents by regression techniques.

Performing Organization: Federal Highway Administration, Washington, D.C. 20590

Expected Completion Date: March 1974

Estimated Cost: $25,000 (FHWA Staff Research)

FCP Project 1S: Motorists' Radio System for Emergency Needs and Advisory Communications

Title: Development and Evaluation of a Motorist Aid System. (FCP No. 41S2252)

Objective: To determine feasibility of system described in Georgia project No. 7203. Establish requirements and specify system and hardware.

Performing Organization: Gamewell, Newton, Mass. 02164

Expected Completion Date: June 1974

Estimated Cost: $51,000 (HP&R)

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

FCP Project 2B: Development and Testing of Advanced Control Strategies in the Urban Traffic Control System.

Title: Variable Cycle Signal Timing Program. (FCP No. 32B2283)

Objective: To develop in detail algorithms for the dynamic optimization of traffic signal control parameters without the previously imposed requirement of a fixed background cycle.

Performing Organization: KLD Associates, Inc., Huntington, N. Y. 11743

Expected Completion Date: February 1974

Estimated Cost: $188,000 (FHWA Administrative Contract)

Title: Radio Frequency Traffic Sensor. (FCP No. 42B5292)

Objective: To develop a radio frequency traffic sensor to replace the road tube and diaphragm switch now used in portable traffic counters.

Performing Organization: Department of Transportation, Albany, N. Y. 12226

Expected Completion Date: March 1974

Estimated Cost: $46,000 (HP&R)

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

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

Title: Disposal of Highway Solid Wastes. (FCP No. 43E-2332)

Objective: To develop procedures and guidelines for the disposal of all highway associated refuse in a manner that will not adversely affect the environment.

Performing Organization: Division of Highways, Sacramento, Calif. 95807

Expected Completion Date: March 1978

Estimated Cost: $182,000 (HP&R)

Title: Improving Driver Performance on Curves in Rural Highways Through Perceptual Changes. (FCP No. 43F1492)

Objective: To develop an operational definition of a curve's perceptual structure and a diagnostic model for curve assignment. To determine the relationship between the perceptual structure road geometry and the driver performance. To implement the developed methodology for curve assessment.

Performing Organization: Ohio State University, Columbus, Ohio 43210

Expected Completion Date: August 1974

Estimated Cost: $66,000 (HP&R)

Title: Development of Techniques for Plant Establishment on the Roadside. (FCP No. 43F2512)

Objective: Investigate methods to improve the establishment and maintenance of permanent types of vegetation on highly erosive roadside soil situations.

Performing Organization: Purdue University, Lafayette, Ind. 46207

Expected Completion Date: December 1975

Estimated Cost: $36,000 (HP&R)

FCP Project 3F: Pollution Reduction and Visual Enhancement

Title: Air Monitoring Program to Determine the Impact of Highways on Ambient Air Quality. (FCP No. 43F3082)

Objective: Measurement of the ambient concentrations of pollutants at three locations in Nashville, Tenn., in order to provide aerometric measurements for comparison to numerical predictive techniques.

Performing Organization: University of Tennessee, Knoxville, Tenn. 37916

Expected Completion Date: March 1975

Estimated Cost: $122,000 (HP&R)

FCP Category 4—Improved Materials Utilization and Durability

FCP Project 4A: Minimize Early Deterioration of Bituminous Concrete

Title: Investigation of Hydrated Lime, Asphalt and Aggregate Interactions. (FCP No. 44A1244)

Objective: To determine: best combinations of asphalts, aggregates, and lime; effects of premixed lime-aggregates on mixture properties; saponification reactions between lime and asphalts; adequacy of Utah immersion-compression test requirements; why lime affects siliceous more than calcareous aggregates.

Performing Organization: Department of Highways, Salt Lake City, Utah 84114

Expected Completion Date: June 1975

Estimated Cost: $50,000 (HP&R)

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

Title: Nighttime Retro-reflective Color of Reflectorized Highway Sign Materials. (FCP No. 34F4033)

Objective: To develop instrumental method for measuring night-appearing retro-reflective color of reflectorized highway signs by CIE Tristimulus data.

Peforming Organization: National Bureau of Standards, Washington, D. C. 20234

Expected Completion Date: February 1974

Estimated Cost: $65,000 (FHWA Administrative Contract)

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

FCP Project 5F: Bridge Safety Inspection

Title: Detecting Structural Deterioration in Bridges by the Randomdec Technique. (FCP No. 35F1422)

Objective: An experimental program to determine the feasibility of using the Randomdec analysis technique on the random vibration signal from a structure to detect fatigue cracking. Signals from laboratory fatigue specimens and actual bridges will be analyzed.

Performing Organization: Nielson Engineering and Research, Inc., Mountain View, Calif. 94040

Expected Completion Date: January 1974

Estimated Cost: $38,000 (FHWA Administrative Contract)

FCP Project 5I: Improved Structural Design and Construction Techniques for Culverts

Title: Performance of Pipe Culverts Buried in Soil. (FCP No. 45I2122)

Objective: To develop and verify an analytical procedure valid for performable culvert structures; establish program of prototype measurements whereby analysis can be developed into a rational design procedure.

Performing Organization: Purdue University, West Lafayette, Ind. 47907

Expected Completion Date: December 1978

Estimated Cost: $74,000 (HP&R)

FCP Project 5J: Rigid Pavement Systems Design

Title: Resealing Rigid Pavement Joints. (FCP No. 45J1244)

Objective: To determine sealers for joints in existing pavements which have reasonable costs, ease of handling and installation, and provide long life. Resealing is difficult because of spalls, improper reservoir shapes, and accumulated debris. Both contraction and expansion joints will be cleaned by numerous methods and resealed with one preformed and three or more liquid sealants.

Performing Organization: Department of Transportation, Albany, N. Y. 12226

Expected Completion Date: March 1975

Estimated Cost: $38,000 (HP&R)

Non-FCP Category 0—Other New Studies

Title: Improving the Durability of Plant Mix Asphaltic Surfaces. (Non-FCP No. 40M2353)

Objective: To investigate materials specifications and mix design procedures used in South Carolina for the purpose of improving the durability of asphalt surfaces without sacrificing other desired qualities such as skid resistance.

Performing Organization: University of South Carolina, Columbia, S.C. 29208

Expected Completion Date: December 1975

Estimated Cost: $126,000 (HP&R)

Title: Evaluation of Drainage Pipe by Field Experimentation, Supplemented by Laboratory Work. (Non-FCP No. 40M3174)

Objective: To investigate the corrosion properties of metal drainage structures in the field, supplemented by laboratory work.

Performing Organization: Department of Highways, Baton Rouge, La. 70804

Expected Completion Date: June 1982.

Estimated Cost: $150,000 (HP&R)

Title: Preformed Elastomeric Joint Sealing Systems—Field Evaluation Phase. (Non-FCP No. 50M3224)

Objective: Conduct field study program to evaluate the adequacy of the tentative guide specifications for sealing joints in portland cement concrete pavements developed in NCHRP Project 4–9; verify or modify guide specifications on the basis of information developed in the field study program and other information from documented research and experience.

Performing Organization: Department of Highways, Salt Lake City, Utah 84104

Expected Completion Date: December 1977.

Estimated Cost: $125,000 (NCHRP)

Title: Sign Reflectivity Test Equipment. (Non-FCP No. 40M3233)

Objective: Design and develop sign reflectivity test equipment for field and laboratory test use for the development of specifications and standards for highway signs and the materials of which they are made and for measurement of sign brightness for maintenance purposes.

Performing Organization: Wilkes College, Wilkes-Barre, Pa. 18763

Expected Completion Date: March 1974.

Estimated Cost: $41,000 (HP&R)

Title: Evaluation of Rapid Pile Load Test. (Non-FCP No. 40S3234)

Objective: To develop a procedure for rapid load testing of piles which will yield information comparable to that obtained from conventional test. Comparisons will include failure load, load vs. settlement, and load transfer vs. depth.

Performing Organization: University of Arkansas, Fayetteville, Ark. 72701

Expected Completion Date: August 1974.

Estimated Cost: $44,000 (HP&R)

Title: Base and Surfacing Evaluation Study. (Non-FCP No. 40S4524)

Objective: Field evaluation of base course designs having high potential for good performance in North Dakota.

Performing Organization: State Highway Department, Bismarck, N.Dak. 58501

Expected Completion Date: December 1977.

Estimated Cost: $220,000 (HP&R)

Title: Correlates of Test Driver Measurements and User Accidents. (Non-FCP No. 40T1752)

Objective: To develop and demonstrate the concept of a test-driver based accident index potential to be applied to specific main rural-suburban highway locations.

Performing Organization: Ohio State University, Columbus, Ohio 43215

Expected Completion Date: January 1975.

Estimated Cost: $68,000 (HP&R)

Title: Development of Performance Profiles of Design Drivers. (Non-FCP No. 40T1762)

Objective: To provide instruments to measure the relationship between various driver characteristics and driving performance.

Performing Organization: ITTE-UCLA, Los Angeles, Calif. 90024

Expected Completion Date: June 1975.

Estimated Cost: $100,000 (HP&R)

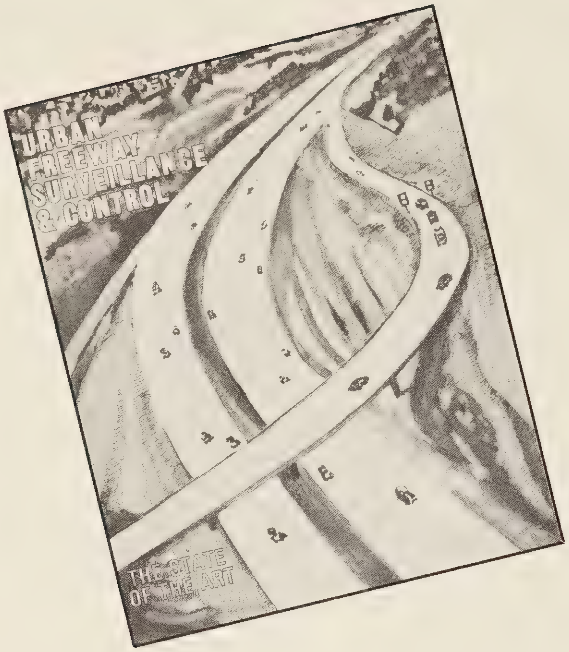
Title: Development of a Laboratory Data System. (Non-FCP No. 40X1013)

Objective: To develop a materials testing laboratory data system making use of modern data processing techniques. The system will be designed to provide up-to-date materials testing data to management, and will incorporate appropriate statistical routines for analysis of such data.

Performing Organization: Department of Transportation, Hartford, Conn. 06115

Expected Completion Date: June 1975.

Estimated Cost: $66,000 (HP&R)



Urban Freeway Surveillance and Control is a research report of interest to planners, engineers, and administrators concerned with the design and operation of highways in urban areas. The report presents the results of numerous research projects in a form that can be understood, digested, and applied by the practicing professionals.

The document is so organized as to introduce the reader to freeway problems that are subject to solution by surveillance and control techniques. Measures and methods to document operational problems are discussed to aid the analyst in determining what surveillance and control systems should be considered. Solutions to freeway problems are presented along with descriptions of the detailed hardware requirements. A summary of existing freeway ramp control projects is presented, and a benefit-cost study of their effectiveness is provided.

A limited number of free copies of the first printing of the report on "Urban Freeway Surveillance and Control" is currently available from the U.S. Department of Transportation, Federal Highway Administration, HRS-33, Washington, D.C. 20590. A second printing of this report is planned for the near future and will be sold by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Highway Statistics, 1971 ($2.85 a copy), a 245-page bulletin, is the 27th in the annual series presenting statistical and analytical tables of general interest on motor fuel, motor vehicles, highway-user taxation, State and local highway financing, road and street mileage, and Federal aid for highways.

The **Highway Statistics** series has been published annually beginning with the year 1945, but most of the earlier editions, except 1966, 1967, 1968, 1969, and 1970, are now out of print. However, much of the information presented in earlier editions is summarized in **Highway Statistics, Summary to 1965** ($1.25 a copy). These documents may be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

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

The following highway research and development reports are for sale by the National Technical Information Service, Sills Building, 5285 Port Royal Road, Springfield, Va. 22151.

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 214641	Urban Traffic Control and Bus Priority System—Operators Manual.
PB 214788	Urban Traffic Control and Bus Priority System—Design and Installation.
PB 215534	Operational Characteristics of Lane Drops.
PB 216990	Program Manual for Macroscopic Simulation of Diamond Interchange Traffic Operations.
PB 217317	Urban Traffic Control and Bus Priority System—Maintenance Manual.
PB 217518	Design Manual for Traffic Signal Control of Diamond Interchange Complexes.
PB 217519	Instrument Considerations for Computerized Traffic Control of a Diamond Interchange Complex.

ENVIRONMENT

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PB 213194	Development of Dwarf Ground Cover for Erosion Control in Colorado. Final Report. (Colorado Department of Highways Report No. CDOH-P&R-R&SS 72-4).
PB 213203	Paving Block Study.
PB 213207	Erosion Prevention During Highway Construction by the Use of Sprayed on Chemicals. Final Report. (Virginia Highway Research Council).
PB 213371	Vegetation Control on Roadsides and Similar Areas—1971 Annual Report. (University of Missouri No. 69-2).
PB 213859	Establishment of Woody Plants by Direct Seeding in California. (California Division of Highways/University of California, Report No. F-5-2).
PB 214286	Prediction of the Magnitudes and Frequencies of Floods in Michigan.
PB 214631	Bikeway Planning Criteria and Guidelines.
PB 214812	Interaction Between Fixed and Vehicular Illumination Systems.
PB 215003	Evaluation of Catch Basin Grates.
PB 215250	Colorado Tunnel Ventilation Study.
PB 215444	A Systematic Cataloging and Evaluation of Plant Materials for Highway Use in Georgia.
PB 216600	Road Design Management Research Project.

IMPLEMENTATION

Stock No.	
PB 211754	Interaction Between Fixed and Vehicular Illumination System—Phaset II Interim Report. (Franklin Institute Research Laboratories Report No. F-C2873/FHWA-RD-72-23).
PB 211795	Highway Maintenance Improvement Research Project. October 1968-December 1971. (Arkansas State Highway Department HRC-25).
PB 211796	Supplement 1—Maintenance Management Guide.
PB 211797	Supplement 2—Maintenance Supervisors Manual.
PB 212743	A Simulated Application of Statistical Quality Acceptance Specifications for Bituminous Pavements. Final Report No. 71-6P. (State of Maine Department of Transportation HPR-1(8)).
PB 213403	Pilot Field Test Evaluation Center. (U.S. Department of Transportation, Federal Highway Administration).
PB 213471	Proceedings, National Conference, AASHO Committee on Computer Technology. Proceedings for meeting May 24 and 25, 1972, Lansing Mich. (Sponsored by FHWA, AASHO, and Michigan Department of State Highways).

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Stock No.

PB 213734 Highway Maintenance Improvement Research Project. Final Report, January-July 1972. (Arkansas State Highway Department/U.S. Department of Transportation, FHWA).

PB 213748 Road Design Management Research Project. Final Report. (Roy E. Jorgensen Associates, Inc./Montana Highway Commission).

PB 213857 Statistical Specification Study—Instruments and Job Control. Final Report, MSHD-RD-72-054. (Mississippi State Highway Department/U.S. Department of Transportation, FHWA).

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PB 214752 Evaluation of Potential Effects of U.S. Freight Transportation Advances on Highway Requirements. Research Phases 1 and 2.