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Part 1

Essential Elements in the Transport of Hazardous Materials

ƆHARACTERISTICS OF HAZARDOUS CARGO SHIPMENTS ƆN VIRGINIA HIGHWAYS

N. K. Hook, Jr.*, Virginia Department of Highways and Transportation,
Arlington; and
John T. Hanna, Virginia Division of Highway Safety, Richmond

The movement of dangerous materials poses potential health and safety hazards to many citizens along routes of travel. The purpose of this paper is to identify the type and frequency of hazardous materials being transported over Virginia highways. Analyses of field interviews with 7,591 truckers to determine type of hazardous cargoes, their origins and destinations, and the compliance with federal and state placarding regulations are presented. Results of the study indicate that approximately 3.6 percent of all trucks on Virginia highways contain hazardous materials; most of them carry flammable liquids.

'SPECIAL problems are inherent in the transportation of certain materials that pose extreme safety and health hazards. When one recognizes that nearly 40 percent of ıll manufactured freight is being shipped on our nation's highways (1) and is cognizant of the potential dangers involved in the transportation of hazardous materials, the ieed for determining the frequency and type of hazardous cargo shipment becomes ıpparent. This report summarizes the frequency of dangerous article shipments and potential dangers involved in these shipments and evaluates the movement of hazardous naterial on highways throughout Virginia.

ƆEFINITION OF HAZARDOUS MATERIALS

\ hazardous or dangerous material is defined as any flammable liquid, flammable solid, oxidizing substance, corrosive liquid, compressed gas, poisonous substance, radioactive substance, explosive, or other substance defined by the Virginia State Corporation Commission, the U.S. Department of Transportation (2), or other authorized regulatory agency.

ƆATA COLLECTION

To determine the general magnitude of problems associated with the transportation of ıazardous materials, field surveys were conducted at eight permanent weigh stations ocated throughout Virginia and operated by the Virginia Department of Highways and Transportation. The location of these survey points is shown in Figure 1. The primary purposes of these surveys were to determine what types and quantities of ıazardous materials were being moved throughout Virginia and to what degree these shipments pose severe hazards to the health and welfare of other persons. Specifically, nformation was collected on each truck arriving at the weigh station to determine

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*Mr. Hook was with Wilbur Smith and Associates when this research was performed.

1. The origin and destination points for each hazardous material shipment as identified on trucker weigh bills,
2. The type of hazardous material being shipped and the quantity of each, and
3. The degree to which truck placarding requirements are met by trucking firms.

Each station was surveyed between 8:30 and 10:30 a.m. continuously for 8 hours in each direction. Data were maintained by direction of travel for a later analysis.

In addition to the trucker surveys, interviews were conducted with major manufacturers and users of hazardous materials and with several trucking firms. These field surveys provided the information required to identify problems associated with the transportation of dangerous materials.

ORIGIN-DESTINATION SURVEY

During the field interviews, 7,591 trucks were surveyed and were found to contain 334 shipments of hazardous materials. These 334 shipments were carried by 274 trucks. Twenty-seven percent of these shipments (91 shipments) had both origin and destination within Virginia, and 31 percent (102 shipments) had either an origin or destination within Virginia but not both. Forty-two percent (141 shipments) passed through Virginia with both an origin and destination outside of the state.

Since Virginia lies in the middle of the United States on the Atlantic seaboard and has a natural barrier to the east, the Atlantic Ocean, and to the west, the Appalachian Mountains, it was anticipated that north-south shipments of hazardous materials would be frequently noted passing through Virginia. However, when the origins and destinations of hazardous cargo shipments were plotted, no significant trends were apparent. Trip desire patterns through and within Virginia are dispersed throughout the state. No major routes were identified as carrying significant volumes of hazardous materials. This may be in part because manufacturers use rail or water transportation for large shipments of a hazardous nature between distant points. Table 1 gives a summary of hazardous cargo shipments by survey location and direction of travel. The weigh stations at Stephens City and Sandston, Virginia, had the highest percentage of dangerous article shipments (5.0 and 4.5 percent respectively). Dahlgren and Dumfries, Virginia, had the lowest percentage of hazardous material shipments (2.0 and 2.6 percent respectively). The overall average of hazardous cargo shipments was 3.6 percent.

TYPES OF HAZARDOUS CARGOES

Table 2 gives the types of hazardous cargoes traveling within Virginia (8-hour survey). Flammable liquids are the most frequent shipments (129 trucks). The second most frequent shipment is corrosive materials (70 trucks). Fourteen trucks surveyed were carrying explosives. No truckers were surveyed hauling radioactive materials, etiologic agents, or class C poisons.

Because of the wide variations in cargo quantities, it is not possible to indicate an average cargo shipment. However, there are two possible exceptions: Truckers hauling flammable liquids and compressed gases generally are restricted in quantities of materials hauled. Most truckers interviewed had either full or empty trucks; only a few trucks were only partially full. The average quantity of flammable liquid hauls was 5,470 gal (20 700 liters), and the average quantity of compressed gas was 6,401 lb (2900 kg) for flammable gases and 7,480 lb (3390 kg) for nonflammable gases. Average quantities were determined from trucks with hazardous materials on board and did not include empty trucks.

DIRECTION OF TRAVEL

An attempt was made to determine the percentage of hazardous cargo shipments by

Figure 1. Field survey locations.

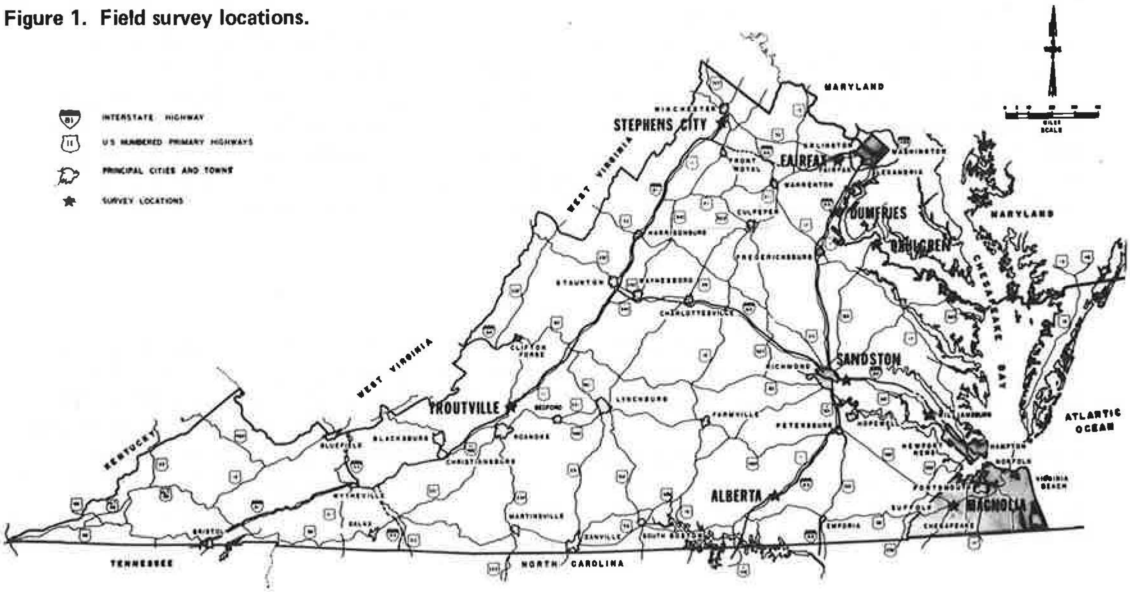


Table 1. Percentage of hazardous cargo shipments by station and direction of travel.

Virginia Location	Route	Day of Week	Total Trucks	Trucks With Hazardous Cargo	Total (percent)
Alberta	I-85				
Northbound		Tuesday	324	11	3.4
Southbound		Tuesday	435	15	3.4
Subtotal			759	26	3.4
Dahlgren	US-301				
Northbound		Monday	192	2	1.0
Southbound		Monday	164	5	3.0
Subtotal			356	7	2.0
Dumfries	I-95				
Northbound		Friday	903	20	2.2
Southbound		Friday	1,169	35	3.0
Subtotal			2,072	55	2.6
Fairfax	I-66				
Eastbound		Thursday	347	15	4.3
Westbound		Thursday	386	13	3.4
Subtotal			733	28	3.8
Magnolia	US-58				
Eastbound		Friday	362	6	1.6
Westbound		Friday	400	25	6.2
Subtotal			762	31	4.1
Sandston	I-64				
Eastbound		Monday	337	23	6.8
Westbound		Monday	390	10	2.6
Subtotal			727	33	4.5
Stephens City	I-81				
Northbound		Wednesday	397	20	5.0
Southbound		Wednesday	478	24	5.0
Subtotal			875	44	5.0
Troutville	I-81				
Northbound		Tuesday	649	19	2.9
Southbound		Tuesday	658	31	4.7
Subtotal			1,307	50	3.8
Total			7,591	274	3.6

direction of travel (Table 3, 64-hour survey). Hazardous article shipments ranged between 2.9 and 4.2 percent by direction of travel. However, the analysis does not indicate a significant hazardous material movement in a particular direction.

A statistical analysis was conducted to determine if the directional distribution of hazardous materials is a predictable occurrence. A chi-square test of independence was conducted to determine if hazardous cargo shipments depend on survey location and, thereby, are predictable on a statewide basis. Based on the results of the statistical analysis, no predictable frequency of hazardous material shipments existed.

PLACARDING

An inventory of dangerous shipments that are not placarded as specified by state and federal rules and regulations was made. As shown in Figure 2, approximately 33.9 percent of all trucks carrying hazardous cargoes did not have placards as required by regulations. However, when compared with the total number of trucks traveling on the highways, only 1.2 percent of hazardous cargo shipments were in violation of federal and state rules and regulations. Truckers gave varying reasons for not having placards properly affixed to the vehicles: Placards were not issued by the dispatcher, and weather conditions prohibited the placards from being affixed.

IMPLICATIONS

Special consideration must be given to any highway incident involving dangerous articles. Because of the nature of the materials, severe hazards that can affect public health and safety are inherent in any dangerous article shipment. It is not possible to generalize about the type of hazard involved by classifying of material (i.e., explosive, flammable, or corrosive) since each class of material will exhibit a wide range of potential dangers. Unless the actual cargo is known, it is advisable to anticipate that the cargo is flammable and explosive and extremely dangerous to health.

Current federal and state regulations that pertain to the transportation of dangerous articles do not require placards that will not burn. Considering the relative dangers of materials being transported, it would be beneficial if placards were required to be nonflammable and legible for a period of time when exposed to fire. This would result in potentially significant benefits to emergency crews responding to an incident involving dangerous materials.

Some cargoes moving over Virginia's highways pose severe dangers to health and welfare of many citizens (i.e., truck load shipments of explosives, certain poisons, and other materials). Further research is needed to determine the needs for specific routing for these materials. It might also be advantageous to have certain materials that are shipped in bulk quantities escorted on the highway and through urban areas.

It was found that hazardous cargo shipments averaged 3.6 percent of all trucks on Virginia highways. This is considerably lower than was initially anticipated before this study was conducted. Some states might, however, have a higher percentage of hazardous material shipments because of manufacturing and industrial facilities and military and aerospace complexes. Therefore, the percentage of hazardous material shipments within Virginia may not be typical of other states because situations will vary between survey points.

Further research might be beneficial to determine

1. The primary mode of hazardous cargo shipments (i.e., water, rail, or highways),
2. The quantities in which hazardous materials are generally transported in other states,
3. The relative dangers of hazardous materials by classification, and
4. Additional precautionary measures and regulations that should be instituted to ensure the safety and welfare of all citizens along routes of hazardous material shipments.

Table 2. Types of hazardous cargoes.

Classification	Number of Shipments	Quantity (lb)	Average Shipment (lb)
Explosive, unclassified[a]	1	240	240
Explosive, class A	7	113,289	16,184
Explosive, class B	1	6,948	6,948
Explosive, class C	5	3,770	754
Flammable liquid	129	705,702[b]	5,470[b]
Flammable solid	19	496,471	26,130
Oxidizing material	7	106,459	15,208
Corrosive material	70	1,044,112	14,916
Flammable compressed gas	48	307,233	6,401
Nonflammable compressed gas	28	209,446	7,480
Poisons, unclassified[a]	6	116,895	19,483
Poisons, class A	3	82,795	27,598
Poisons, class B	9	131,384	14,598
Poisons, class C	0	0	0
Etiologic agents	0	0	0
Radioactive materials	0	0	0
Cryogenic materials	1	35,000	35,000
Total, lb[c]	205	2,654,042	12,947

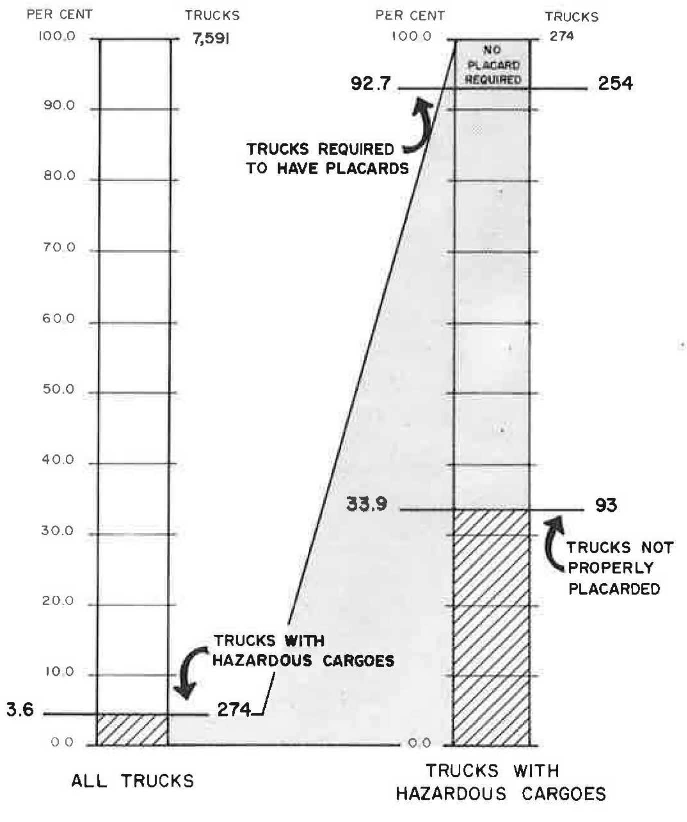
Note: 1 lb = 0.45 kg. 1 gal = 3.8 liters.

[a]Indicates that the shipping document did not indicate product by name or class such as A, B, or C explosive or poison.
[b]Gallons.
[c]Represents split classification shipments and, therefore, will not compare with other tables.

Table 3. Percentage of hazardous cargo shipments by direction of travel.

Direction	Total Trucks	Trucks With Hazardous Cargo	Percent
Northbound	2,465	72	2.9
Southbound	2,904	110	3.8
Eastbound	1,046	44	4.2
Westbound	1,176	48	4.0
Total	7,591	274	3.6

Figure 2. Placarding regulation compliance.



ACKNOWLEDGMENT

We wish to express our appreciation to the National Highway Traffic Safety Administration and to the Virginia Division of Highway Safety for providing funds for the study. The Virginia Department of Highways and Transportation provided invaluable assistance in permitting the use of weigh stations during the data collection phases of the study. In addition, the assistance of the Federal Highway Administration and the Office of the Secretary of Transportation provided valuable input in the initial research of this report.

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CHEMICAL TRANSPORTATION EMERGENCY CENTER

John C. Zercher, Chemical Transportation Emergency Center

The Chemical Transportation Emergency Center was established by the Manufacturing Chemists Association as a voluntary project of the chemical manufacturing industry. It is designed to provide advice or assistance to those involved in transportation accidents involving chemicals. Its services are available 24 hours a day via a toll-free inbound wide area telephone service number from any point in the continental United States. The center is a two-step operation. First, on identification of the product involved, immediate action information is read from files prepared in advance. Second, the shipper or other sources of expertise are contacted for additional counsel or on-site assistance. This paper describes the nature of the operation and its capabilities and limitations and summarizes a a number of the incidents in which the Chemical Transportation Emergency Center has been involved since it began operating on September 5, 1971. Its relationship to the transportation research community is also discussed.

•ON an icy December morning, a tank truck loaded with sulfuric acid was enroute to Dallas, Texas, on I-30 when, near Greenville, Texas, the driver was forced to take evasive action to avoid a motorcyclist who was skidding on the icy road. The end results were an overturned truck and an injured driver. The load of acid was in unknown condition at the time.

A young mechanic, enroute to work, stopped to assist. The driver appeared to be in shock, but he insisted that someone telephone 800-424-9300 to report the accident. Not really knowing why, the young man called as instructed, reporting the accident and providing the local sheriff's phone number.

His call was received by the duty communicator at the Chemical Transportation Emergency Center (CHEMTREC), who immediately contacted the sheriff for more details, getting the names of the product involved, the carrier, and the shipper.

After giving the sheriff information on the sulfuric acid, the communicator called the safety director in the carrier's home office in Pennsylvania to advise him of the accident and of his injured driver. By coincidence, the carrier had a terminal in Greenville. The safety director then directed the terminal people to provide assistance to the scene. Although less than 6 miles (9.7 km) away, they were not aware of the accident involving one of their trucks. They immediately sent assistance. As a follow-up, CHEMTREC notified the shipper so that he could provide product expertise to the handling of the incident.

Thus, through a single emergency facility, assistance was quickly provided to both the carrier and the emergency services involved in this incident.

CHEMTREC was established by the Manufacturing Chemists Association (MCA). It began operation on September 5, 1971, and provides immediate action response information to the scene of a chemical transportation accident when a phone call is received identifying the product involved. The call goes from the emergency scene to the CHEMTREC office, where a two-step operation goes into effect. First, immediate action information regarding the product is read from files prepared in advance, and, then, the communicator contacts the shipper or other sources of expertise for additional counsel or on-site assistance.

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The files contain telephone numbers to permit establishing the proper contact, within the shipper's facilities, to reach someone at any time of the day or night who is knowledgeable about the proper way to handle an emergency situation in which the shipper's product is involved. This is a voluntary program of the MCA member companies aimed at providing timely and accurate information to the emergency services, carrier personnel, the general public, and others who might be involved in transportation accident situations.

The assistance of this center is available to any involved person by calling one phone number from any state within the continental United States. This telephone is manned 24 hours a day, and the number has been and continues to be publicized throughout the country and to emergency and carrier personnel. However, CHEMTREC is not a depository of general information, such as how a shipment should be marked, or a policing agency. Instead, it is a source of help in emergencies, providing immediate guidance on what to do in case of spills or leaks, fire, or exposure. A short description of the operation is presented in the CHEMTREC brochure, which can be made available to those who need it.

When police, fire, or other emergency service personnel come onto the scene of an accident involving chemicals in transportation they are understandably concerned about what is in the containers. In general, the fire services training is geared to flammables, such as gasoline and fuel oils, and usually they are quite well prepared to cope with these. When they face a chemical of an unknown nature, however, there is a possibility of considerable apprehension simply because they do not know what to expect. As a result, the fire services have been particularly active in searching for quickly accessible and easily understood information that would help them evaluate a situation and take proper precautions for the protection of the general public and for their own safety. The chemical industry is well aware of this.

There have been accidents in the past few years that certainly justify this position. Some accidents involving one or more hazardous commodities have resulted in fire and explosion, and have caused widespread destruction and havoc in populated areas.

The National Transportation Safety Board (NTSB) has frequently pointed out the large volume of hazardous commodities that is moved on this country's transportation systems. Similarly, NTSB has noted the information problem in handling transportation emergencies. In its report of the January 1, 1968, Dunreith, Indiana, train wreck, NTSB devoted considerable attention to the difficulty fire officials had in obtaining information on the nature of the materials that were burning and on appropriate fire fighting and control techniques.

CHEMTREC is a major part of MCA's continuing effort to support these emergency services and, as experience is indicating, the carriers. In September 1969, with the encouragement of the U.S. Departments of Transportation and Health, Education, and Welfare, the president of MCA established a study group to consider setting up a system that would be applicable to all producers and shippers of hazardous chemical materials.

It was concluded that a national center and a single telephone number had substantial advantages over other possibilities. It was felt that a single center would be more accessible to carriers and emergency service personnel and would provide shortened response time for action and feedback. The proposal contemplated that the center would be located at MCA headquarters in Washington and that it would have telephone coverage 24 hours a day. After review and recommendation by concerned technical committees, the proposal was adopted in June 1970 by the board of directors of MCA, and funds were authorized for its implementation.

So that the number is made readily available to carriers and emergency services, shipping documents should be marked with the notation: For help in chemical emergencies involving spill, leak, fire, or exposure, call toll-free 800-424-9300 day or night (call 483-7616 in Washington, D.C.). This wide area telephone service (WATS) is identified by area code 800 and provides direct dial service from all the contiguous states.

When an emergency call is received from a policeman, fireman, or others, the CHEMTREC communicator on duty determines what happened and where and when it occurred, the product name, shipment source, name of the company that made shipment, name of the carrier, car or truck number, the consignee, whether there are injuries, and other information that might be helpful. If there are any unusual conditions, such as weather, or if the accident is in a populated area, this is also determined. Most importantly, the communicator establishes who called, where the person is located, and how the person can be called back.

The communicator will then obtain the appropriate card from the file and provide the caller with response and action information for the product or products involved, by giving basic information such as hazards and what to do in case of spills, leaks, fire, and exposure. This informs the caller of the hazards, if any, and provides sufficient information so that immediate first steps can be taken in controlling the emergency.

Information on products, trade names, and personnel contacts is made available from shippers, trade associations, and other interested groups, such as the Energy Research and Development Administration (ERDA) and the Department of Defense (DOD). This is stored on cards in visible index, tub type of files. After the product is identified, access time to the alphabetized cards is only a few seconds.

The file cards on chemicals have the same general format as Chem-Cards but contain more information. Specific information, such as synonyms, odor, effect with water, nature of product, and hazards, is presented along with details on what to do in case of a spill or leak, fire, or exposure. Experience has indicated little need for physical data other than flash point, ignition temperatures, and vapor density. These are provided where applicable.

Next, the communicator relays the details of the accident to the shipper, who has the expertise needed to deal with the situation. Shipper contact information is also stored on file cards. When notified, the shipper becomes responsible for any future action in regard to the emergency. Based on experience to date, in well over 4,000 incidents, the validity of this two-step approach has been well confirmed.

For certain products, mutual aid programs exist, in which case the communicator's first call may be to someone other than the shipper. Depending on the commodity and manufacturer's preferences, it could, for example, be to the Chlorine Institute, National Agricultural Chemicals Association, or the Bureau of Explosives. When notified, these organizations then establish liaison between the accident scene and the shipper.

In early 1973, the Chlorine Institute initiated its Chlorine Emergency Plan to formalize the service it had been rendering for many years. The nearest producer will respond to the scene of an incident regardless of whose material it is.

The National Agricultural Chemicals Association has some 40 emergency teams throughout the country. On receipt of a call concerning a pesticide, the teams are prepared by their regional directors to evaluate the problem and, if necessary, to send qualified personnel to the accident scene at once.

These groups have proved to be very capable in handling problems of their respective industries. CHEMTREC cooperates with such arrangements and with the organized systems of member companies. Arrangements have been made with ERDA response facilities in case of an incident involving radioactive materials. DOD maintains a response system for items under its control and can readily activate its explosive ordnance disposal teams to look after them. Both ERDA and DOD have been quite responsive to our calls, and CHEMTREC and the Canadian Chemical Producers' Association emergency program work together when needed.

Under appropriate circumstances, various offices of government or civilian agencies are notified. The U.S. Department of Transportation or the National Transportation Safety Board is normally alerted in major accident situations.

To maximize its effectiveness, CHEMTREC should have as broad coverage of chemical products as possible; thus it has long been expanded beyond MCA member companies. As the development of the program continues, information and emergency contacts have been, and continue to be, welcomed from nonmember companies as well. MCA member companies represent over 90 percent of the production capacity of basic industrial chemicals in the United States and Canada. However, it is recognized that the member company shipments represent only part of the hazardous materials shipments made in this country, and it is obviously desirable to be able to provide shipper backup information whenever possible.

Occasionally CHEMTREC gets calls regarding products of nonmembers, who are not registered in the files. When direct calls are made to these organizations, excellent cooperation is received in getting proper information back to the scene of the incident.

A significant percentage of the file cards are for proprietary items and trade names. And, by far, the greater portion of these are mixtures of two or more compounds. Frequently, different hazards will be brought to the mixture by the various components, and this will result in a multihazard product being shipped. Some shippers of proprietary items prefer not to identify all components of a product but to provide the necessary hazard information. Cross-referencing is necessary in most cases. Single component trade names are also listed by chemical name. Many products have common synonyms: for example, methanol, methyl alcohol, and wood alcohol. These are all in the files. Shipping paper descriptions, as required by DOT are filed. If that is the only information available in an accident situation, at least some response information can be provided.

It is extremely important to note that spelling of chemical names can be critical in getting the proper information. The difference in ethanal and ethanol is appreciable. Names like trimethylene, which is a flammable gas, and trimethylamine, which is a flammable poisonous gas, are easily confused, and care must be taken to ensure proper identification.

One point should be made clear: It is not practical to have a genius, capable of answering all questions, on the telephone when someone calls in. There is a capable individual on duty who can elicit the necessary information from the caller, respond with preestablished advice applicable to the products reported to be involved, and inform shipper personnel so that they bring their expertise to bear on the problem. Retired military personnel were the initial choice for this position. They are mature, dependable, acquainted with emergency situations, and experienced in communications.

The CHEMTREC communicator must limit the advice to the accident scene to the information preestablished in the files. The communicator is not permitted to ad-lib and is well trained in communication and in searching out those who can be of further assistance.

CHEMTREC normally refers people to Poison Control Centers in cases where materials have been ingested and maintains a list of all of these in the country that can be passed on when needed. This has been done in instances such as a person drinking a windshield washer compound and children eating or drinking household cleaners. However, CHEMTREC is being called on to assist the Poison Control Centers in instances where they cannot determine the composition of a product.

As techniques for locating people improve, it is unusual for CHEMTREC to be unable to reach a known shipper. However, if the shipper is not known, it can be difficult to arrange for the second phase follow-up. In these cases, standard references are maintained to provide additional help, and the communicator is authorized to quote from these. Included are the National Fire Protection Association's Fire Protection Guide on Hazardous Materials, The Condensed Chemical Dictionary, the Merck Index, and the MCA's safety publications.

Identification of the product involved is essential. Without it, little help can be provided. The name should be on the shipping papers in the cab of a truck or in the engine or caboose of a train. DOT regulations require the identification of hazardous materials on these papers. If they cannot be found, those involved should try to develop some identification of the shipper or vehicle identification. The tractor or trailer number or license and the carrier's name will give CHEMTREC a chance to locate the product identity and the shipper. Tank car reporting marks are useful, and some cars carry the shipper's name. Carrier associations work with CHEMTREC to assist in this type of search. It may not always be successful, but the percentage of successful completions in these cases is surprisingly high.

Although hazardous materials are involved in about 75 percent of the transportation incidents reported to CHEMTREC, it is necessary to advise those involved when the product presents few, if any, problems. In this way, unnecessary delays in returning to normal operations are avoided. A surprising number of calls have involved titanium dioxide, which is similar to sand. It is moved in large quantities, as it is the primary pigment now used in white paint. But a truck driver does not recognize this fact.

An interesting case in which fire services were summoned for use on an unknown product occurred in Santa Rosa, California. A boxcar of 54,000 lb (24 500 kg) of bagged material called fural residue was smoldering, and no one would touch it until the hazards were determined. CHEMTREC had difficulty obtaining the shipper's proper name or location. The state was identified as Tennessee, but no town was indicated. Finally, with the help of several telephone operators, the shipper was located in Memphis where a vice-president was contacted, who identified the product as ground corn cobs.

Nonemergency communications with the users can be quite important to CHEMTREC. Much planning went into the operation before it started, but the need is recognized for making continuing improvements to best serve those who call on this service. To this end, CHEMTREC is and will continue to be working with interested individuals and associations to determine those changes within its capabilities that will make it more effective.

In its first 35 months of operations, CHEMTREC received about 18,814 incoming calls of which 7,081 or 38 percent were emergency calls. Of these, CHEMTREC assisted in 3,372 instances: 2,686 or 80 percent for transportation-related emergencies and 686 or 20 percent for non-transportation-related emergencies. Many of the calls were made simply to confirm CHEMTREC's existence.

Assistance has been provided in situations ranging from barge accidents and major train derailments to leaks in small packages. Tank cars and drums have been the containers involved in about two-thirds of the incidents reported. A number of calls have come from ships at sea. Generally, these involved packaged goods that have been distressed when the vessels were involved in storms.

Recently a call came from the London Fire Brigade. A drum of a product originating in New Jersey enroute to Spain was leaking at Heathrow Airport outside London. CHEMTREC advised the brigade that the product described was a harmless dye.

During CHEMTREC planning, it was anticipated that calls from emergency services (fire and police) would predominate. So far, however, carriers (65 percent of calls) are far ahead in making use of the service. Hopefully, this will dispose of many problems before emergency attention is needed.

The distribution, by location of the incident, of calls to CHEMTREC was 43 percent for railroads, 41 percent for highways, 11 percent for terminals or piers, and 5 percent for airlines and ships. For highway incidents, many problems arise or are discovered when the truck reaches the terminal. The distribution, by container type, of calls to CHEMTREC was 37 percent for tank cars, 31 percent for drums, 9 percent for tank trucks, and 23 percent for other containers.

Occasional calls come from highway maintenance personnel, who encounter chemicals that are lost from trucks or that are otherwise spilled. In these cases, it is helpful to have a supervisor evaluate the problem and obtain as much information as possible before calling CHEMTREC. The highway maintenance personnel of the San Francisco Bay area have such a system, and it works well. It keeps drivers from calling with irrelevant problems.

In a recent survey of all types of transportation incidents involving hazardous materials, about a third involved corrosives, and fewer than 20 percent were flammable liquids.

For many years there were a number of companies with efficient emergency response organizations, each with its own telephone. Since the organization of CHEMTREC, there has been a dramatic increase in these. Although each is excellent in itself, there is no need to proliferate a multiplicity of telephone numbers to be used in case of emergencies.

CHEMTREC, by providing a single number throughout the United States, can simplify the problem. It will make use of the numbers of other emergency response organizations, when needed, but the caller only needs one number, that of CHEMTREC.

I understand that the transportation research community, particularly as represented by the Transportation Research Board, concentrates on activities aimed at improving the design or operation of the transportation system. Although MCA is active in this arena with respect to transportation of hazardous materials, CHEMTREC is primarily aimed at providing a meaningful response to those situations where incidents occur.

Carriers, emergency services, environmental control personnel, highway maintenance people, and others require information and sometimes assistance when chemicals are distressed in transportation; CHEMTREC functions exclusively to this end. It has no reportive or investigative functions. Its planning is not aimed specifically at modifying a part of the transportation system but at how to be responsive to its needs in chemical transportation emergencies. However, its information and experiences are shared with those involved in system planning.

The chemical industry has moved vast quantities of hazardous materials. Relatively, there have been few major incidents; however, have occurred despite concerted attention to accident prevention, which continues with ever-increasing emphasis. There is no question, however, of the need to support emergency services in coping with problems involving chemicals so that the public safety is protected when accidents do occur.

CHEMTREC provides such support by providing immediate and accurate information to help in chemical transportation accidents.

DETERMINING HIGHWAY SHOCK INDEX

John H. Grier,
Military Traffic Management Command Transportation Engineering Agency

The U.S. Army, Navy, Air Force, and Marine Corps have jointly sponsored and participated in the development of a shock index for highway transportation. A numerical shock index, associated with a particular vehicle-load combination, can now be determined at a low cost by applying simple static field measurements. The shock index provides classification for a vehicle-load combination in regard to probability of shocks transmitted to the cargo during highway shipments.

•IN 1967, representatives of the U.S. Army, Navy, Air Force, and Marine Corps agreed that it should be possible to establish shock indexes that would be representative of the cargo environment for various transport modes. Together, the services formed a steering committee to initiate and guide the development of a highway shock index (SI). The highway mode was selected because of the relative ease in controlling the environment and related variables.

As an initial step, the steering and advisory committee let a $53,000 contract to General Testing, Inc., Springfield, Virginia, to determine and develop an SI equation that could be used to classify highway cargo vehicles in terms of vehicle shock to the cargo. In addition and in conjunction with the General Testing contract, a $13,000 contract was let to J. A. Johnson, Inc., Short Hills, New Jersey, to check and verify the General Testing, Inc., project objective. General Testing ran comprehensive static and dynamic shock evaluation tests by using five classes of cargo trucks.

General Testing mostly performed controlled laboratory tests. J. A. Johnson was to validate the feasibility of the General Testing classification procedure and to test it on public roads to establish the accuracy of method on the road. From this check, it was concluded that an SI classification is both feasible and needed by the military community but that more engineering expertise is required to improve accuracy before the classification procedure can be adopted.

Accordingly, the Military Traffic Management Command Transportation Engineering Agency (MTMCTEA) initiated a comprehensive SI field test program using Fort Eustis facilities, military equipment, and personnel to develop a practical test for obtaining usable impact data. A military 5-ton (4.5-Mg) M52 tandem tractor with a 12-ton (10.8-Mg) M127 tandem trailer was used for this phase of the test program. Using military personnel and equipment considerably reduced research costs and ensured technical control of the field work. As a result of these tests, a procedure for testing commercial cargo trucks was developed.

During July 1973, limited field tests were initiated on the first of three leased commercial cargo trucks; all field work was completed by April 1974. Support for these tests was provided by the U.S. Army Transportation Center and Fort Eustis. MTMCTEA engineers performed the planning, supervision of tests, analyses, and development of concepts and their application.

Publication of this paper sponsored by Committee on Transportation of Hazardous Materials.

PURPOSE OF SHOCK INDEX

The purpose of the highway SI is to provide a means for selecting highway cargo vehicles on the basis of their rough riding characteristics. The selection is not based on the vehicle configuration but on the combined payload spring rate K of the springs and tires on an axle. SI makes it possible to select a relatively soft riding vehicle for fragile cargo and thus to minimize the possibility of damage to the cargo. The SI rating system applies to restrained cargo only.

The SI for a cargo vehicle should be representative of the roughest ride area on the truck cargo bed. Previous tests have shown and recent tests have confirmed that, under normal operating conditions, for a two-axle cargo truck, the roughest ride on a truck cargo bed is found over the rear axle or, for a truck-tractor semitrailer combination, it is found either near the rear axle of the trailer or over the fifth wheel of the truck-tractor, depending on which axle has the higher payload spring rate.

Under normal operating conditions, maximum shocks on the cargo bed will occur in the vertical direction. Based on extensive tests by MTMCTEA and other organizations, a maximum shock of 10*g* is considered reasonable for a very rough road surface. Consequently, the highway SI is based on a scale of 0 to 10g. The numerical values of SI vary from 5 to 0; 5 corresponds to 0g, and represents the softest ride.

The deadweight of the vehicle is not involved in the determination of SI; the unloaded weight of the vehicle is already in place and, therefore, is not involved in the determination of the payload spring rate. The tests have shown that of the three major variables, percentage of maximum payload, tire pressure, and speed, percentage of maximum payload has a major effect on SI, whereas tire pressure in the practical range and speed causes relatively minor changes.

Since percentage of maximum payload has the most effect on the ride on the truck cargo bed, a graph relating the payload axle spring rate, axle payload, and SI was developed (Figure 1). To develop Figure 1, tests were conducted on a range of cargo vehicles. The payload capability of these vehicles varied from 13,000 lb (5900 kg) on a two-axle truck to 24,000 lb (10 900 kg) on a two-axle truck-tractor, single-axle trailer combination to 40,000 lb (18 140 kg) on a three-axle truck-tractor, two-axle semitrailer combination.

The vehicles were instrumented to measure shock on the cargo bed and were driven over fixed, unyielding bumps at various speeds at different tire pressures and with different payloads.

The repeatability of data measurements recorded on the test course was satisfactory in spite of the many variables that affect a dynamic test of this type. Approximately 80 percent of all data recorded over the axles of the trucks was used for Figure 1 and Table 1.

SHOCK INDEX GRAPH

Based on the SI graph (Figure 1), several conclusions can be made. As axle payload increased from zero, the shock index increased to some optimum load for the vehicle and, thus, provided a softer ride. The dashed lines on Figure 1 indicate a trend reversal in which increasing the axle payload causes a decrease in shock index and, thus, provides a progressively rougher ride. There is an optimum payload for all vehicles that will provide the softest ride for the cargo. This optimum load can be readily selected from Figure 1 when the combined axle payload spring rates for the vehicle are known.

High, erratic shock values are most likely to occur with very light or maximum payloads because when the loads are light, the vehicle springs are relatively stiff and when the loads are very heavy, bottoming out of the springs may occur. The most erratic results will occur over the fifth wheel area because of the concentration of load at the kingpin.

Figure 1 shows that for a relatively soft ride the vehicle payload axle spring rate should be about 7,000 lb/in. (1250 kg/cm). For an axle payload of 3,000 lb (1360 kg),

Figure 1. Payload axle spring rate versus shock index.

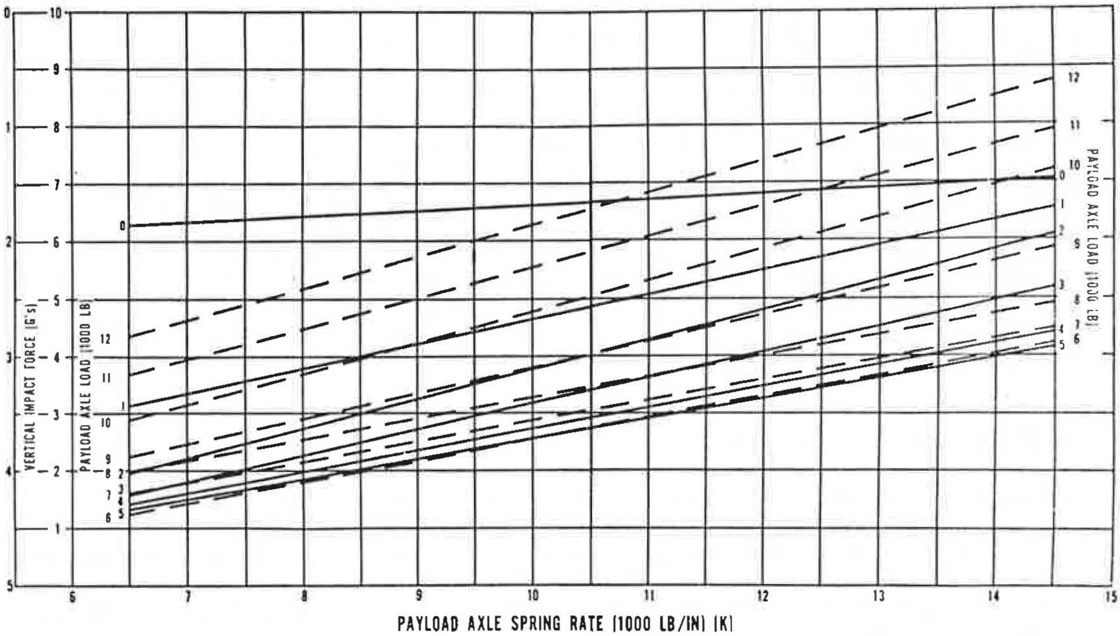

Figure 2. Rear view of truck.

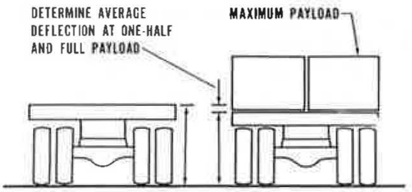

Figure 3. Axle payloads.

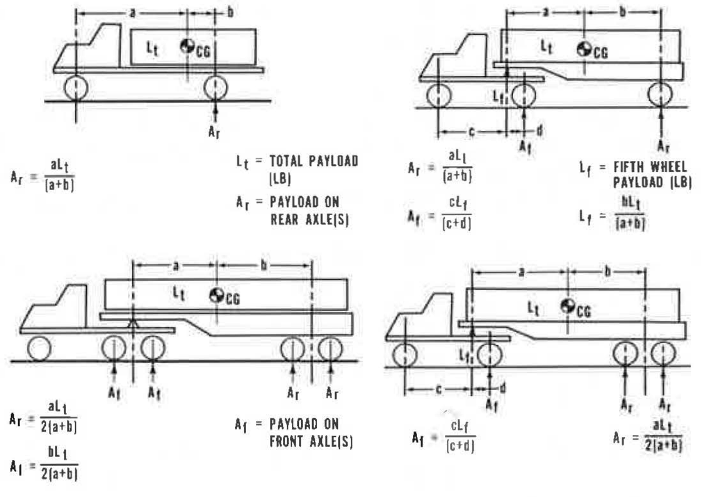

Table 1. Shock index values.

Payload Axle Load (lb)	Payload Axle Spring Rate (lb/in.)																
	6,500	7,000	7,500	8,000	8,500	9,000	9,500	10,000	10,500	11,000	11,500	12,000	12,500	13,000	13,500	14,000	14,500
0	1.85	1.85	1.80	1.80	1.75	1.75	1.70	1.70	1.65	1.65	1.60	1.60	1.55	1.55	1.50	1.50	1.45
1,000	3.40	3.30	3.20	3.10	3.00	2.90	2.75	2.65	2.55	2.45	2.35	2.25	2.15	2.05	1.95	1.80	1.70
2,000	4.00	3.85	3.75	3.60	3.50	3.35	3.20	3.10	2.95	2.85	2.70	2.60	2.45	2.35	2.25	2.10	1.95
3,000	4.20	4.05	3.95	3.85	3.75	3.60	3.50	3.40	3.30	3.15	3.05	2.95	2.85	2.70	2.60	2.50	2.40
4,000	4.25	4.15	4.05	3.95	3.90	3.80	3.70	3.50	3.50	3.40	3.35	3.25	3.15	3.05	2.95	2.85	2.75
5,000	4.30	4.20	4.10	4.05	3.95	3.85	3.75	3.70	3.60	3.55	3.45	3.35	3.25	3.15	3.10	3.00	2.90
6,000	4.35	4.25	4.15	4.05	3.95	3.85	3.75	3.70	3.60	3.50	3.40	3.30	3.25	3.15	3.05	2.95	2.85
7,000	4.15	4.05	3.95	3.90	3.80	3.70	3.65	3.55	3.45	3.35	3.30	3.20	3.10	3.00	2.90	2.85	2.75
8,000	4.00	3.90	3.80	3.70	3.60	3.55	3.45	3.35	3.25	3.15	3.05	2.95	2.90	2.80	2.70	2.10	2.00
9,000	3.90	3.75	3.65	3.55	3.40	3.30	3.20	3.10	2.95	2.85	2.75	2.60	2.50	2.40	2.30	2.15	1.95
10,000	3.55	3.40	3.25	3.10	3.00	2.85	2.75	2.60	2.45	2.30	2.20	2.05	1.90	1.80	1.65	1.50	1.40
11,000	3.15	3.00	2.90	2.75	2.60	2.50	2.35	2.25	2.10	2.05	1.85	1.70	1.55	1.45	1.30	1.15	1.05
12,000	2.80	2.65	2.55	2.40	2.25	2.10	2.00	1.85	1.70	1.60	1.45	1.30	1.20	1.05	0.90	0.75	0.65

Note: 1 lb/in. = 0.178 kg/cm. 1 lb = 0.45 kg.

the cargo would most likely not be subjected to a shock of over 2g, and the SI rating for the vehicle would be about 4.1.

For a vehicle payload axle spring rate of 10,000 lb/in. (1790 kg/cm), the maximum expected shock to the cargo should not exceed about 4g for axle payloads of 3,000 to 9,000 lb (1360 to 4080 kg). This vehicle would have an SI of about 3.

For a vehicle payload axle spring rate of 13,000 lb/in. (2320 kg/cm), the maximum expected shock to the cargo should not exceed about 6g for axle payloads of 3,000 to 9,000 lb (1360 to 4080 kg). This vehicle would have an SI of about 2.4.

For all ranges of payload, because of the many variables, dynamic behavior, and variable environment associated with the vehicle-road relationship, some radical inexplicable shock values will occur. In the test leading to the development of Figure 1, about 20 percent of the recorded values were inexplicable and were accordingly discarded.

DETERMINING SHOCK INDEX

The procedure for estimating SI for a specific cargo truck involves two steps.

1. The truck must be loaded and unloaded, and measurements of how much the cargo bed deflects under one-half and full payload must be taken.
2. The payload axle load must be known; this can be determined on a set of portable scales or by calculation.

This information must be obtained by physical measurements because of the high variable internal friction in leaf springs, variable stiffness in tire sidewalls, and general construction of the overall suspension system of the vehicle. Correlation between the manufacturer's spring rate for a leaf spring of a vehicle cannot be made with the installed spring because, in the manufacturer's test procedure, the test is performed without center clamps and shackles and the spring ends are mounted on rollers so that they are free to move (1). When the SI for a specific make and model of truck has been determined, it should apply to others of the same make and model with the same type of springs and tires.

The following information is required so that SI can be determined:

1. Vertical deflection at one-half and full payload of the truck bed at rear axles or at rear axles of truck-tractor for truck-tractor, semitrailer combination and
2. Payload axle load causing the vertical deflections.

The following procedures are used to determine combined (springs and tires) vertical deflection at axles:

1. Check tire air pressure, and adjust to operating pressure.
2. Position axles on scales, or, if scales not available, on a uniformly smooth, level, unyielding surface and then unload vehicle.
3. Accurately measure the height of the cargo bed on each side of the truck at the axles. If the vehicle is on scales, note unloaded load of axles.
4. Use dummy concentrated weights, if available, to simulate axle payload. Load with center of gravity directly over axle for single-axle vehicles or midway between tandem axles. If concentrated weights are not available, use available homogeneous weights and uniformly load truck bed. Accurately measure the height of the cargo bed on each side of the truck at the axles (Figure 2).

The truck should be loaded and unloaded several times, and an average deflection should be accurately determined at one-half and full payload by the method below:

1. Place full load on the truck and measure the truck bed height,
2. Unload to one-half full load and measure the truck bed height,

3. Unload truck and measure the truck bed height,
4. Place one-half full load on the truck and measure the truck bed height,
5. Place full load on truck and measure the truck bed height, and
6. Repeat above cycle 5 times for 10 measurements.

Accuracy of measurements should be within $\frac{1}{32}$ in. (0.8 mm).

Payload per axle at one-half and full payload is then determined: (a) If vehicle is on scales, read recorded weight, subtract axles unloaded weight, and, if there are tandem axles, divide by 2 and (b) if scales are not available, use one of the equations in Figure 3 to determine the single-axle payload at one-half and full payload.

The combined payload spring rate K for axles is then determined:

$$K = \frac{\text{full payload axle load in lb - one-half payload axle load in lb}}{\text{average deflection at full payload in in. - average deflection at one-half payload in in.}}$$

Now that K has been determined for the axles, the SI can be read directly from Figure 1 or Table 1. The most accurate reading can be obtained by using Figure 1 since a table must be based on some arbitrary interval of K. An interval of 500 lb/in. (89 kg/cm) is used for Table 1.

To use Figure 1, enter K on horizontal scale, read vertically to axle payload for trip, and read horizontally for SI. SI for each axle should be checked, and the lower numerical values should be used for the SI. This will represent the roughest expected ride on the cargo bed. The SI can be obtained, at the same time, for all axle payloads from 0 to 12,000 lb (5443 kg). It need be determined only once for vehicles of the same make and model with the same type springs and tires.

To use Table 1, use the K in the table that most nearly corresponds numerically to the K determined by physical measurement. The maximum error in SI due to using the table will be 0.625; in most cases, the error will be considerably less. The SI for each axle (if the vehicle is a truck-tractor, semitrailer combination) should be checked, and the lower numerical values should be used for SI.

For example, determine the SI for a two-axle truck-tractor, single-axle semi-trailer combination. Payload axle loads for the rear axle of the tractor and the trailer axle are to be 10,000 lb (4536 kg) each.

The truck was loaded to one-half and full payload, and deflections were measured. Scales were used to determine the payload axle load on each axle. The following data were obtained on the trailer axle: 12,288 lb (5573.7 kg) for full payload axle load, 6,123 lb (2777.3 kg) for one-half payload axle load, 1.127 in. (2.85 cm) for average deflection at full payload, 0.687 in. (1.73 cm) for average deflection at one-half payload, and

$$K = \frac{12{,}288 \text{ lb} - 6{,}123 \text{ lb}}{1.127 \text{ in.} - 0.687 \text{ in.}} = 14{,}000 \text{ lb/in. } (2497 \text{ kg/cm})$$

Enter K on Figure 1, read vertically to the payload axle load that the truck is to transport [10,000 lb (4536 kg)], and read horizontally to SI. For K = 14,000 lb/in. (2497 kg/cm) and for payload axle load = 10,000 lb (4536 kg), SI = 1.52. SI from Table 1 is 1.50.

This procedure should also be used on the rear axle of the truck-tractor and 1.50 should be used as the SI for the truck with 10,000-lb (4536-kg) payload axle loads. The SI for all other payload axle loads can be determined directly from the graph or table by using the value of K for the truck, since K is independent of the payload.

CONCLUSIONS

The research (2) developed a set of semiempirical relationships to equate the performance of the vehicle and the cargo with the significant variables affecting the ride. The findings of General Testing, Inc., are not the ultimate answer to the problem of cargo ride but can be used to build a firm set of requirements for the safe transportation of all cargo.

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TRANSPORTABILITY CRITERIA HANDBOOK

Clyde H. Perry, Newport News, Virginia

ABRIDGMENT

●THE Transportability Criteria Handbook is a condensed discussion of criteria and test procedures for guidance and design, development, and procurement of materiel to ensure its compatibility with existing and foreseen transportation systems. Emphasis is placed (a) on dimensional and weight limitations and those environmental considerations affecting reliability of military materiel and systems when they are moved through the transportation system and (b) on test procedures capable of proving survival capability of military items in those environments encountered in intermodal transportation. Criteria and related test procedures are based on normal transportation environments encountered and do not include consideration of transportation accidents or incidents.

The handbook contains research, development, test, and evaluation transportation-oriented criteria that, if used for guidance in the design and development of military materiel, will ensure that this materiel is designed, engineered, and constructed so that it can be efficiently moved by available means of transportation throughout the world.

The Transportability Criteria Handbook was prepared cooperatively by the military services. A summary of this handbook was prepared for publication by the Transportation Research Board; however, publication of the summary is being withheld pending approval by the Department of Defense.

Publication of this paper sponsored by Committee on Transportation of Hazardous Materials.

Part 2

Planning, Budgeting, and Performing Highway Maintenance

U.K. DEVELOPMENTS IN HIGHWAY MAINTENANCE SINCE THE MARSHALL REPORT

B. E. Cox, Lincolnshire County Council, England

Recommendations in the Marshall Report encouraged research into many areas of highway maintenance and accelerated the progress of several ongoing developments. The research concerning highway maintenance in the United Kingdom is described, and progress is reviewed. Particular areas studied that may have application to U.S. practices are discussed in some detail. These include a methodology for roadworker and field management training; the evaluation and trials of maintenance standards; means of obtaining objective assessments of maintenance needs and priorities, including the use of measuring equipment and structural assessment systems; a computerized approach to the production of estimates and allocation of resources; the identification of organizational principles; comparability of costing and accounting systems; data collection; and work and method study. Other common problems that have only been tentatively explored or have yet to be studied are also discussed. The paper develops an objective, numerate approach to the management and execution of highway maintenance.

•THE Marshall Report (1) has had a great impact on research in highway maintenance. Many post-Marshall research projects have been omitted to enable some understanding of developments applicable to practices in the United States.

So that interest in the Marshall Report could be maintained, a steering committee was set up to consider the recommendations and implementation of the report.

In conjunction with the establishment of the steering committee, research teams to study the organization and the economics of maintenance were organized from personnel of highway authorities from the different regions of the United Kingdom, the U.K. Road Research Laboratory (now the U.K. Transport and Road Research Laboratory), and the U.K. Ministry of Transport (now the U.K. Department of the Environment) to advise on maintenance problems requiring research, to assist in providing data, to consider the results of research, and to assist in providing opportunities for controlled trials of improved methods and techniques of maintenance.

HIGHWAY MAINTENANCE RESEARCH TEAM

The research teams on highway maintenance were set up in September 1970. Initially, four teams were established:

1. A county research team on the organization of maintenance,
2. An urban research team on the organization of maintenance,
3. A county research team on the economics of maintenance, and
4. An urban research team on the economics of maintenance.

The research team was to advise the U.K. Transport and Road Research Laboratory (TRRL) on specific maintenance problems requiring research, to assist in providing

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data for maintenance research studies, to consider TRRL research results on maintenance, and to help provide opportunities for controlled trials of improved methods and techniques of maintenance.

PREVIOUS MAINTENANCE RESEARCH

Most research work done on roads in the United Kingdom before 1970 was from the viewpoint of materials and not of maintenance. A very limited, hurried research program had been carried out for the Marshall committee primarily to identify areas requiring investigation.

Factors considered in previous research have been the source of information and its accessibility, the availability of the resources required, and the urgency or time restraints. Four methods have been used:

1. Research contracts with consultants or local authorities,
2. Local authority researchers acting individually or in groups,
3. Local authority researchers in conjunction with TRRL groups, and
4. TRRL groups.

Typical examples of each method are

1. A cost study by 19 highway authorities under contract to TRRL,
2. A computerized system to produce estimates of resources required and work programs developed by a highway authority under contract to TRRL,
3. A comprehensive manual on surface dressing by a researcher and specialist subgroup,
4. A study of highway authorities' maintenance organization by a local authority researcher and TRRL staff,
5. Development of a maintenance rating system by local authority and TRRL researcher, and
6. Studies of paving operations on a number of major highway contracts by TRRL.

RESTRUCTURING RESEARCH TEAMS

As there was not a great deal of difference between the urban and rural interest, the urban and county research teams were combined on January 1, 1973, and the economics and organization teams were combined to form one team on maintenance in December 1973.

To spread involvement with the subject, a number of task forces headed by a researcher were formed to tackle specific subjects, but the remaining researchers were co-opted from authorities throughout the United Kingdom.

CURRENT RESEARCH PROGRAM

The current research program includes

1. Program for resource allocation and production of estimates;
2. Plant maintenance and costing systems;
3. Surface dressing manual;
4. Review of standards, engineering, and economic levels;
5. Comparison of contract and direct labor operations;
6. Maintenance rating system;
7. Analysis of cost study data;
8. Organization of highway departments;
9. Techniques, organization, and costs of overlaying, reconstruction, and resurfacing;

10. Techniques, organization, and costs of patching and trench reinstatement;
11. Survey of street lighting systems;
12. Assessment of risk of not doing maintenance; and
13. Management information systems for formulating and estimating costs of overall systems.

ROADWORKER TRAINING

The Marshall Report stated that gains in efficiency from greater attention to training may well be as great as or greater than can be obtained in any other way, and the committee made a number of recommendations (1).

Pre-Marshall Training

Some highway authorities started training programs, the most notable being a regional scheme covering southwest England. A nationally recognized craft qualification for roadmen (2). National conditions of service for roadmen were related to rates of pay, skills and a basis of payment were related to job descriptions, and a defined range of skills was established to enable highway authorities to develop a multiskilled labor force (3). A Local Government Training Board (LGTB) was also established.

Throughout the United Kingdom, there were some 45,000 roadworkers and supervisors, but training only applied to some 700 students involved in the national craft training program, and under 1,000 person weeks/annum were devoted to other systematic training off the job.

Post-Marshall Training

The steering committee and the LGTB were responsible for implementation of the recommendations on training.

Programs

First priority was given to training centers. Research was carried out to establish the criteria for the centers. The stages of implementation were identified, such as the compilation of data on age and grading profiles, labor turnover, and forecasts of future demand for labor so that the volume of training required could be calculated. Training audits were recommended to establish the additional amount of training necessary to update, develop, and extend the skills of the existing labor force.

Methods

A three-phase program was produced:

1. New entrants were taught basic roadman skills,
2. Progressive training was administered up to and including skilled roadman, and
3. Additional skills or preparation was made available for promotion to supervisory or technician grades.

Alternative methods were devised for the second and third phases respectively by using the national qualification method and the modular courses at training centers. The training program is shown in Figure 1, and the modular courses are given in Table 1.

The national conditions of service for roadmen were amended to relate pay grades to training and to make managers responsible for assessing training. Personnel fore-

Figure 1. Training program.

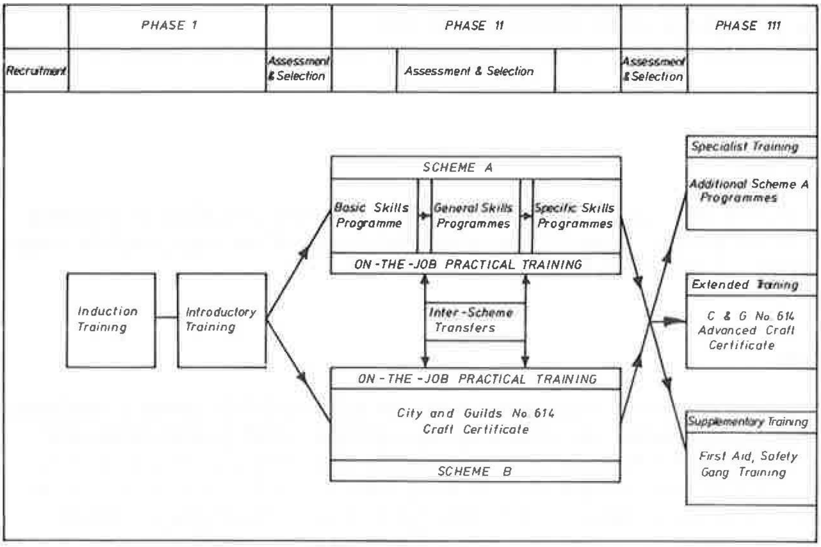


Table 1. Modular courses.

Skill Level	Course Group	Course Number	Course Title
Basic	B	1	Basic roadworking operations
General	D	1	Roadmaking-flexible construction
	D	2	Roadmaking-rigid construction
	D	3	Paints, plastics, powered hand tools
	D	4	Highway fittings and furniture
	D	5	Highway horticulture
	D	6	Light plant operation, part 1
	D	7	Light plant operation, part 2
Specified	F	1	Basic setting out
	F	2	Manholes, catch pits, gullies
	F	3	Curb laying
	F	4	Pipe laying and jointing
	F	5	Fence erection
	F	6	Walling (e.g., drystone)
	F	7	Trench timbering
	F	8	Shuttering
	F	9	Steel fixing
	F	10	Reinforced concreting
	F	11	Scaffolding
Specialist	G	1	Specialist setting out

casting, selection, and recruitment policies and the planning, control, and recording of individual training programs are also required. There is provision for appeal by employees who feel unreasonably denied opportunities for training (4).

Materials

The steering committee established a panel to recommend preferred methods of construction and maintenance and, jointly with LGTB, to produce instructor manuals.

Other Post-Marshall Developments

Developments in national qualifications have enabled an integrated system for progression from skilled roadman to highway superintendent.

EVALUATION AND DEVELOPMENT OF MAINTENANCE STANDARDS

The Marshall committee recommended a set of initial standards for all the functions of highway maintenance and recommended that economic studies should be set in hand for the development of objective standards (1).

The steering committee recommended the adoption of the initial standards, subject to minor modifications, to assess the condition of roads and the adequacy of maintenance but recognized that achieving all the standards might be a long-term project in light of the availability of funds and pressure on national and local budgets. Because of the short time for research, the Marshall standards are largely subjective, and research is required to evaluate the initial standards and to develop more objective standards.

Cost of Adopting Marshall Standards

A cost study was carried out by 19 highway authorities under contract to TRRL since the standards could not be developed without first determining the effect of the initial standards.

The objectives of the study were

1. To estimate costs of raising all roads in a designated area to Marshall standards over a 5-year period,
2. To estimate the annual costs of maintaining the same roads above the Marshall standards thereafter, and
3. To estimate costs for the same roads on the basis of current local maintenance standards.

Three pilot studies were initially undertaken to establish appropriate organization methods and procedures and to identify difficulties. A total of 3,330 miles (5360 km) of roads of all categories were inspected and assessed.

The data obtained were used to estimate the cost of implementing the Marshall standards throughout the United Kingdom.

Engineering Levels of Highway Maintenance Standards

The objective of this study is to assess the Marshall standards for bituminous highways by comparing the maintenance needs, as specified by the standards, with the assessment of a panel of experienced engineers and with the needs indicated by transient deflection measured with a deflectograph or Benkelman beam. A number of highway authorities under contract to TRRL are providing a range of urban and rural sites for assessment, including construction details and traffic volume. Where construction details are not fully known, cores will be drilled or trial holes dug. Panel members will be unaware of the apparent treatment needs indicated by the Marshall standards from field inspections or the deflectograph measurements, but their opinions will be recorded in a standard manner.

This is a short-term evaluation that is programmed to be completed within a year. A study is also to be carried out of the economic levels of highway maintenance standards, and both studies will be associated with work on estimating the risk attached to deferring maintenance.

USE OF MEASURING EQUIPMENT

The Marshall committee recommended that all highway authorities should make full use of new apparatus becoming available for measuring a road's condition (1): a sideway-force coefficient routine investigation machine (SCRIM) and the Lacroix deflectograph.

Sideway-Force Coefficient Routine Investigation Machine

SCRIM is a machine developed by TRRL for routine monitoring of skidding resistance of roads. The machine is basically a truck-mounted water tank with a test wheel mounted between the front and rear wheels to measure skid resistance in the nearside wheel track and to provide a continuous measurement of skidding resistance on a printout. Items such as changes in surface material and road classification numbers can be recorded. SCRIM can test at speeds ranging from 9 to 62 mph (15 to 100 km/h). The machine has been widely used and is available for purchase and hire by highway authorities in the United Kingdom.

The information obtained with SCRIM can be used to identify roads requiring antiskid treatment, to supplement other data in studies of accident sites, and as part of the data for a complete condition survey. A SCRIM machine has been used by the Greater London Council to monitor the entire metropolitan road network and to intensively study the skid resistance at traffic-light-controlled intersections and at other known accident spots so that a relationship between skid resistance and accident levels at standardized road locations can be established.

Deflectograph

The deflectograph, a mechanical equivalent of the Benkelman beam, was originally developed, tested, and proved by the French Road Research Laboratory. TRRL has modified the machine to suit stiffer British pavements, and it is now generally available to highway authorities.

The machine measures the transient deflection every 11.5 ft (3.5 m) in both wheel tracks, and a typical day's operation can process about 4 miles (6 km) of highway. The survey can be backed up by a highway coring team to ensure accurate information about the existing road structure.

A printer is used with the machine and produces a graphical trace of the samplings. From this original information, a graphical block diagram processing technique is used to facilitate engineer interpretation of various roadway characteristics (Figure 2).

New Works

Criteria have been developed for assessing new works during construction by assessment at subbase, base, and surfacing levels with any consistent deviations investigated

Figure 2. Operations in analysis of deflectograph survey.

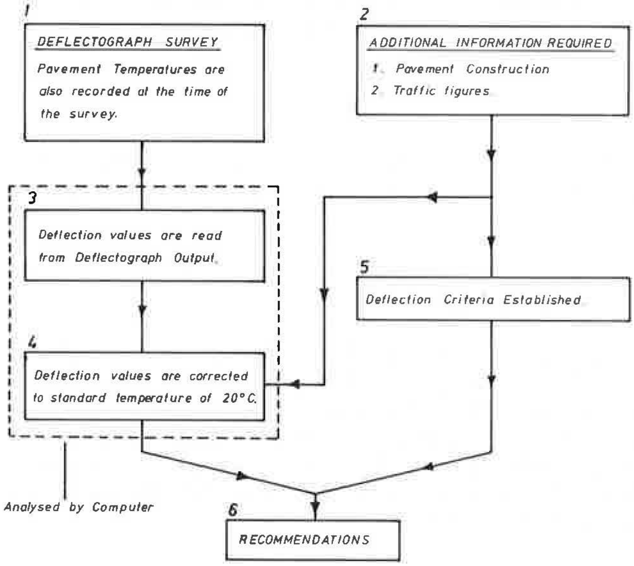
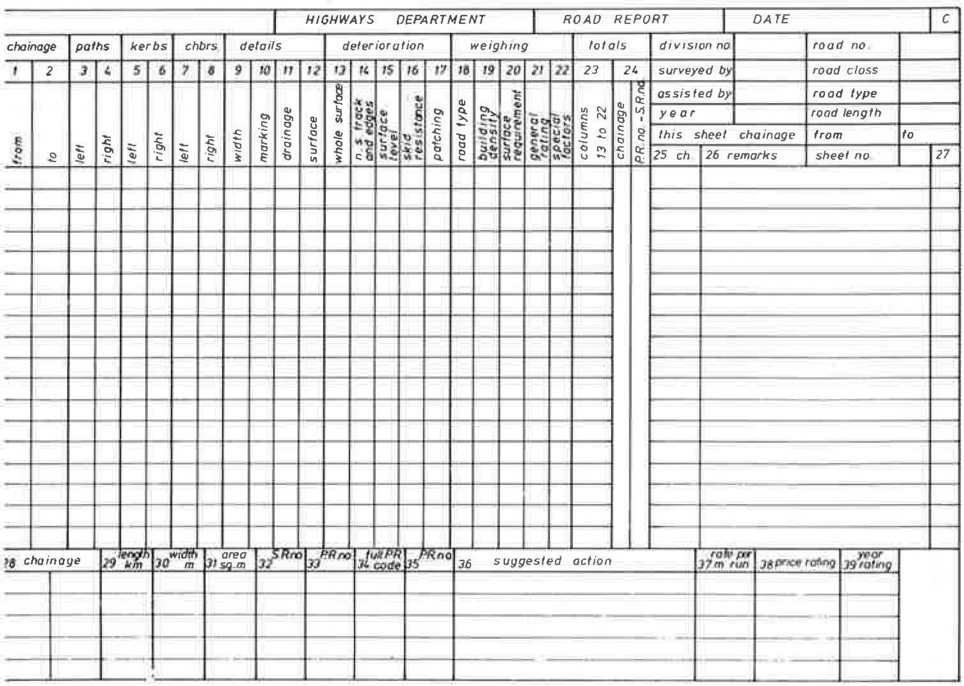


Figure 3. Inspection sheet for maintenance rating system.



at the relevant construction stage. This technique monitors compliance with specification and adequacy of design method and may well lead to the specification of performance criteria from road pavements at the commissioning stage.

Surfacing Policies

From deflectograph assessments, the relative strengthening properties of different designs and thicknesses of bituminous materials can be assessed, and an optimum economic surfacing policy evolved.

Highway Damage

It is frequently claimed that road openings such as by public utilities have caused damage to the highway. Diversion routes, abnormal loads, and changes in traffic patterns due to traffic management programs have also been held responsible for damage caused by maintenance engineers. Previously such damage could only be assessed by visual inspection and engineering judgment. A survey before and after deflectograph measurement can quantify the damage so that the engineer can cost remedial works to be apportioned to the cause of damage.

STRUCTURAL ASSESSMENT SYSTEMS

The Marshall committee recommended that authorities should use a maintenance rating system as the basis of regular documented inspection of all their roads (1). A maintenance rating system (1) was produced based on visual assessment; points were given to various defects, which were subsequently weighted, and then each assessed aspect was judged critical or satisfactory. The system's defect is that results are primarily based on an inspector's subjective visual assessment. A typical inspection sheet for maintenance rating is shown in Figure 3.

Requirements of Structural Assessment System

A system was needed that minimized subjective judgment and optimized an objective, numerate, quantitative approach.

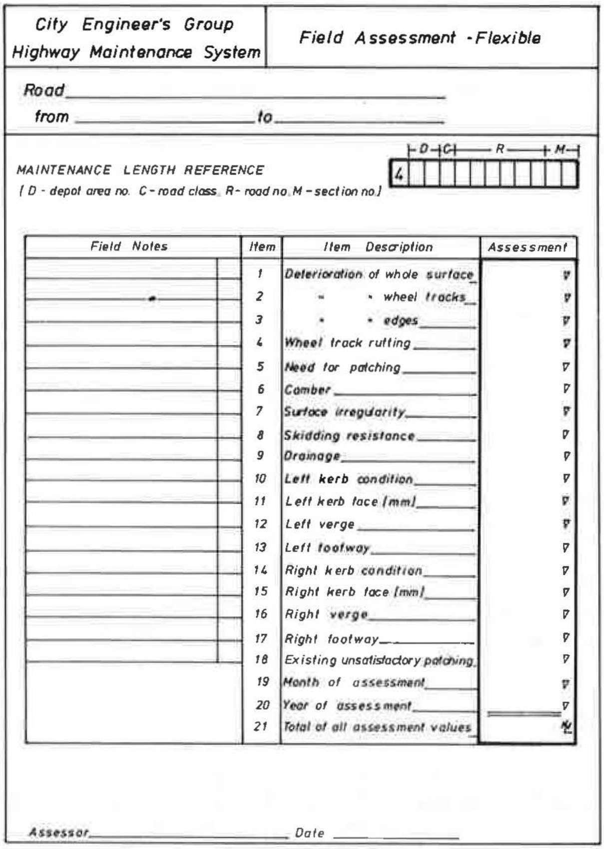
MARCH System

The MARCH system is a coarse-data system in which the data are collated by totals of defects, e.g., length, areas, and numbers within a given length of road, so that the locations of individual defective lengths, areas, or units making up the totals are not known. Data are collected in a form from which the computer input can be directly punched. The output includes priority lists of maintenance lengths and treatments required based on the worst defect present and lists of maintenance lengths with full assessment and inventory data. The system also includes a rough costing option with an editing facility to produce finer costs. An inspection sheet is shown in Figure 4, and the system outline in Figure 5.

CHART System

The CHART system is a fine-data system in which the defects data are located by distance along a road from the start of each section, and this enables precise analysis. An inspection sheet is shown in Figure 6.

Figure 4. MARCH inspection sheet.



City Engineer's Group
Highway Maintenance System

Field Assessment - Flexible

Road ____________________

from ____________ to ____________

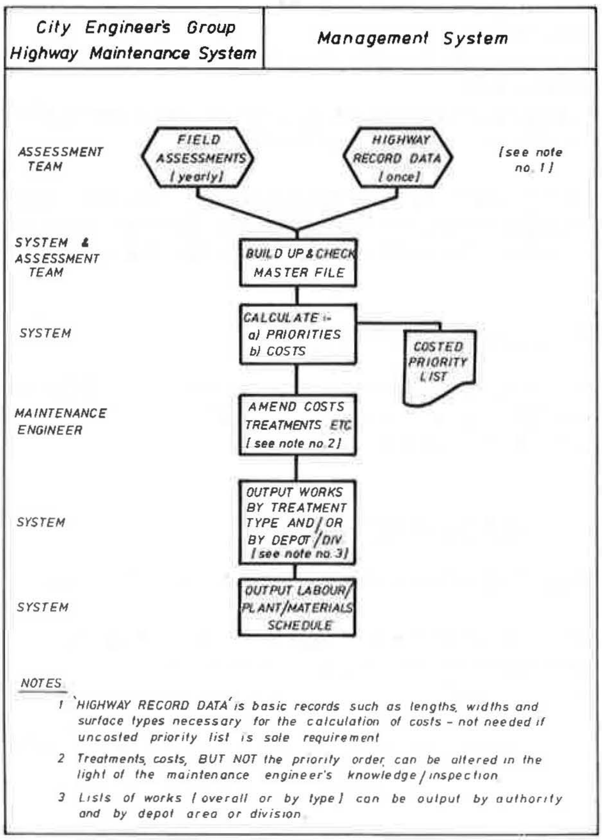
MAINTENANCE LENGTH REFERENCE
(D - depot area no. C - road class. R - road no. M - section no.)

D | C | R | M
4

Field Notes	Item	Item Description	Assessment
	1	Deterioration of whole surface	
	2	" " wheel tracks	
	3	" " edges	
	4	Wheel track rutting	
	5	Need for patching	
	6	Camber	
	7	Surface irregularity	
	8	Skidding resistance	
	9	Drainage	
	10	Left kerb condition	
	11	Left kerb face (mm)	
	12	Left verge	
	13	Left footway	
	14	Right kerb condition	
	15	Right kerb face (mm)	
	16	Right verge	
	17	Right footway	
	18	Existing unsatisfactory patching	
	19	Month of assessment	
	20	Year of assessment	
	21	Total of all assessment values	

Assessor ____________________ Date ____________

Figure 5. MARCH system outline.



The output includes a map of all roads inspected, showing the location of defects and features along the road; histograms of the combined ratings for all defects present; critical subsections, i.e., 330-ft (100-m) lengths; and individual defect and treatment length lists in order of priority of need for treatment.

Application of Systems

The MARCH coarse-data system may be more suited to urban areas where treatment lengths, i.e., city streets, are comparatively short and where the precise location of defects is less critical than an assessment of overall condition. The CHART system, however, seems more appropriate to rural areas where treatment lengths are longer but are only part of the total length of a road.

PROGRAM FOR RESOURCE ALLOCATION AND PRODUCTION OF ESTIMATES

The Marshall committee recommended that highway authorities should introduce management control systems to provide full information for the planning of future demand on labor, plant, and material resources (1).

Pre-Marshall System Development

A system that was partly manual and partly computer based was developed by the Lindsey (now Lincolnshire) County Council. It used a standard computerized system for bills of quantities production together with

1. A detailed comprehensive list of items of work [library of standard operations (LOSO)] normally encountered in highway works arranged under heads compatible with standard practice;
2. Normal methods for study and work measurement techniques applied to each LOSO operation; and
3. Unit rates synthesized from work-study data subdivided into labor, materials, plant, and total costs for each LOSO item.

This system was used for producing and pricing bills of quantities for estimation and resource requirements, but considerable difficulty was experienced in manually updating wage rates, material prices, and plant rates.

Post-Marshall System Development

The obvious development required was to transfer this sytem to a computer and to eliminate the manual operations. Therefore, a TRRL contract was entered into with the Lindsey County Council.

Comparison With Traditional Methods

The traditional bill of quantities approach to estimation uses

1. Labor and materials constants and multipliers,
2. Published prices of measured work, and
3. Historical costs.

This approach is not effective for job control. More reliable cost data, the use of

Figure 6. CHART inspection sheet.

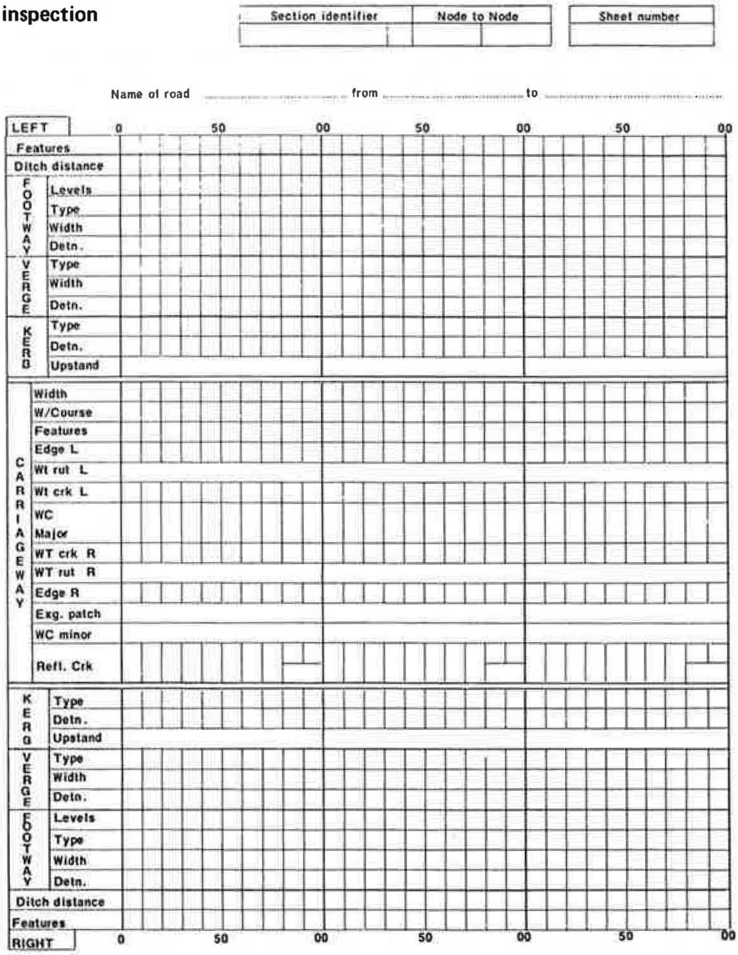
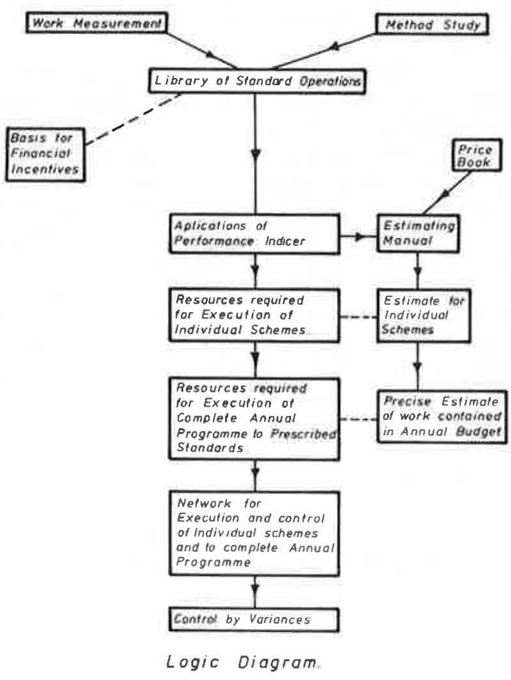


Figure 7. Program for resource allocation and production of estimates.



work-study data, and preferably activity-based bills of quantities based on direct labor work are needed to provide a method for accurate estimation and the effective control of work and costs.

The computerized system produces activity or nonactivity, priced or unpriced, bills of quantity for direct labor or contract schemes. Resource requirements and materials schedules for direct labor work and drawn networks for activity-based programs can be linked to computerized costing systems and PERT analysis systems.

System Advantages

Advantages of the management control system include

1. Estimation of resources free from subjective judgment and past history,
2. Resource requirements fully documented and available for use by any engineer,
3. Unbiased unit rates providing facility for checking validity of rates in contract tender documents, and
4. Itemized traditional bills of quantities and activity-based bills of quantities produced in direct relationship to an associated network.

Scope of System

The system can be extended to cover all construction and maintenance work and thus encompass all the operations of a direct labor organization. The logic for the development of the complete system is shown in Figure 7.

HIGHWAY AUTHORITIES MAINTENANCE ORGANIZATION

The Marshall committee recommended that all highway authorities should reconsider their maintenance organization in an attempt to provide more effective and efficient use of resources (1). Therefore, after the Marshall report, a research team was set up to identify the functions common to all the maintenance organizations and to define the principles of organization by which these functions could be performed most efficiently. This is a long-term study, but the advent of local government reorganization necessitated an urgent study.

The team's report (5) describes the desirable principle that emerged from surveys of 19 highway maintenance organizations. An attempt was made to relate the functions of a maintenance organization to the scope of the overall workload of a highway department in relation to the effective employment of resources. Based on the principle of corporate management, there are proposals on organizational structure that incorporate determination of staffing by job evaluation and objective assessment of workload. It is suggested that, for maximum efficiency, a structure should have short, direct lines of communication and use modern methods of information transmission; control is emphasized.

The structure suggested in the report is related primarily to circumstances envisaged in the new, nonmetropolitan U.K. counties, but there may be underlying principles of effective maintenance management that have a wide application; this may be revealed by the results of the long-term study.

SURFACE DRESSING MANUAL

The Marshall Report defined the objective and provided a standard of critical highway deterioration justifying treatment by surface dressing (1).

The Need for a Manual

Although the technique of surface dressing is well advanced in the United Kingdom and considerable research has been carried out, the end result is not always satisfactory because the wealth of knowledge available has never been combined into a single guide to the subject. Therefore, a subgroup was set up to produce a surface dressing manual.

Scope and Content of Surface Dressing Manual

The manual attempts to provide a readable, comprehensive description of surface dressing and contains the following:

1. A complete list of publications about the various aspects of surface dressing, and
2. A section on planning, including site inspection, selection of materials, selection and running of the plant, preparation of the surface, delivery, storage, and testing of materials; a section on treatment, including traffic control, sweeping before dressing, protection of ironwork, application, sampling of materials, rolling, sweeping after dressing, replacement of road markings, warning signs, recording work, work study, and bonus incentive; and a section on post treatment, including immediate post treatment, interim post treatment, and historical records.

RECOMMENDATIONS ADOPTED

A number of recommendations in the Marshall Report are well on the way to full implementation:

1. Adoption by highway authorities of common accounting heads for maintenance activities,
2. Production of standard specifications for contract maintenance and the supply of materials,
3. Universal adoption by highway authorities of work-study-based incentive programs,
4. Bulk purchasing systems for materials,
5. Rationalization of highway responsibilities in the reform of local government, and
6. Minimization of the effect of heavy axle loads on structurally weak minor roads by prescribing truck routes.

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USER DELAY COST MODEL FOR HIGHWAY REHABILITATION

Mehmet Karan and Ralph C. G. Haas, Department of Civil Engineering, University of Waterloo

Recently, traffic volumes on many highway facilities have increased to the extent that rehabilitation operations can cause long delays and extra operating costs to the users. Consequently, in addition to the construction costs of rehabilitation, user cost has become an extremely important factor in the total economic evaluation of highway improvements. This paper describes a comprehensive methodology for calculating user costs caused by rehabilitation operations on highways. A model based on engineering and economics has been developed and is capable of predicting extra user costs associated with rehabilitation operations. A number of major variables are considered; they include highway type, geometric characteristics, construction factors such as time and length of job, and traffic handling method. The model has been computerized and can be used for either in-depth project evaluation or for large-scale network planning. The capability of the methodology is demonstrated with several typical example problems. The results emphasize that, for certain situations, user costs of rehabilitation operations may reach extremely high values. The neglect of user costs can result in major errors in the economic evaluation of alternative highway pavement rehabilitation strategies.

•REHABILITATION operations on highways have in the past been considered in terms of construction requirements. Vehicular traffic was considered only as something that needed to be accommodated. Therefore, in economic terms, highway engineers were only dealing with the pure construction cost portion of the problem. Since traffic volumes were often not too heavy, this approach was reasonable for many situations.

During the past decade, however, large traffic volumes on many highways have resulted in the need for extensive maintenance, resurfacing, and reconstruction of many portions of the highway network. Engineers have begun to realize that, in addition to construction costs, an additional factor of user delay costs, due to the interruption of traffic, is involved in the problem (1, 2, 3, 4). These user delay costs may be considered as extra vehicle operating costs plus actual time delay costs to the user.

Today, rehabilitation operations represent one of the major activities of many highway departments. In Ontario, for example, an average of 8,000 miles (12 875 km) of highways undergo rehabilitation (excluding user cost); in the United States the cost for rehabilitation has reached over $1 billion. In 1972, expenditure on major improvements in England amounted to approximately $140 million (7).

The magnitude of these numbers clearly indicates the importance of highway rehabilitation in transportation and suggests the need for considering user delay costs in economic evaluations.

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IMPORTANCE OF USER DELAY IN PAVEMENT MANAGEMENT SYSTEM

In a pavement management system, the problem of user delay costs may be considered in an overall manner in the planning phase and in a detailed sense in the design phase. Because of the many possible combinations of layer materials and thickness increments, the designer is able to generate a number of alternative strategies for the problem. To estimate the costs and benefits of each strategy, techniques that predict the outputs of that strategy are used first. Then, values are placed on these outputs so that all strategies may be compared and so that the designer may be suitably guided in selecting the optimal strategy (3, 4).

In practice, the main factor usually considered in this selection is the cost of each alternative. As a consequence, the importance of determining costs with reasonable accuracy over the chosen analysis period becomes very clear. Since user costs can reach very high values, their neglect may lead the designer to an unrealistic and uneconomical solution. Therefore, the cost of user delays that occur because of rehabilitation operations, such as maintenance and resurfacing, needs to be included in the overall cost of the strategy.

OBJECTIVES OF PAPER

The general purpose of this paper is to provide a methodology for calculating user delay costs caused by highway rehabilitation operations. More specifically, the objectives are to

1. Define the role of the user cost concept within the context of the pavement management system,
2. Define a user delay cost system and its subsystems,
3. Describe a computerized model for estimating user delay costs, and
4. Demonstrate the application of the model to individual projects and network priority programming studies.

DEVELOPMENT OF MODEL

Basic Structure

The model is basically composed of two main phases. In the first phase, the time delays caused by rehabilitation operations are calculated. In the second phase, costs of delays are determined through an economic evaluation procedure. Figure 1 shows the two main phases and their component activities.

The model first calculates capacities before and during the construction period (8). Hourly demand volumes are determined from the use of a submodel discussed later. These capacities and demand volumes are then analyzed to determine the difference in travel times before and during the construction period.

Evaluation of the outputs of the first phase is the next step so that the total cost of the extra time spent in the construction zone can be determined. In this evaluation phase, only the operating costs of vehicles and users' time costs are considered. Accidents and discomfort costs through the rehabilitation area are not considered.

Traffic Handling Methods Considered

The control of traffic during construction is one of the most important aspects of performing rehabilitation on highways. Protection of the rehabilitation crew from motor vehicles and safety of the traffic flow are required. This area is of sufficient importance that most highway departments, such as in Ontario (9), have their own traffic control and construction sign manual.

The type of traffic handling method used is also extremely important in the structure of the user delay cost model. Each type results in a different effect of construction on the traffic flow and varying delays to the user.

The method used for any particular situation depends mainly on the type of highway, its geometrics, and the presence or absence of shoulders, frontage roads, or other alternate routes.

The number of alternative methods that can be appropriate for a particular problem is usually limited by the geometrics and environmental characteristics of the highway. If a situation occurs in which alternate methods can be used, then the selection depends on the volume of traffic approaching the construction zone.

The following most common methods of handling traffic are considered in the model:

1. For two-lane highways without shoulders, two flagmen are generally posted at each end of the rehabilitation area to stop traffic in one direction while traffic from the other direction proceeds through (method 1, Figure 2). In the presence of shoulders, traffic in the nonrehabilitation direction can be diverted to the shoulder while the other traffic uses their lane (method 2, Figure 3).
2. For four-lane highways, if one lane is closed (method 3), traffic in the rehabilitation direction gets only one lane (Figure 4). It may sometimes be desirable to close all lanes in one direction (method 4). In this case, all rehabilitation traffic is usually diverted to the other direction and occupies the inner lane (Figure 5).
3. For six-lane highways with nontraversable medians, the three lanes in each direction are usually rehabilitated in three stages (method 5). In the first stage, the outer lane is closed and traffic uses the other two lanes. When this is finished, then both outside and median lanes are closed. In the last stage, two outside lanes are opened, and only the inside lane is closed (Figure 6).
4. For both four- and six-lane highways, where a detour can be used (method 6), all the traffic in the rehabilitation direction is channeled to the detour (Figure 7).

Determination of Capacities

Initial capacity (before construction) is an important factor in predicting speeds before construction. However, capacity during construction is also involved because of the changes in the geometric layout of the highway.

The initial capacity of the highway section can be directly determined for given initial geometric and traffic characteristics by using the Highway Capacity Manual (HCM) (8) approach. However, capacity calculations for the construction period involve the problem of determining new geometric layouts of the roadway. In this case, psychological effects should also be considered. Since there is no generally acceptable technique that combines subjective and objective factors, the assumptions given in appendixes A, B, and C[1] have been made in the development of the model.

As a result of these assumptions, determination of capacities during the construction period can be made in the same way by using the HCM procedures.

Estimation of Hourly Demand Volumes

Estimation of hourly demand volumes is extremely important in the overall structure of the user delay cost model because the accuracy of the model depends mainly on the capacity-demand analysis from which delays are determined.

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[1] The appendixes of this paper are available in Xerox form at the cost of reproduction and handling from the Transportation Research Board. When ordering, refer to XS-60, Transportation Research Record 554.

Figure 1. General structure of model.

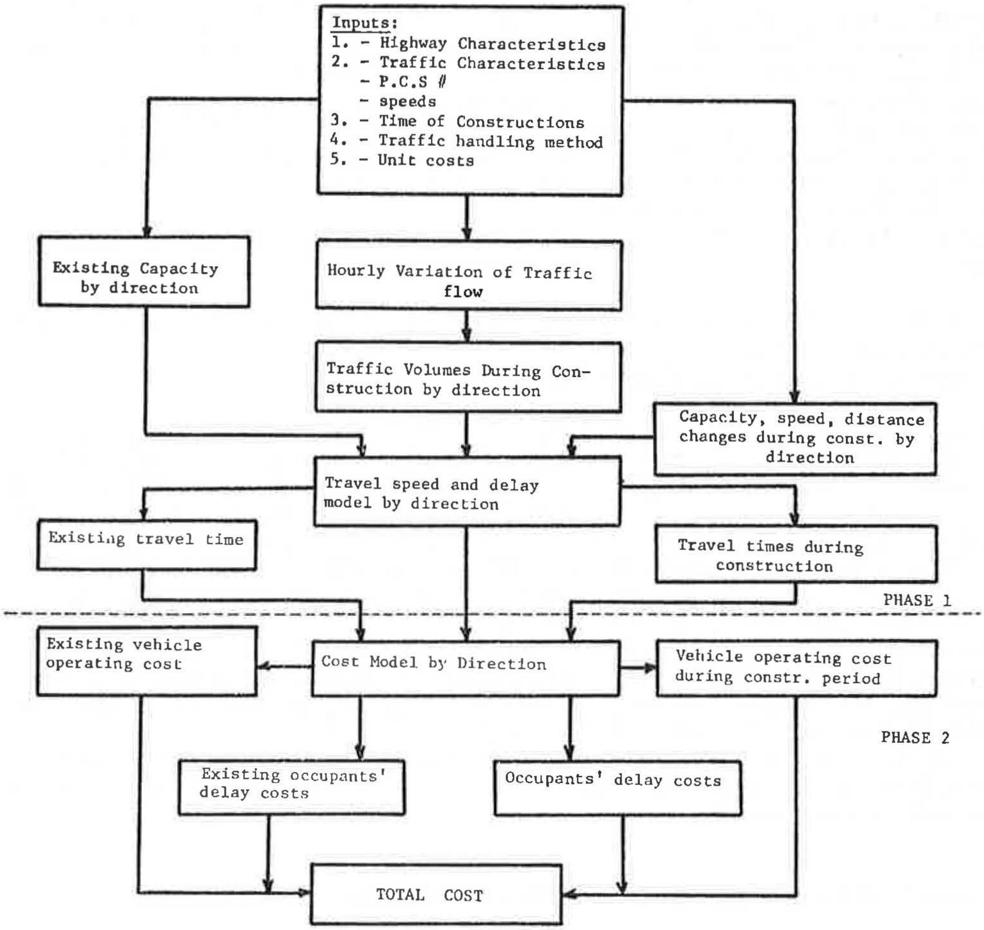


Figure 2. Method 1 for two-lane highways without shoulder.

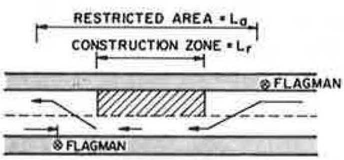


Figure 3. Method 2 for two-lane highways with shoulder.

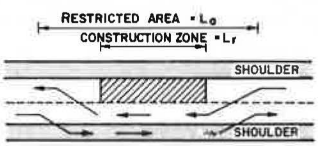


Figure 4. Method 3 for four-lane highways, one lane closed.

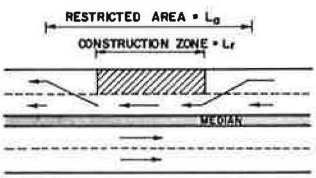
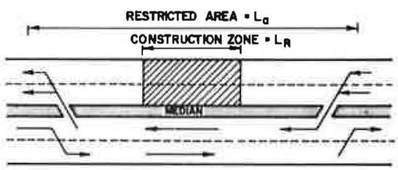


Figure 5. Method 4 for four-lane highways, two lanes closed.



There may be several ways, including sophisticated techniques of structuring a model, to predict hourly variation of traffic flows. In this investigation, however, a deterministic type of approach and permanent counting station (PCS) data were used.

The problem of developing a general traffic pattern that is applicable to every highway in an agency's network is difficult because of the large variety of factors that can affect the pattern on any particular link. However, if the highway network can be broken down into relatively homogeneous groups, then each group can be represented by one traffic pattern. Most agencies achieve this through a PCS system such as in Ontario. The PCS provides detailed traffic information and the opportunity of grouping highways that have similar traffic characteristics.

Based on this concept and the PCS in Ontario, the following relationships were developed:

1. Average annual daily traffic (AADT) versus monthly average daily traffic (ADT), i.e., monthly factors; and
2. Hourly volumes versus ADT, i.e., hourly factors.

These hourly factors should be developed for each month of a year. Because of practical considerations, however, 6 months (November to April) were excluded from the model (i.e., under the assumption that rehabilitation is not carried out in the winter). The rest were grouped as summer season (July and August) and off-season (May, June, September, and October) because of the similarities in traffic patterns. Two groups were tested against three groups (May and October, June and September, July and August), and there was no significant difference in the resulting factors. Therefore, the two-group method was used for simplicity.

Currently, few, if any, agencies perform rehabilitation on weekends. Nevertheless, assuming that in future this situation might change, the same relationships were developed separately for weekend days. A detailed documentation of these and previously described relationships is given elsewhere (10).

The following formula is then used to estimate hourly demand volumes (if AADT volumes, PCS number, and time of rehabilitation in terms of month, weekday, or weekend day and hour are known):

$$\text{hourly traffic demand volume} = \text{AADT} \times \text{monthly factor} \times \text{hourly factor} \tag{1}$$

Travel Speed and Delay Submodel

Three types of delays to motor vehicles can occur because of rehabilitation operations. These are due to low speeds, speed change cycles, and queues. Delays caused by low speed and speed change cycles are computed from the speeds before and during construction that are determined from the HCM speed-flow relationships.

Assuming that all vehicles approach the rehabilitation area at the same speed (speed before construction) and travel at the same restricted speed through the area of influence, the delay per vehicle is computed as the normal travel time through the area (i.e., without restrictions) minus the travel time at the reduced speed (due to rehabilitation).

Acceleration and deceleration delays are not calculated separately because they are taken into account in developing the cost tables of speed change cycles.

Queuing Models

It has been assumed in this investigation that traffic flow is not stopped by any cause external to the traffic stream in all traffic handling methods, except in method 1. In method 1, vehicles in one direction are from time to time forced to stop to give way to the traffic in the other direction. These two flow situations correspond to uninterrupted and interrupted flows, respectively, as designated in the HCM.

Since operational characteristics in these two flow situations are completely different, two different techniques are used for calculating delays in each situation, as described in the following sections.

Queuing Model for Uninterrupted Flow

The model used for uninterrupted flow conditions requires that a record be kept of cumulative arrivals and departures on an hourly basis. Cumulative arrivals are calculated from the hourly demand volumes, and total vehicles served are determined on the basis of capacities.

The graphs in Figure 8 are obtained from hourly cumulative arrivals and departures. If cumulative arrival and departure graphs are denoted by A(t) and D(t) respectively, the area between A(t) and D(t) gives the total delay due to the rehabilitation operation. In the user delay cost model, however, the average delay per vehicle and average queue length in each hour are used rather than the total delay and total vehicles affected.

The vertical distances between A(t) and D(t) at half hours give the average hourly queue lengths AQL. Similarly, horizontal distances at half hours give the average hourly queuing time AQT for vehicles.

Queuing Model for Interrupted Flow

It is assumed that the rehabilitation area in method 1 basically works as a simple signalized intersection with two signal phases and no turning movements. This is because of the similarity in vehicle movements and other operational characteristics.

In view of this assumption, the following techniques, which are mainly applicable for signalized intersections, have been used for determining signal and queuing delays in method 1.

Degree of Saturation Less Than One

For the case in which degree of saturation is less than one (this represents the situation where intersection discharge capacity is greater than the arrival rate; when the arrival rate exceeds the discharge capacity, the degree of saturation is greater than one), Webster's method (11) is used to calculate average delay per vehicle due to red and green phases during a signal cycle. The assumption is made that cycle characteristics remain constant (fixed time cycle) through the construction period. The number of vehicles affected in each hour is equal to the hourly demand volumes.

Degree of Saturation Equal to or Greater Than One

When the degree of saturation is equal to or greater than one, Webster's method gives an unrealistic solution of infinite delay. This might be correct if demand volumes were always greater than the discharge capacity; however, in reality, after a certain period of congestion flow, demand volumes begin to decrease, and then capacity exceeds the input rate. Therefore, infinite delays cannot occur.

The following deterministic model is developed for determining delays when the degree of saturation is equal to or greater than one. This model, like the queuing model for uninterrupted flow, also requires a record of cumulative arrivals and departures, but on a cyclic basis.

Cumulative arrivals and departures for each cycle are calculated based on Figure 9. Then, graphs A(t) and D(t) are obtained. For each hour, the area between the graphs A(t) and D(t) gives the total hourly delay. These total hourly delays are then divided by hourly demand volumes to determine the average delay per vehicle in each hour.

Figure 6. Method 5 for six-lane divided highways.

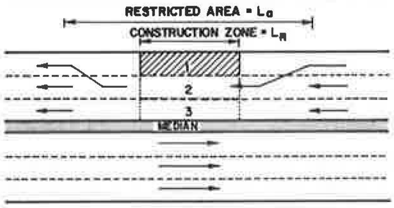


Figure 7. Method 6 for four- and six-lane highways, detour.

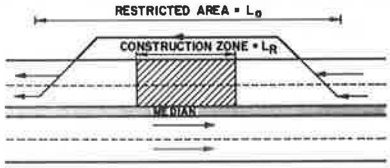


Figure 8. Queuing model.

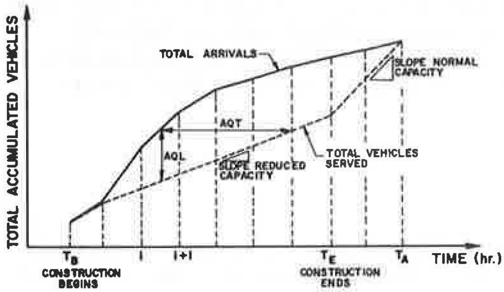


Figure 9. Deterministic queuing model for interrupted flow.

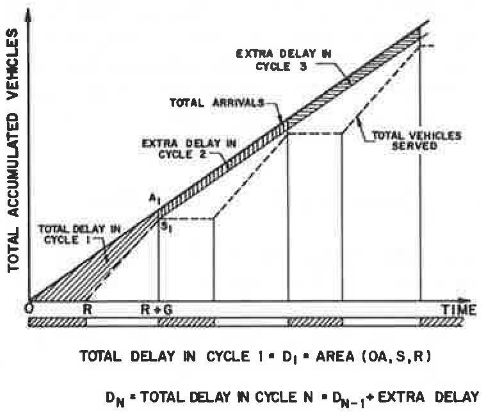
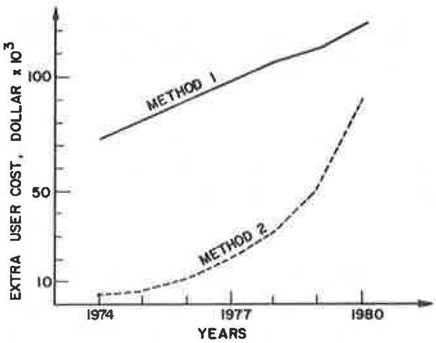


Table 1. Method 1 and 2 costs for two-lane highways.

Construction Year i	Method 1 User Cost in Year i (dollars)	Method 1 Present Value in 1974 (dollars)	Method 2 User Cost in Year i (dollars)	Method 2 Present Value in 1974 (dollars)
1974	72,743	72,743	3,066	3,066
1975	80,057	74,127	5,841	5,409
1976	87,516	75,031	11,191	9,594
1977	94,911	75,343	18,738	14,875
1978	102,737	75,515	32,075	23,576
1979	110,446	75,167	53,755	36,585
1980	118,165	74,464	88,638	55,857

Figure 10. Variation of user cost by years for methods 1 and 2.



User Delay Cost Equations

The total daily user delay cost (TUDC) is calculated from the following formula:

$$TUDC = \sum_{1}^{n} (CARCST + SUTCST + TRACST) \tag{2}$$

where

n = number of hours in construction period,
CARCST = total hourly delay cost for passenger cars in dollars per hour,
SUTCST = total hourly delay cost for single-unit trucks in dollars per hour, and
TRACST = total hourly delay cost for transport trucks in dollars per hour.

$$CARCST = CARCS1 + CARCS2 \tag{3}$$

$$SUTCST = SUTCS1 + SUTCS2 \tag{4}$$

$$TRACST = TRACS1 + TRACS2 \tag{5}$$

where

CARCS1 = hourly user cost for passenger cars in rehabilitation direction,
SUTCS1 = hourly user cost for single-unit trucks in rehabilitation direction,
TRACS1 = hourly user cost for transport trucks in rehabilitation direction,
CARCS2 = hourly user cost for passenger cars in nonrehabilitation direction,
SUTCS2 = hourly user cost for single-unit trucks in nonrehabilitation direction,
TRACS2 = hourly user cost for transport trucks in nonrehabilitation direction.

Each of these directional costs is composed of cost of stopping or slowing down, cost of traveling at low speed, and cost of delay. The following equation is given for passenger cars in the rehabilitation direction, but the same idea is used for all other vehicle types and directions.

$$\begin{aligned} CARCS1 = {} & CARSTP \times STPCST + CARSLOW \times SLOWCST \\ & + CARSLOW \times (OPCSTC - OPCSTB) \times MILE \\ & + IDLECST \times (CARSTP \times QUEDEL + CARSLOW \times SPDDEL) \\ & + TIMECST \times (CARSTP \times QUEDEL + CARSLOW \times SPDDEL) \end{aligned} \tag{6}$$

where

CARSTP = number of cars stopped in rehabilitation direction because of congestion;
STPCST = cost of stopping from the speed before construction, per passenger car;
CARSLOW = number of cars slowed down in rehabilitation direction because of rehabilitation;

SLOWCST = cost of slowing from the speed before construction to reduced speed, per passenger car;
OPCSTC = operating cost during construction period, per passenger car;
OPCSTB = operating cost before construction period, per passenger car;
IDLECST = idling cost per passenger car;
QUEDEL = average hourly queuing delay in rehabilitation direction;
SPDDEL = speed delay in rehabilitation direction due to low speed, per passenger car;
TIMECST = cost of time for passenger cars; and
MILE = length of influenced area.

The first component in equation 6 gives the cost of stopping and slowing down. Nevertheless, in this investigation, it is assumed that, if demand volumes exceed capacity, all vehicles stop, otherwise all vehicles slow down. Therefore, in equation 6, either the first or second item in the first component is always ignored according to the presence or absence of a queuing situation.

The second component concerns the cost of traveling at low speeds through the rehabilitation area. The third component gives the operating cost of idling, and the last component gives the time cost of delays.

All unit costs needed in equation 6 can be taken from cost tables developed by type of vehicle (passenger car, single-unit truck, and transport truck). An example, for Ontario conditions, is shown in appendix A. Because these unit costs can change rapidly, an updating process is required. Detailed documentation of a computerized method for such an updating process is provided elsewhere (10) and uses, as base year information, the type of data in appendix A.

MODEL APPLICATION

Necessity of Computerization

The model in the previous section could be used in the form of a procedural manual in which the methodology is presented in tables and graphs to keep the calculations simple. Because of the nature of the problem, however, a computer program is preferable. This is because of the solution time involved and because the large number of mathematical calculations would make a manual solution quite inefficient. Therefore, the whole methodology has been computerized for easy application by using a main program and 14 subroutines (10).

The following sections provide several examples of application.

Example Problem for Two-Lane Highways

A section of two-lane highway with 7,000 AADT of equal directional split, 12-ft (3.7-m) lanes, and obstruction on one side at 5 ft (1.5 m) is considered for methods 1 and 2 for a forthcoming resurfacing. The section has been assigned to the relevant PCS for the area. It is assumed that rehabilitation begins on a weekday in August 1974 at 7 a.m. and, including 2 weekend days, continues for 10 days. The road is rehabilitated for 5 hours each day and has a 1-mile (1.6-km) area of influence.

It is further assumed that 60- and 40-sec green phases, with a total cycle length of 140 sec, are used in method 1 for rehabilitation and nonrehabilitation directions respectively. This means that the capacity of the roadway section will be reduced significantly. Because of these reduced capacities and high-demand volumes, oversaturated flow conditions occur for almost every hour for both weekday and weekends. Consequently, each vehicle approaching the rehabilitation area stops and waits in a queue. Average hourly delay per vehicle goes up as high as 0.98 hours on weekdays and 1.13 hours on weekends (as determined by the queuing submodel).

In addition, because of the congested flow within the influenced area of one line (1.6 km), average operating speeds drop down to 28 mph (45 km/h). The total (extra) user cost for the 10 working days, based on the computerized model (10) and the unit cost tables in appendix C, can be calculated as $72.743. Table 1 gives this cost and the costs for future years up to 1980 (i.e., if resurfacing were delayed). These future costs increase because of increasing traffic volumes, which are assumed for the example to compound at 5 percent per year.

If method 2 were used to handle the traffic instead of method 1, then the resulting reduction in capacity would still exceed the demand. Therefore, no queuing situation occurs. Because of the changes in volume/capacity ratios, speeds are reduced. However, in the rehabilitation area, vehicles travel much faster than they do in method 1. As a result, the total user cost of rehabilitation for the 10 days is calculated as $3,066, as given in Table 1. Future costs for method 2 for this situation are also given in Table 1 and are based on the same annual traffic growth rate of 5 percent.

Figure 10 compares the extra user costs for methods 1 and 2. It is quite apparent that method 1 results in very high user costs for all years although, relatively, user costs would be incurred with method 2 up to about 1977.

Example Problems for Four-Lane Highways

A four-lane expressway with 1,500 AADT, 12-ft (3.7-m) lanes, adequate shoulders on one side, and 5-ft (1.52-m) shoulders on the other is considered for methods 3, 4, and 6. The time characteristics of the rehabilitation are assumed to be the same as used in the previous example for methods 1 and 2.

In method 3, when one lane in one direction is closed to the traffic, the normal directional capacity of 2,506 is reduced to 1,146 vehicles/hour. However, hourly traffic demand volumes do not exceed the reduced capacity either on a weekday or on a weekend day. Therefore, no queuing delays are caused by the traffic. The reduction in speeds due to reduced capacity is also not very large. Consequently, in this method the user cost due to 10 days of rehabilitation operation has the low value of $1,266 in 1974 (Table 2).

Suppose, for the same rehabilitation operation, method 4 is used to handle the traffic during construction. In this case, the reduction in capacity becomes so great that demand volumes on weekend days exceed the capacity. This means that vehicles are delayed in queues in addition to the low-speed delays. These extra queuing delays constitute the major part of the user cost on weekends. For this reason, on each weekend day $3,377 of high user cost occurs; however, rehabilitation on each weekday causes only $535 of extra user cost. In this method, the total user cost of the entire operation is $11,036 for 1974, as given in Table 2.

If traffic in the rehabilitation direction is diverted to the frontage road (method 6), which has two 10-ft (3-m) lanes and 4-ft (1.2-m) shoulders on both sides, no queuing situation occurs. Reductions in speed are also minimal because of the large discharge capacity. As a result, negligible total user costs of $231 occur because of the 10 days of work, as given in Table 2.

Time of the rehabilitation, in terms of month of the year and hours of the day, has an extreme importance in the user cost concept, mainly because of the changes in traffic characteristics. Tables 3 and 4 give these effects for month and hours of the construction for method 3. Night and early morning paving operations could result in very substantial user cost savings for the given example (Table 4). There would be, however, extra construction costs associated with such policies and possibly increased safety hazards.

Example Problems for Six-Lane Highways

A six-lane freeway with 12-ft (3.7-m) lanes and obstruction on one side at 5 ft (1.5 m) is to be rehabilitated. Suppose the highway section has an AADT of 25,000 vehicles and

Table 2. Method 3, 4, and 6 costs for four-lane highways.

	Method 3		Method 4		Method 6	
Construction Year i	User Cost in Year i (dollars)	Present Value in 1974 (dollars)	User Cost in Year i (dollars)	Present Value in 1974 (dollars)	User Cost in Year i (dollars)	Present Value in 1974 (dollars)
1974	1,266	1,266	11,036	11,036	231	231
1975	1,461	1,353	15,072	13,956	251	232
1976	1,690	1,449	22,295	19,114	286	245
1977	2,335	1,853	35,273	28,001	334	265
1978	2,843	2,090	46,030	33,833	384	282
1979	3,427	2,332	60,375	41,090	463	315
1980	4,369	2,750	80,521	50,742	543	342
1981	5,678	3,313	109,942	64,150	617	360
1982	7,356	3,974	150,021	81,051	696	376
1983	9,541	4,773	196,446	98,272	771	385

Table 3. Effect of month of construction on user cost for method 3.

	June		August		October	
Construction Year i	User Cost in Year i (dollars)	Present Value in 1974 (dollars)	User Cost in Year i (dollars)	Present Value in 1974 (dollars)	User Cost in Year i (dollars)	Present Value in 1974 (dollars)
1974	316	316	1,266	1,266	229	229
1975	387	358	1,461	1,353	254	235
1976	462	396	1,690	1,449	286	245
1977	550	437	2,335	1,853	338	269
1978	644	474	2,843	2,098	401	295
1979	743	506	3,427	2,332	471	320
1980	846	533	4,364	2,750	549	346
1981	954	556	5,678	3,313	632	369
1982	1,065	575	7,356	3,974	717	387
1983	1,181	590	9,541	4,773	809	404

Table 4. Effect of time of day on user cost for method 3.

	August					
	7 a.m. to 12 noon[a]		1 to 6 p.m.[a]		1 to 6 a.m.[a]	
Construction Year i	User Cost in Year i (dollars)	Present Value in 1974 (dollars)	User Cost in Year i (dollars)	Present Value in 1974 (dollars)	User Cost in Year i (dollars)	Present Value in 1974 (dollars)
1974	1,266	1,266	2,177	2,177	25	25
1975	1,461	1,353	2,554	2,272	27	25
1976	1,690	1,447	2,742	2,351	30	25
1977	2,335	1,453	3,100	2,461	32	25
1978	2,843	2,090	3,914	2,876	35	25
1979	3,427	2,332	5,780	3,933	37	25
1980	4,314	2,750	12,034	9,589	39	25
1981	5,678	3,313	26,656	15,553	42	24
1982	7,356	3,974	47,351	25,582	45	24
1983	9,541	4,773	74,598	37,318	47	23

[a]Construction period.

a traffic composition of 80 percent passenger cars, 15 percent transport trucks, and 5 percent single-unit trucks. The section has been assigned to the relevant PCS. The total length of the section is 10 miles (16 km). Because of the available personnel and equipment, only 2 miles (3.2 km) of a lane can be rehabilitated each day between 7 a.m. and 12 noon. Rehabilitation begins on a Tuesday in August 1974 on the outer lane. According to method 5, on the first Tuesday, the outer lane will be closed to traffic; on Wednesday, the two outside lanes will be closed to traffic; and on Thursday, only the inside lane will be closed. The same situation is then repeated four times for the next consecutive 3-day groups.

During the 10 days on which rehabilitation is on outer and inner lanes, the reduced capacity of the section can handle the traffic volumes approaching the construction zone. Therefore, no queuing situation occurs. Total user costs of $1,326 occur mainly because of the fluctuations in speeds and low speed delays.

During the 5 days on which both the middle and outer lanes are closed, vehicles wait in long queues. Consequently, very long delays occur. As a result of these long delays, the user cost of this period has the large value of $16,317. Thus, the total user cost of the 15-day rehabilitation operation becomes $17,644.

Summary Tables for Network Priority Programming Application

The model developed and computerized in this study can be used by transportation agencies and individuals for both research and practical purposes. At the network planning level, however, where the user cost subroutine may need to be run many times, the model could be uneconomical to use in its detailed, present form because of the total solution time required. Therefore, for planning purposes, the model can be used to generate summary user cost tables for different traffic handling methods, demand volumes, and average conditions. These approximated tables can then be used at the planning level instead of the model itself.

Tables in appendix B give these average user delay costs per day for the six traffic handling methods considered in this investigation. They incorporate the most up-to-date unit prices available (i.e., as given in appendix C). An updating process that considers changes in these unit prices in the form of price elasticities has also been developed in the study and forms the basis of this paper.

CONCLUSIONS

1. User costs associated with rehabilitation operations may reach such high values that their neglect can result in major errors in the economic evaluation of alternative pavement rehabilitation strategies.
2. The major variables that affect these extra user costs are time of construction (hour, day, month), traffic volume, traffic handling method, and type and geometric characteristics of the facility.
3. A computerized model for calculating user delay costs (including extra vehicle operating costs) has been developed. The model may be applied, in a detailed sense, to individual project situations or, in an overall way, to network evaluation of a number of projects.

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HOT-MIXED MEMBRANE FOR BRIDGE DECK PROTECTION

Dale B. Mellott, Pennsylvania Department of Transportation;
John Saner, Illinois Department of Transportation;
Bernard Prince, Howard, Needles, Tammen and Bergendoff; and
John H. Kietzman, Johns-Manville Research and Development Center

A ½ to ¾-in.-thick (12.7 to 19.1-mm) hot-mixed membrane has been evaluated as a protective interlayer on bridge decks in seven states since 1966. Permeability, bonding, and stability under heavy traffic have been satisfactory and equivalent to other effective membrane systems at all locations. Requirements for mixing and placing with standard paving equipment are described. Compared with other membrane systems, the primary advantages of the hot-mixed membrane appear to be low cost, minimal deck preparation, use of standard paving materials and equipment, and ability to withstand heavy traffic for extended periods before there is a need for a wearing course. For one installation on a truck viaduct in Illinois in 1972, stone chips were pressed into the hot-mixed membrane mat to provide a textured surface in place of a wearing course. The hot-mixed membrane has been approved for use by the Illinois Department of Transportation. It is currently being used for bridge deck protection on a number of Interstate highways.

•THIS report discusses cooperative field projects for evaluating performance of an asphalt membrane mix developed by Johns-Manville Research and Development Center (J-M) in 1965. In 1966, small-scale tests were performed at two locations on the New Jersey Turnpike, and in 1967, further testing was done in four states. These tests used sheets of the mix precalendered to ⅛- and ¼-in. (3.2- and 6.4-mm) thickness. Based on the satisfactory performance of these tests, in 1970 and 1971 field trials were initiated by using standard paving machines to place the hot mix directly on bridge decks. The main purpose was to determine the ability of a thin layer of the hot mix to compact to a continuous impermeable layer when it was reheated by a hot asphalt concrete overlay (wearing course) and rolled.

This report concerns the paver-laid applications of the membrane in New Jersey and Pennsylvania, Illinois, Massachusetts, and New York State where more extensive evaluation of the membrane has been done. Results of the original field trials with the membrane mix placed as preformed sheets are included only to give a 7-year performance history of the basic mix.

MIX FORMULATION

The mix consists of standard paving materials: fine-aggregate blends and 60 to 85 penetration asphalt and asbestos fiber (Tables 1 and 2). Aggregate gradation, based on field service tests in 1965, is designed to give minimum thickness. The combined use of asbestos and high asphalt content is based on pavement technology developed since 1960 (3, 4, 5, 6, 7).

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Design and Control

The various membrane mixes placed cover the entire range of specified gradations, asphalt penetrations, and fiber and asphalt contents to evaluate their performance without use of prior laboratory mix design tests or criteria. No laboratory mix design appears to be necessary.

Quality control tests for the J-M hot-mixed membrane can be performed at the batch plant. Marshall tests have been used at several locations in the United States and Canada for quality control.

Production Methods

Standard asphalt paving pug mills were used to produce the membrane mix. Addition of the cold asbestos in sealed polyethylene bags required hot bin aggregate temperatures of 450 F (232 C) minimum to obtain the final membrane mix temperature of 350 F (177 C). A minimum of 30 sec of dry mixing of the aggregates after the addition of the asbestos is necessary to ensure thorough dispersion of the fiber. Wet mixing should continue until aggregates are thoroughly coated. (See appendix 1 for specified procedures.)[1]

Placeability

Factors evaluated that influence placeability include asphalt grade and content, paver type and speed, mix temperature, mat thickness, and ambient temperature. Two objectives in placeability testing were determination of a continuous mat with little or no skipping and a minimum mat thickness. Tearing in the mat is not critical if width of the check cracks is limited to a maximum of $\frac{1}{16}$ in. (1.6 mm). By design, the high asphalt content of the mix produces self-healing of the mat during subsequent reheating and rolling of the wearing course.

Pavers

One of the factors controlling placeability is the paver. The seven mixes (different aggregates and asphalts) placed by different paver models give a general basis for rating respective ability to place the membrane mix. Barber-Greene pavers used at four locations all placed satisfactory mats. These projects included four different models, 60 to 70 and 85 to 100 penetration asphalts, and mix temperatures from 295 to 350 F (146 to 177 C). Barber-Greene pavers have a reputation for being especially suited to place sheet asphalts similar to gradation of the membrane mix.

Two of the three Blaw Knox pavers gave poor mats, one of which can be attributed to low mix temperature. The third Blaw Knox machine gave a good mat with a mix at 345 F (174 C) but required hand-shoveling to help distribute the mix to the end of the auger. The problem appeared to be incomplete distribution of the mix by the auger in front of the screed. This was in part caused by densification of the mix in the truck at the first two locations.

At one location, the Pioneer paver used showed good placeability but only after the mix temperature was raised to 350 F (177 C).

Maximum paver speed for a good mat varied from 10 to 18 ft/min (3 to 5.4 m/min). At higher speeds, the mat showed a tendency to tear, especially at lower mixing temperatures. Keeping the screed heated at or above the mix temperature appeared necessary with all pavers.

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[1] The complete appendixes are available upon request from M. Leman, Johns-Manville AFD, Box 5108, Denver, Colorado 80217.

It is probable that, at temperatures near 350 F (177 C) and by proper machine adjustments, a variety of other paver types and models may prove satisfactory for placing the hot-mixed membrane at the desired $\frac{1}{2}$ to $\frac{5}{8}$-in. (12.7 to 15.9-mm) thickness. [A nominal thickness of $\frac{5}{8}$ to $\frac{3}{4}$ in (15.9 to 19.1 mm) may be necessary to produce a good mat when the deck profile is rough.] The responsibility rests with the contractor.

Mix Temperature

As is apparent from the above discussion, mix temperature is another critical factor in controlling placeability. All but one of the mixes placed at temperatures in the upper range [330 to 350 F (166 to 177 C)] gave good placeability [the exception being a mix at 355 to 375 F (179 to 191 C) placed by a Blaw Knox paver]. Only the Barber-Greene pavers gave good mats in the lower temperature range [295 to 315 F (146 to 157 C)].

Other Factors

Mixes containing more than 15.5 percent asphalt tended to densify in the truck and inhibited placeability by some pavers. The same effect appeared to be caused in one mix by a fines content above the specified 16 percent passing No. 200 mesh. There was no evidence that the variety of aggregate types had a significant effect on placeability.

PERFORMANCE

Impermeability

Field evaluation included four direct procedures for detecting permeation of deicing salts through the membrane. The following methods had previously proved effective in the evaluation of the precompacted membrane sheets placed in 1967 and 1968:

1. Conductive copper foil tapes permanently installed on the concrete deck under the membrane,
2. Inspection of the cracks on the underside of the deck where water leakage had occurred before the membrane was installed,
3. Water permeability tests on cored sections, and
4. Resistivity tests using the California method.

Calibration tests show that electrical resistance between the parallel, disconnected copper foil tapes was inversely proportional to moisture on the concrete surface. The tapes placed several inches (centimeters) apart were capable of distinguishing between water condensed or trapped under the membrane and deicing salt solutions (Figure 1). Resistance values recorded recently suggest that no significant amount of deicing salts have penetrated through the paver-laid membranes since the fall of 1971 (Table 3). This was confirmed by recent inspection of the underside of the structures in Scranton, Philadelphia, and New Jersey. Where efflorescence at cracks indicated previous leakage, no water or dampness is now visible after heavy rainfall, except under walkways and dividers.

Calibration of conductive tapes without covering with a membrane suggests that salt solution reaching only a short section of the tape will give a low resistance reading by a short-circuit effect.

Location of conductive tape (pairs) and resistance readings taken periodically since 1971 on various bridge decks are given in Table 3. Tape readings taken immediately after paving were low at several locations on the New Jersey Turnpike projects, and this indicated penetration of roller water. Readings taken at weekly or monthly intervals thereafter show continuous increase despite heavy rainfall. Apparently the mem-

Table 1. Hot-mixed membrane composition.

Material	Aggregate (percent)	Range (percent)	Total Weight of Preferred Mix (percent)
Aggregate			
Crushed screenings[a]	40 to 60		
Natural sand[a]	40 to 60		
Asphalt, 60 to 85 penetration		14 to 16	14.5[b]
Fiber, Johns-Manville ASBALTIC of equivalent		5 to 6	5[b]

[a]Porous aggregates such as slags and weathered stone are precluded.
[b]Ratio of minimum fiber to asphalt = 0.35.

Table 2. Aggregate gradation of hot-mixed membrane.

Sieve Size	Aggregate and Filler Range	Percent Passing Preferred Mix
⅜ in.	100	100
No. 4	98 to 100	98
No. 8 (or No. 10)	80 to 95	93
No. 16	60 to 88	70
No. 30	45 to 75	52
No. 50	28 to 55	35
No. 100	16 to 40	20
No. 200	10 to 16	12

Note: 1 in. = 2.5 cm.

Figure 1. Effect of water and salt solution on electrical resistance between parallel copper tapes before membrane cover.

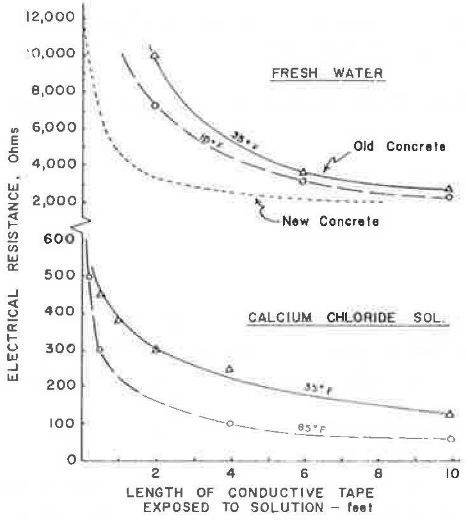

Table 3. Performance evaluation with conductive tapes of U.S. paver-laid membrane.

			Conductive Tapes Under Membrane			
				Electrical Resistance (minimum)		
Location	Authority	Placement Date	Number of Pairs Placed	Ω	Date Recorded	Interpretation of Resistance Values
New Jersey Turnpike and bus overpass	New Jersey Turnpike Authority	8/13/71	10	2,000	3/2/72 (connecting wires cut)	No salt penetration
Scranton Expressway, Pennsylvania	Pennsylvania DOT	8/71	3	3,350	3/23/73	No salt penetration
Schuylkill Expressway, Philadelphia	Pennsylvania DOT	10/71	3	2,430	7/25/73 (connecting wires cut)	No salt penetration
Massachusetts Turnpike, Palmer, Massachusetts	Massachusetts Turnpike Authority	8/71	5	5,000	3/10/72	No salt penetration
US-130 and NJ Secondary Route 522	New Jersey DOT	7/12/72	8	3,800	3/29/74	No salt penetration except at curb
US-130 and Pennsylvania Railroad		7/14/72	10	2,075	3/29/74	
Fifth Avenue Bridge over Eisenhower Expressway, Chicago, Illinois	Illinois DOT	6/14/72	1 northbound	1,000	6/19/74	Trace of salt penetration
			1 southbound	40,000	6/19/74	No salt penetration

brane mat was effectively sealed during rolling of the wearing course, and the entrapped water was gradually absorbed or diffused into the concrete deck.

At locations where the membrane mat was impermeable as placed, the underlying deck was dried by the hot mix and resulted in high resistance readings. As the moisture in the concrete deck normalized and slowly absorbed moisture from the air, resistance decreased but remained at levels that indicate impermeability.

Cores were drilled from the bridge decks on the New Jersey Turnpike and the Schuylkill Expressway for water permeability tests. Results on the turnpike cores (Table 4) show that the membrane was impermeable in each section, including those sections where minimum thickness of the membrane was $\frac{1}{32}$ in. (0.8 mm). Similar results (normalization of moisture in the deck) were obtained from the expressway cores. On both bridge decks, the wearing course sections were very tight but permeable in all but one core.

The California resistivity test, published after initiation of the hot-mixed membrane field projects, provides a portable method of measuring permeability at any location on the bridge deck. To date, the California procedure has been used to evaluate hot-mixed membrane installations in Ottawa and Chicago.

Tests on the Portage Bridge in Ottawa (Table 5) showed readings ranging from 8 million to 50 million Ω/ft^2 (86 million to 538 million Ω/m^2), well above the 0.5 million Ω/ft^2 (5.3 million Ω/m^2) suggested as the definition of complete impermeability.

Resistivity tests were performed on the Fifth Avenue Bridge (over the Eisenhower Expressway) in Chicago on June 19, 1974. Tests were performed at 5-ft (1.5-m) spacing on 42 areas on the deck: 21 on the outside wheel path of the southbound lane and 21 on the nontrafficked areas of the deck. The readings at each location are given in Table 6. Based on California's criteria for evaluating these measurements, 30 tests were satisfactory [$\geq$500,000 Ω/ft^2 (5 380 000 Ω/m^2)], 7 tests were doubtful [100,000 to 500,000 Ω/ft^2 (1 076 000 to 5 380 000 Ω/m^2)], and 5 were unsatisfactory [$<$100,000 Ω/ft^2 (1 076 000 Ω/m^2)].

Calendered (precompacted) sheets of the same membrane mix installed in 1967 and 1968 show a satisfactory 4 or 5-year performance history. Electrical resistance values measured by using the California method (2) show that the J-M membrane sheets placed on the New Jersey Turnpike in 1967 have remained impermeable. Figure 2 shows crack resistance of the membrane mix under the New York Thruway bridge at Newburgh as of September 1973 (center girder divides the membrane sheet on right from the sealer application on left). Electrical resistance measured by conductive tapes under the membrane sheets in New Jersey and Illinois also demonstrate impermeability. Sheets installed without an overlay in New York, Illinois, New Jersey, Ohio, and Maryland have shown good bonding since 1967. Table 7 gives permeability ratings for conductive tapes under membranes on the Cicero Bridge in Chicago.

Unfortunately, the California calibration criteria do not differentiate between resistance within concrete containing condensed moisture and concrete permeated by deicing salts. Based on calibration of conductive tapes (Figure 1), there should be a different range of values for the two conditions. Future calibration studies may define these ranges. Inspection of the underside of cracked bridge decks should confirm the calibration results.

Stability

The potential effect of membrane thickness on stability under heavy traffic was an important consideration. At several locations excessive thickness of the mat occurred because of poor screed control. For example, at one end of the New Jersey Turnpike ramp, the mat was more than 1 in. (2.5 cm) thick, and in one local area on the Schuylkill Expressway, the mat was more than $1\frac{1}{2}$ in. (3.8 cm) thick. No instability under heavy traffic has occurred at any of these locations with excessive membrane thickness nor in mixes produced with the 85 to 100 penetration asphalt.

The initial assumption that stability would be maintained by the specified fiber concentration has been confirmed to date.

Table 4. Permeability of core sections from bus overpass bridge.

Core Number	Membrane Thickness (in.) Average	Membrane Thickness (in.) Minimum	Permeability[a] (ml/min) Membrane Layer	Permeability[a] (ml/min) Wearing Course[b]
1	3/16	1/16	0	0.07
2	1/8	1/32	0	0.30
3	5/8	3/8	0	0
4	5/8	1/2	0	0.20
5	9/16	7/16	0	0.30
7	13/16	11/16	0	0.20

Note: 1 in. = 2.5 cm. All cores included a layer of portland cement concrete bonded to the membrane. Heating the cores to 160 F (71 C) was required to separate the concrete from the membrane layer.

[a]18-in. (46-cm) head of water.

[b]1½-in. (3.8-cm) nominal thickness of asbestos-asphalt concrete containing 2½ percent ASBALTIC fiber and 7½ percent asphalt.

Table 5. California resistivity test results for hot-mixed membrane on Portage Bridge.

Test	Location: Distance From Hull, Quebec (ft)	Location: Distance From Curb (ft)	Resistivity (1 million Ω/ft^2)[a] 1 hour	Resistivity (1 million Ω/ft^2)[a] 2 hours
1	5	10	50	50
2	8	5	50	50
3	25	7	50	50
4	33	11	50	20
5	41	6	50	50
6	52	7	50	50
7	67	11	20	12
8	90	5	30	15
9	101	8	15	8
10	115	4	50	50

Note: 1 ft = 0.3 m. 1 Ω/ft^2 = 10.76 Ω/m^2. Ground resistance on wetted curb and sidewalks equaled 5,000 Ω. California criteria for impermeability = 0.5 million Ω/ft^2 (5.4 million Ω/m^2).

[a]30-min initial sponge soaking.

Table 6. California resistivity test results for Fifth Avenue Bridge.

Location	Shoulder	Wheel Path	Location	Shoulder	Wheel Path
0	—[a]	500,000	55	—[a]	—[a]
5	—[a]	200,000	60	—[a]	300,000
10	500,000	120,000	65	—[a]	300,000
15	700,000	70,000	70	—[a]	300,000
20	500,000	85,000	75	—[a]	—[a]
25	—[a]	60,000	80	—[a]	—[a]
30	—[a]	120,000	85	500,000	—[a]
35	—[a]	120,000	90	—[a]	—[a]
40	—[a]	70,000	95	500,000	500,000
45	—[a]	60,000	100	600,000	—[a]
50	600,000	600,000			

Note: All values are in ohms/ft^2 (1 Ω/ft^2 = 10.76 Ω/m^2).

[a]Infinity.

Figure 2. Preformed membrane sheets.

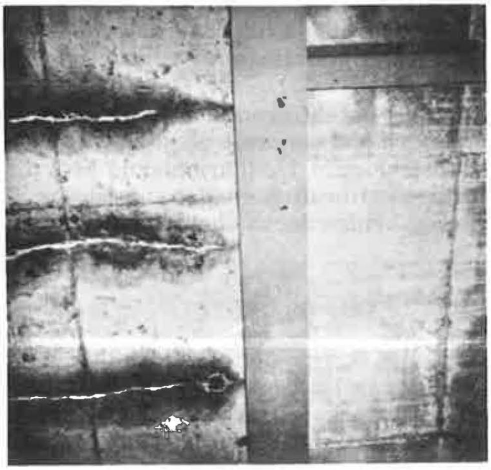

Table 7. Permeability measurements evaluated by conductive tapes under membrane.

Date Placed	Electrical Resistance (Ω) 1-in. Spacing	Electrical Resistance (Ω) 4-in. Spacing
November 1968	4,800	10,000
March 1969	3,000	6,500
June 1969	2,400	4,600
September 1969	1,500	3,800
December 1969	5,200	7,500
April 1970	3,200	3,800
June 1970	6,300	8,100
October 1970	2,200	2,900
April 1971	2,000	1,600
November 1971	4,000	5,000
February 1972	4,500	7,000
June 1974	3,000	4,000

Note: Each tape was rated as impermeable. Wetting of concrete between parallel tapes, 10 ft (3 m) long, installed with 4-in. (10-cm) spacings without a membrane cover, showed resistance readings of 3,200 Ω with fresh water and 40 Ω with a 3 percent solution of NaCl.

The membrane mix was used to resurface a ½-mile-long (805-m) truck viaduct in Decatur, Illinois, in 1972. Because of the structural design of the bridge built in 1926, it was necessary to maintain the overlay thickness at <1 in. (2.5 cm). In place of a wearing course, ⅜-in. (9.5-mm) traprock chips (100 percent retained No. 10 mesh) precoated with 1 percent MC-70 were rolled into the surface of the mat to provide surface texture.

To facilitate complete compaction, a pneumatic roller was used in the final rolling.

Current performance evaluation shows no instability of the membrane mix directly under truck traffic. Inspection of the underside of the deck shows complete impermeability of the membrane overlay. Some chip loss has been noted, but tests by Illinois DOT show that skid resistance provided is sufficient for this situation.

Bonding and Crack Resistance

Bond strength of the membrane mix to the concrete deck appears to be very good. This is confirmed by the 7-year performance of preformed (calendered) sheets of the same mix that were placed both as interlayers and as wearing surfaces in five states.

Electrical resistance values and visual observations at all membrane locations to date demonstrate excellent bonding of the membrane mixes to concrete decks and to the overlying surface courses. This includes locations where very light tack coats were used. Recurring blisters formed in one membrane overlay where a heavy tack coat was used under the membrane mix. The tack coat should be no more than 0.1 gal/yd^2 (4.3 $liters/m^2$).

At several locations traffic removed all visible tack coat from the deck before the membrane mix was laid. Therefore, the need for any tack coat is questionable.

Blisters often form in the membrane during initial rolling when roller water is entrapped before compaction is completed. These blisters are to be expected and confirm impermeability of the mat. They disappear once the mat cools to ambient temperatures.

Crack resistance of the membrane mix was demonstrated by inspection of open cracks on the underside of the deck. At all locations inspected in March after heavy rainfall, these cracks were dry. Future crack resistance of the membrane will be evaluated at these locations.

On the Schuylkill Expressway, expansion joints were covered by the membrane and asphalt concrete, and expansion joints were to be installed in the future. In March, cracks were visible in the wearing surface over the expansion joints. The absence of water seepage under the deck at these joints suggests that the membrane interlayer has not cracked to date.

Edge Effects

Potential problems in compaction and bonding adjacent to curbs and appurtenances, typical of many asphalt overlays, were evaluated by placing conductive tapes close to and parallel with the curbs under three of the bridge membranes. Electrical resistance values recorded during and after paving made it possible to check effective compaction as shown by water permeability.

Two of the three tape sets closest [6 or 7 in. (15 or 18 cm)] to the curbs of three bridges in New Jersey showed presence of deicing salts. The remaining eight sets showed no penetration of deicing salts vertically or laterally from the edge based on the tape calibration (Figure 1). This demonstrates the need for special attention to edge protection procedures.

CONCLUSIONS AND RECOMMENDATIONS

1. Performance data to date indicate the hot-mixed membrane provides an excellent impermeable barrier for bridge deck protection.

2. Satisfactory placeability requires a paver capable of placing sheet asphalts at temperatures from 325 to 375 F (163 to 191 C).

3. The membrane mat appears to be self-sealing when covered with the hot-mixed wearing course and rolled. Areas poorly compacted (hand work at curbs) and small cracks (tearing) densify and knit together to form a continuous, watertight interlayer.

4. Bond strength and crack resistance are good at all locations, and no instability has occurred to date. The application in Illinois of the membrane without an overlay allows visual observations of the crack resistance and stability of the hot-mixed membrane.

5. In-place cost of the ½ to ⅝-in.-thick (12.7 to 15.9-mm) membrane mix is estimated to be approximately equal to a standard 1½-in.-thick (38-mm) binder course. The ability of the membrane mat to sustain traffic should minimize traffic control problems and cost.

The membrane hot mix placed by a paver can be placed at ambient temperature as low as is permitted by standard asphalt pavement. The membrane was used on the Schuylkill Expressway in October and on the New York Thruway in November because low ambient temperatures precluded use of other membrane systems that had originally been specified. On the thruway when the ambient temperature was 42 F (5.6 C) the hot-mixed membrane was placed on a 1½-in. (38-mm) wet deck without difficulty.

Another advantage is the ability of the mat to sustain traffic before it is covered with the wearing course. On the Schuylkill Expressway, each membrane section placed at night sustained heavy traffic from 12 to 36 hours before it was covered with asphalt concrete. The traffic had no visible effect on the membrane mat.

Similarly, the thickness of the membrane reduces the possibility of puncturing the membrane by the wearing course or a rough deck surface. The only deck preparation necessary in most cases is replacing structurally unsound sections of the deck.

The following changes are based on the total experience in the hot-mixed membrane projects and should be considered in future contract specifications:

1. The use of 85 to 100 penetration asphalt (at locations where 60 to 85 penetration asphalts are not available) has proved satisfactory. The lower cohesion of mixes made with 85 to 100 penetration asphalt may facilitate placeability.

2. Nominal thickness of the membrane mat should be ⅝ to ¾ in. (15.9 to 19.1 mm) to accommodate bridge decks with rough profiles.

3. The membrane mat should be well sanded (coarse sand) before it is rolled to guard against dry spots on rollers that will stick to and pull up the thin mat.

4. Special sealing procedures should be used along gutters, curbs, and dividers to inhibit lateral migration of deicing salts under the membrane mat through the porous surface of the concrete deck. A paint coating of asphalt emulsion or hot-poured sealer is advisable at these locations.

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DISCUSSION

R. C. Donnaruma and W. H. Clark III, New York State Thruway Authority; and
T. E. Snure, County Asphalt, Inc.

This is an excellent paper on the research and development work on the hot-mixed membrane concept that we think is ready to be implemented. We would like to add our recent experience in implementing this research on five bridge rehabilitation projects.

As noted in the paper, the New York State Thruway Authority had participated in the initial development work on the hot-mixed membrane research by Kietzman at Johns-Manville. During the time this paper was being prepared (September 1973 to October 1974) the New York State Thruway Authority implemented this research on two major structures totaling approximately 22 lane miles (35.4 km) or 166,950 yd^2 (139 570 m^2) of deck surface. An additional 1,350 yd^2 (1130 m^2) was placed in 1974 at a contractor's request (substituted for a conventional membrane) to speed up a smaller project. In addition, 18,340 yd^2 (15 222 m^2) will be constructed in 1975, and an experimental bridge rehabilitation project with 6,140 yd^2 (5133 m^2) will be produced based on a modification of our specification.

Although the history of the cost per square yard for this material has been quite favorable on our larger installations [\$1.43 to \$4.98/yd^2 (\$1.86 to \$6.47/m^2)], cost was not a major factor in the decision to use this material. About 70 percent of the volume has been placed at night, and the requirements were that all lanes be open to traffic in the morning. Scheduling and traffic control constraints necessary to maintain income during the rehabilitation work, especially important during the traffic volume declines resulting from the energy crisis, posed such severe materials problems in selecting a membrane system that the most satisfactory course of action was to implement the J-M research rather than to be limited by conventional membrane systems. The biggest roadblock in this process was a deficient technology for the material because it was still in the formulation stage and was not a controlled production item for large-scale projects.

Our main experience to date has been where dead load and curb height have limited the wearing course above the membrane to a nominal 1-in. (2.5-cm) thickness. When only a 1-in. (2.5-cm) submersion was used, it was assumed that the membrane layer was acting structurally as part of the wearing surface, and, therefore, a mix design method was required to formulate a proper mixture. Because of the unusual mastic properties of the mix, a modified Marshall design method was used where the stability is determined at a flow value of 30 units (it normally will not reach a maximum stability). The mixture's stability is sensitive to filler content and sand particle shape. In all cases, where we have formulated the mixture for a minimum Marshall stability of 800 lbf (3560 N) at flow = 30 units, the mixture has required application temperatures from 375 to 425 F (190 to 220 C) to achieve a good quality mat. The mixture has been judged difficult to pave because of its cohesiveness, which gives it a high propensity for tearing. However, in one pass, a 3/8-in.-thick (9.5-mm) and up to 37-ft-wide (11.3-m) membrane has been successfully placed in ambient temperatures down to 35 F (2 C) by our contractors.

High mixing and handling temperatures will have an aging or hardening effect on the asphalt cement. However, by being impervious and protected by a dense asbestos modified wearing course, further aging, oxidation, and hardening are minimized throughout the life of the membrane/pavement system. Therefore, we are not overly concerned with this aspect.

Our results to date indicate that a membrane of acceptable quality (resistance by the California method exceeds 500,000 Ω) has been produced. Mixtures meeting our modified Marshall design method criteria have apparently been sufficiently stable (no noticeable deformation) to withstand traffic loadings unprotected during construction and in service with a 1-in. (2.5-cm) wearing course. In addition to the favorable in-place costs, other benefits include speed of application, less rigorous surface preparation required with this system, and ability of the membrane to withstand traffic during construction. These advantages have substantially reduced contractor occupancy time, traffic control costs, and user cost.

The mix temperature range of 375 to 425 F (190 to 220 C) has caused serious manufacturing engineering problems. During the production of 3500 tons (3 175 000 kg) of the mix for two thruway projects, County Asphalt, Inc. found that automatic temperature sensors and controls in their plant were not designed for the 550 F (288 C) fine-aggregate temperature required to bring the cold filler, cold asbestos, and 350 F (177 C) asphalt cement up to a 400 F (205 C) final mix. Therefore, the plant temperature control had to be controlled manually. Lubrication problems developed in the screens and hot elevators. Until the switch was made to synthetic high-temperature grease, the plant had to be greased twice during each shift (even on that schedule, two sets of screen bearings and one set of hot-elevator bearings were lost). Cooling the dryer down slowly to prevent warping or cracking is strongly suggested. Despite the care taken by County Asphalt, Inc., its dryer did crack at the tire. It should also be noted that, for safety reasons, fuel oil cannot be used as a release agent in the haul trucks. A polymer release agent was used that proved to be satisfactory.

Handling the asbestos fiber has presented no safety problems in projects to date. However, in a project to be completed in the coming year, we encountered resistance from one large asphalt concrete producer to bid on a project in their immediate area because the legal department of their parent organization interpreted that even when the sealed-bag handling method was used (a sealed plastic bag that, when added to the pug mill, melts, releasing the asbestos), the full Occupational Safety and Health Administration asbestos standards would apply. Johns-Manville and most other producers think the full standard does not apply to the sealed bags. This safety aspect is obviously open to interpretation. Because of this problem, future research should explore the use of alternate mix modifiers such as reclaimed rubber or no modifier when the surface course is of sufficient thickness to materially reduce the stresses on the membrane.

Our implementation of the hot-mixed membrane has led us to slightly different conclusions than those presented by the authors. This is because our main experience to date has focused on design, which limited the wearing course above the membrane to a nominal 1 in. (2.5 cm), and because we took an engineering approach rather than a research approach to the material. However, we feel our work can be applied to the more general use and should be taken into account in future applications. We find we differ with the authors on four main points:

1. Our results indicate that the hot-mixed membrane should be laboratory designed to conform to the requirements of the installation. Many trial mixes produced in the laboratory, which conform on paper to the J-M guide specifications, have been deficient in void content and stability or both. If one of these deficient mixes were placed on a deck and were subjected to 30,000 vehicles the next day, the contractor, agency, and public would not benefit.
2. Although this material could be produced in most conventional asphalt concrete

plants, it is definitely a special handling material and cannot be sandwiched into normal plant production at a convenient moment of the day. For applications for which the mixture design dictates high handling temperatures, special techniques must be used in the manufacture of the material.

3. Most late model paving machines are of the same basic design; therefore, there appears to be no reason to prefer one manufacturer over the others. The membrane is very difficult to pave because of its cohesive nature. It is important that the paver be in perfect adjustment (which will preclude the use of worn, outdated equipment) and that it be operated by an experienced paving crew in strict accordance with recognized good paving practices.

4. We have experienced no pickup problems where water was used as a release agent on the steel wheel roller and question the insistence on the use of a sand broadcast during compaction. However, if traffic is to be put on the membrane during construction, sand must be used to deslick the membrane surface.

AUTHORS' CLOSURE

The work by the New York Thruway Authority engineers is certainly noteworthy. Although their design procedures might be desirable for their special situation, we think that, for normal membrane use, their procedures would unnecessarily complicate production and placement of the hot-mixed membrane.

In 1971, a hot-mixed membrane that did comply with the J-M specifications was placed on the thruway. It was placed at a temperature of 350 F (177 C) and showed good placeability at ½-in. (12.7-mm) mat thickness. The thruway engineers' subsequent design of a membrane mix for the Tappan Zee Bridge in 1972 was based on the premise that Marshall stability would be a prerequisite for satisfactory performance when a 1-in.-thick (2.5-cm) overlying wearing course was used. Their final Marshall design mix with 100 percent angular aggregate (stone screenings) and 50 to 60 penetration asphalt was a predictable result of the original premise. The initial problems in placing this mix with a Blaw Knox paver and the necessity of raising mix temperature as high as 425 F (220 C) are not surprising, based on our initial experience in Massachusetts and New Jersey.

In 1961, the American Oil Company demonstrated the ability of short asbestos fibers to prevent rutting of asphalt pavements at high asphalt contents (50 percent above normal) (3). Field tests confirmed this independence of high asphalt content. The initial asbestos-asphalt membrane evaluation involved placing preformed sheets of the membrane (same formula as used subsequently in hot-mixed applications) on concrete decks without an overlay to observe bonding and wear resistance under direct heavy traffic. Since 1966 and 1967 when these sheets were placed (at six locations in six states), no evidence of instability has been observed.

Since 1969, no instability has been reported in the hot-mixed membrane interlayer placed at more than 20 locations; this interlayer was made of local mat thickness exceeding 1 in. (2.5 cm) and 85 to 100 penetration asphalt in many places. If and when the future performance of the J-M membrane shows signs of instability, laboratory mix design tests may be justified. Currently, we prefer to avoid the problems encountered by the New York Thruway Authority and the special requirements by which it has achieved a workable system.

As pointed out to us by contractors in Massachusetts and New Jersey, some paving machines have been designed specifically for rapid placement of granular asphalt concrete, and some of these pavers are not capable of spreading thin layers of fine-aggregate mixes in front of the screed. If true, this should be considered by each contractor in placing the membrane mix. By keeping the mix formula open for on-the-job changes (within the specified ranges), placement of membrane mixes since 1970 has, at most locations, proved to be satisfactory at reasonable mix temperature. This includes mixes placed with Blaw Knox pavers (e.g., on the Scranton Expressway).

PARTIAL-DEPTH PRECAST CONCRETE PATCHING

Marion F. Creech, Virginia Department of Highways and Transportation

Experiments were performed with partial-depth precast concrete patching to determine the feasibility of the method. In the experiments, prefabricated slabs of various sizes, stockpiled near the pavement repair site, were installed in machine-cut holes in the pavement and cemented into place to make 68 patches. To determine the feasibility of using the cutting machines to prepare deteriorated areas for cast-in-place patches, 22 such patches were installed. Two Klarcrete machines were used to prepare the holes for patching. In the precast patching operations 292.5 ft^2 (27.17 m^2) were installed in 88 working hours, and in the cast-in-place operations 101.5 ft^2 (9.43 m^2) were installed in 26.4 hours. Major conclusions from the experiments were (a) precast patching is feasible, and the machines used to cut the holes did a creditable job; (b) additional projects in the 300 to 500-ft^2 (27.9 to 46.5-m^2) range are needed to develop a sophisticated methodology for increasing production; and (c) a commercial domestic epoxy resin is desirable that will cure as rapidly as the imported product (30 min).

•THE experiments discussed were conducted in an effort to find new, economical methods of repairing deteriorated portland cement concrete (PCC) pavements. In conventional repair, in which the spalled concrete is sawed and removed with jack hammers and a wet mix is poured in the hole, several undesirable things may occur:

1. An excess of good concrete is often removed, especially in depth;
2. Not enough concrete contiguous to the spalled area is removed, and, therefore, the patch material is bonded to unsound concrete;
3. Poor compaction occurs because of improper vibration or no vibration;
4. The patch material adheres poorly to the surrounding concrete; and
5. Long curing times are usually necessary.

Poor compaction, attempts to bond good concrete to bad, and improper bonding of the new material to the old are probably the major reasons for patch failure. Of major importance to the function of the highway is the blocking of lanes for long periods of time to allow the patch material to cure. This removal of lanes from service lowers the capacity of the highway, interrupts the traffic flow, increases motorists' frustrations, and increases the accident potential, especially under night conditions, because of the weaving action made necessary by the barricades.

In view of the many problems associated with cast-in-place patching, new methods of repair are being sought.

PURPOSE

This project was initiated to determine the feasibility of using precast concrete patches in the repair of PCC pavements. Some of the specific objectives were to determine

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1. The average length of time required to remove the deteriorated concrete, insert a precast patch, and allow the cementing material to cure sufficiently to open the repaired section to traffic;
2. The cost of precast patching, if possible;
3. If the wire mesh reinforcing steel in the concrete pavement presents a problem to the machine cutting the holes;
4. If the machines used to cut the holes are adaptable to cutting different dimensions and the ease with which they may be adjusted for different configurations;
5. If precast patching operations can be set up in a production line in which the first crews cut holes with the machines and the next crew places and cements the patches; and
6. The durability of precast patches.

TEST SITE

The westbound lanes of Va-44, the Virginia Beach-Norfolk Expressway, in Virginia Beach were selected for the project. Va-44 is a four-lane divided highway built to Interstate standards and opened to traffic in June 1968. It was constructed of 9-in.-thick (23-cm) jointed reinforced concrete pavement and incorporated tabular metal joint inserts. The joint spacing is 61.5 ft (18.75 m). On most roads in which the inserts have been used, joint spalling has occurred, and Va-44 is no exception. Exactly why the spalling occurs is not well understood, but certain events have been observed. First, the metal insert rusts out, and this allows the sealer to sink into the joint. Then, the joint is susceptible to entry of foreign materials, which in many cases are noncompressible. Such materials block any subsequent expansion of the slabs, and spalling occurs. Another explanation traces the spalling to the small intrusions made in the concrete by the metal inserts. This is revealed by cores taken at the joints. When rusting occurs, a weakened plane evidently is formed and results in spalling. Figure 1 shows the dimensions and cross section of the 2¼-in. (5.7-cm) tabular metal joint.

Foremost among the reasons for selecting this site for study was the fact that the eastbound lanes had just been repaired in the conventional manner (joints were sawed and resealed), and the westbound lanes were scheduled for repair in the winter of 1974 to 1975. The site thus presented an excellent opportunity to observe the two types of patching side by side.

PRECAST CONCRETE PATCHING

In modern industry, many items are prepackaged, prefabricated, or precast. Nowhere is this more prevalent than in construction. There are numerous examples of coliseums built with prefabricated concrete sections hauled to the site and attached to each other to form the finished structure. Many bridge components are prefabricated. The list of prefabricated products is quite large and growing; therefore, it is not surprising that precast or prefabricated road repair products are now being introduced. The experiment performed in this study had to do with partial-depth precast concrete patches for PCC pavements.

Precast patching consists of prefabricating a supply of various size concrete slabs, stockpiling them near the pavement repair site, using a machine to cut holes to desired dimensions in the pavement, installing the slabs, and cementing them into place with an appropriate material such as a two-component epoxy grout system.

Slabs

Prefabricated slabs may be cast in various ways; however, for this experiment two methods were used. The majority of the slabs were cast by a hydraulic press designed for the purpose. The slabs were very dense and had high compressive strengths. All were cast in 2-in. (5.1-cm) thicknesses and in sizes ranging from 2 × 3 ft × 2 in.

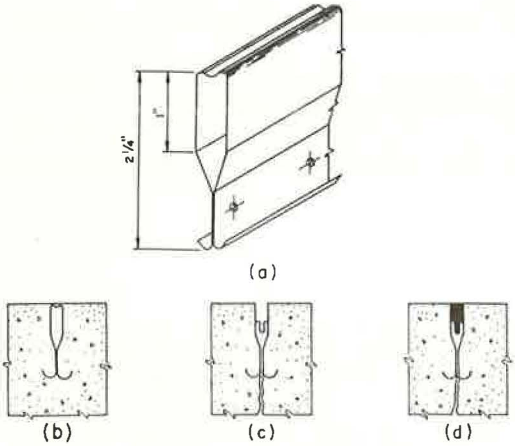

Figure 1. Tabular metal joint insert: (a) cross section, (b) as installed, (c) after crimping, and (d) after sealing.

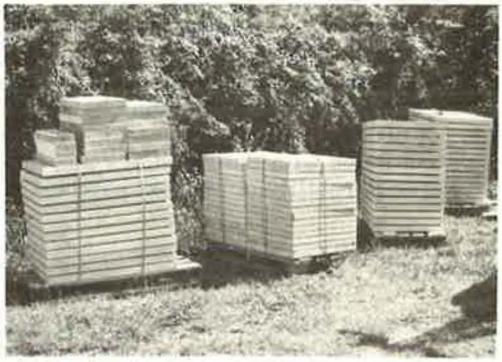

Figure 2. Stockpile of hydraulically pressed, precast concrete slabs.

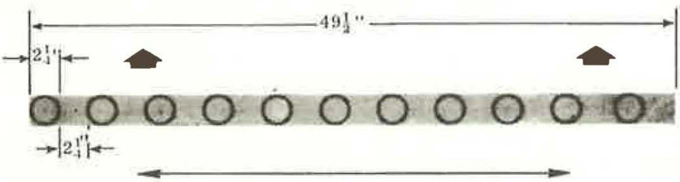

Figure 3. Configuration of cutting heads of the general purpose concrete repair machine.

Figure 4. General purpose concrete repair machine cutting a hole.

Table 1. Technical details of Klarcrete general purpose concrete repair machine.

Item	Value
Overall length, ft	14
Length without tiller, ft	10.37
Width, ft	7.5
Overall height, ft	4.5
Weight, lb	4,000
Power required, compressed air[a], ft^3/min at 100 psi	600
Cutting heads[b]	
Diameter, in.	2¼
Distance between heads, in.	2¼
Air consumption per head, ft^3/min at 100 psi	30 to 35
Life, hours	100 ± 25
Strokes per min	1,500
Maximum cutting depth, in.	4
Accuracy, in.	±⅛
Width of cut, in.	4.5 to 49.5

Note: 1 ft = 0.3 m. 1 lb = 0.45 kg. 1 in. = 2.5 cm. 1 ft^3 = 0.03 m^3. 1 psi = 6.9 kPa.

[a]The Klarcrete machine is pneumatically and hydraulically operated and pneumatically controlled on a sequential system.

[b]There are 11 tungsten carbide cutting heads, composed of a motor and a head; each head (except the first one) can be controlled individually. The cutting face is made up of 6 tips intersecting in the center of the head at 60 deg. Depth of the cut depends on forward speed of the machine.

(0.61 × 0.91 m × 5.1 cm) to 1 × 2 ft × 2 in. (0.31 × 0.61 m × 5.1 cm). Figure 2 shows the stockpile of hydraulically pressed slabs used on this project in the equipment yard adjacent to the job site.

Another type of precast slab used in the experiment, Wirand, was cast at the Virginia Highway and Transportation Research Council. It contained metal fibers for strength and was cast in the conventional manner. The Wirand slabs ranged in dimensions from 2 × 2 ft × 2 in. (0.61 × 0.61 m × 5.1 cm) to 1 × 1 ft × 2 in. (0.31 × 0.31 m × 5.1 cm).

Three of the pressed slabs were treated to produce a polymer impregnated concrete for the purpose of determining whether the impregnating process increases resistance to salt action. The treatment was a 9 to 1 mixture of methyl methacrylate and trimethylopropane trimethacrylate and 1 percent by weight of vazo 52 solution. Embeco 411 A was used for the cast-in-place patches.

Machines

The holes for the experiment were cut with two Klarcrete machines. These machines remove the pavement by striking it with percussive hammers, each of which delivers approximately 1,500 blows/min. The power source for the machines is compressed air. The general purpose concrete repair machine, as its name implies, was designed as a multiple purpose machine. It contains 11 cutting heads that operate independently. The heads are 2¼ in. (5.7 cm) in diameter and are spaced 2¼ in. (5.7 cm) apart. They are mounted on a carriage that allows vertical movement, and that in turn is attached to a transverse carriage that allows lateral movement. The lateral movement is necessary for the uniform removal of the concrete over the width of operation. The width of cut can be varied from 4½ in. (11.4 cm) (diameter of cutting head plus space between cutting heads) to 49½ in. (1.3 m) in 4½-in. (11.4-cm) increments by adding or deleting cutting heads. Figure 3 shows the configuration of the cutting heads (two-headed arrow indicates that the heads move to the right and left on a transverse carriage to cut area between).

The cutting heads, which require no lubrication and are free to rotate, break the concrete into small particles of a gradation not much larger than sand and cause no damage to the surrounding concrete. The machine works on the principle that concrete is stronger under compression than it is under tension. The concrete is compressed by the hammers, and, when the pressure is released, small amounts of concrete are expelled from the surface. The machine removes the surface by the number of impacts rather than the force of individual impacts. The general purpose concrete repair machine is capable of cutting a hole with square sides and flat bottom as large as 4 × 4 ft × 4 in. (1.2 × 1.2 m × 10.1 cm). Such large holes, in most cases, are not practical; therefore, the machine is designed so that hole sizes may be reduced by 4½-in. (11.4-cm) increments each time a cutting head is shut off. The other dimension is adjustable in 6-in. (15.2-cm) increments by stops on the frame of the machine. The depth of the hole was determined by measurement, and, when the proper depth was reached, the machine was shut off. A large number of hole sizes are possible. Figure 4 shows the general purpose machine cutting a hole. The technical and physical characteristics of the machine are given in Table 1.

In addition to the general purpose machine, a smaller machine designed exclusively for hole cutting was used. It required a compressor working at 250 ft^3 (7.1 m^3)/min at 100 psi (689.5 kPa). Its operation is similar to that of the larger machine although it has only four cutting heads and can cut a maximum size hole of only 1.5 × 2 ft (0.46 × 0.61 m). Like the larger machine, its hole-cutting dimensions can be adjusted by taking cutting heads out of action. The larger machine is self-propelled, and the smaller one is not. This is a disadvantage because its weight is too great to allow ease of movement and setup by hand by the operator. In Table 1, all of the data under cutting heads are applicable to the smaller machine, except the data pertaining to the width of cut and the information in the footnotes. Figure 5 shows a rear view of the smaller machine with the four cutting heads visible, Figure 6 shows the machine in operation, and Figure 7 shows a hole prepared for patching.

Figure 5. Rear view of smaller hole-cutting machine, cutting heads visible.

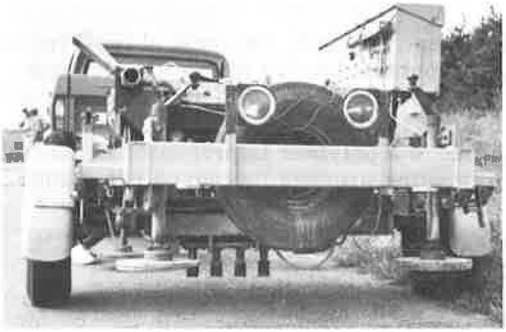

Figure 6. Smaller machine in hole-cutting operation.

Figure 7. Hole prepared for precast patching.

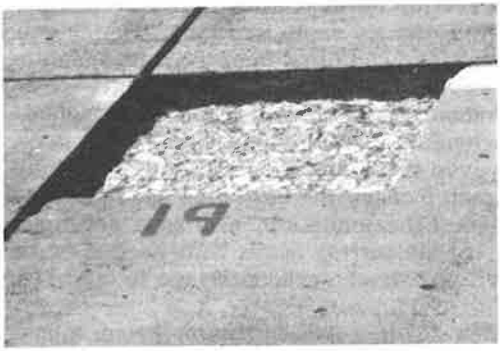

Table 2. Quantities specified for experiment.

Item	Quantit (ft^2)
Removal of pavement, 2-in. depth	408
Removal of pavement, 4-in. depth	20
Removal of pavement, 2- and 4-in. depth	150
Partial-depth patch, 4 × 6 ft × 2 in.	2
Partial-depth patch, 3 × 4 ft × 4 in.	1
Partial-depth patch, 2 × 2 ft × 4 in.	1
Partial-depth patch, 1 × 4 ft × 2 in.	1
Partial-depth patch, 4 × 3 ft × 2 in.	10
Partial-depth patch, 2 × 2 ft × 2 in.	25
Partial-depth patch, 1 × 2 ft × 2 in.	10
Wirand patch, 2 × 2 ft × 2 in.	10
Wirand patch, 1 × 2 ft × 2 in.	10
Cast-in-place joint spall and pavement spall repair	150

Note: 1 in. = 2.5 cm. 1 ft = 0.3 m. 1 ft^2 = 0.09 m^2.

Figure 8. Hole 1 after cutting and cleaning.

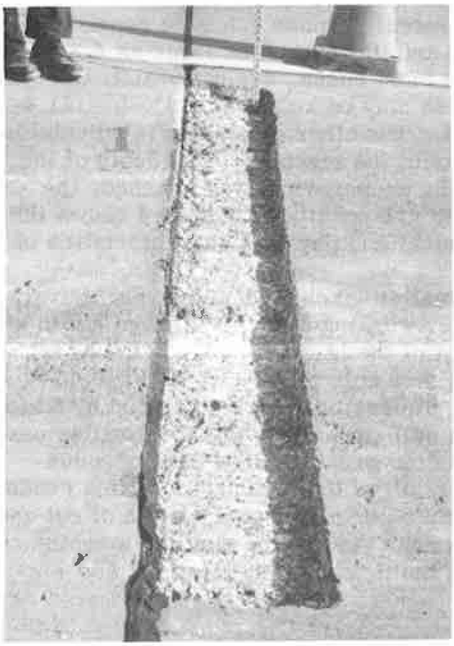

Figure 9. Patched area requiring more than one slab.

Epoxy

The epoxy used meets AASHTO M200-65. The formulation consisted of adding ½ gal (1.9 liters) of catalyst to 1 gal (3.8 liters) of resin and mixing them thoroughly for 3 min or more. Sand was then mixed with the epoxy until it reached the desired consistency. The ratio was approximately 5 to 10 parts sand to 1 part epoxy. A total of 56 gal (211.9 liters) were used, 52 from the United States and 4 from England. The epoxy from the United States appeared to do a good job, but a disadvantage was that it needed 3 hours at approximately 100 F (≈37.8 C) road temperatures to cure sufficiently to allow traffic on patches. The epoxy shipped from England cured sufficiently in 30 min.

EXPERIMENTS

On patch 1, because of the configuration of the deteriorated concrete, 1 × 10 ft (0.31 × 3.1 m), it would not be possible to adhere to the patch sizes designated in Table 2 [repairs were made from Parks Avenue to 3 miles (4.8 km) west of Parks Avenue]. The decision was made to remove only the deteriorated concrete and to saw the slabs if necessary. This procedure had an added advantage because the smaller machine could be kept operating since it is limited in the size hole it can cut (otherwise, it could have been used in the preparation of only 21 holes).

The experiment was performed on 15 working days in June 1974, when 90 patches were placed. For the holes for some patches, such as patch 1 (Figure 8), the cutting machines had to be repositioned three times. For others only one setup was necessary (Figure 7). Repositioning the machine greatly increased the time necessary for cutting a hole; in fact, almost as much time was required to set up and adjust for the cutting operation as was required to cut the hole. In many cases, however, more than one setup was necessary, and more than one slab was needed to fill the hole (Figure 9). When a slab of a not-available size was needed, it was sawed from a larger slab as shown in Figure 10.

The handwork necessary in preparing the holes consisted of removing the steel mesh with a small hand tool as shown in Figure 11. This resulted in the grid pattern in Figure 12. The handwork also consisted of removing small amounts of concrete at the few joints that had bad concrete below the level cut by the machine. Figure 13 shows a hole from which concrete along the joint had to be removed by hand. In such cases, the crack was filled with epoxy grout up to the level of the remainder of the hole, and the patch was installed in the normal manner. After a hole was prepared for patching, it was sounded to make certain all deteriorated concrete had been removed.

Since all holes were approximately 2.5 in. (6.4 cm) deep and the slabs were 2 in. (5.1 cm) thick, a 0.50-in. (1.3-cm) layer of epoxy grout was necessary to bring the patch up to the level of the surrounding pavement. The width of epoxy around the slab depended on the accuracy of the cut of the hole and the slab. However, the variance was from 2.75 to 0.50 in. (6.99 to 1.27 cm). Figure 14 shows crack widths for a typical patch. If there had been more exact control of hole configuration and slab size, less epoxy would have been necessary. However, other than the slight waste of material, no harm seems to have been done. Experience seems to show that painting improves the bond. Figure 15 shows the epoxy grout in the bottom of the hole. In the installation of the slabs, a slight excess of epoxy was forced up along the cracks. The excess was troweled off and the patch finished. To determine that a good bond had been obtained between the patch and old concrete, each precast patch was sounded after the epoxy had cured.

Table 3 gives the physical dimensions of the installed precast patches. Installation time includes the time required for moving and positioning the machine, cutting the hole, mixing the epoxy, and setting the slabs. The smaller patches required approximately 1 hour to install. The larger, more complicated patches, for which the machine had to be repositioned, took substantially more time to install. The average times for the operations involved are given in Table 4.

Figure 10. Precast slab being sawed to proper dimension.

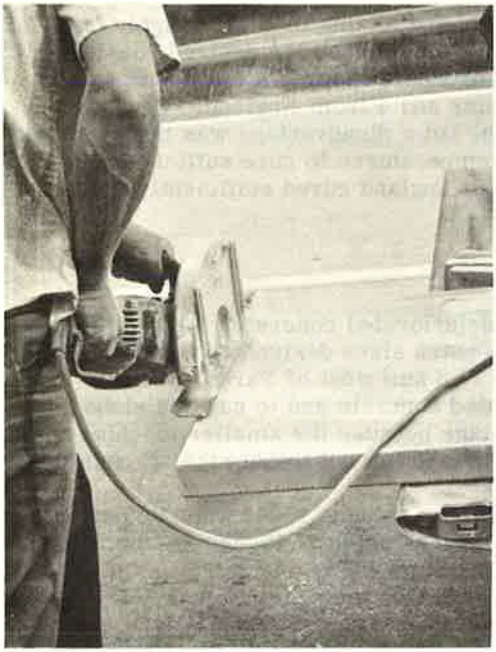

Figure 11. Steel mesh being removed from hole with hand tool.

Figure 12. Grid pattern left after removal of steel mesh.

Figure 13. Hole from which deteriorated concrete along joint had to be removed with hand tool.

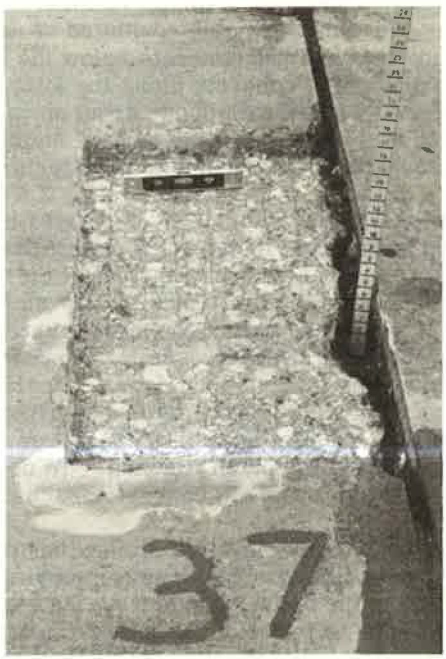

Figure 14. Dimensions of crack around patch.

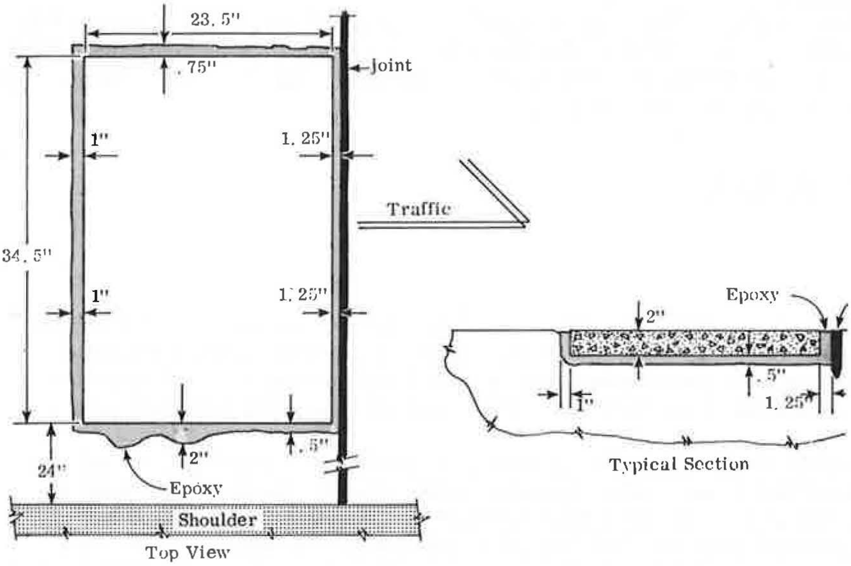

Figure 15. Half finished patch, epoxy grout in right portion of hole.

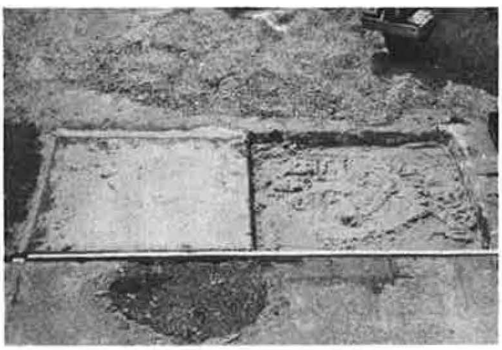

Table 3. Physical dimensions of installed precast patches.

Number of Patches	Patch Size[a] (ft)	Average Installation Time (min)	Total Area (ft^2)	Total Time (min)
1	1 x 1	56	1	56
15	1 x 2	61	30	915
1	1 x 7	146	7	146
1	1 x 10	220	10	220
14	1.5 x 2	61	42	854
1	1.5 x 3	112	4.5	112
1	1.5 x 4	102	6	102
14	2 x 2	72	56	1,008
14	2 x 3	87	84	1,218
5	2 x 4	92	40	460
1	3 x 4	133	12	133
68	—	—	292.5	5,224

Note: 1 ft = 0.3 m. 1 ft^2 = 0.09 m^2.
[a]Each at 2-in. (5.1-cm) thickness.

Table 4. Average times for patching operations.

Operation	Time (min)	Percentage
Setting up machine	17.4	23
Cutting hole	41.6	54
Mixing epoxy and installing patch	17.8	23
Total	76.8	100

Table 5. Data for cast-in-place patching.

Number of Patches	Patch Size[a] (ft)	Average Time per Patch (min)	Total Area (ft^2)	Total Time (min)
2	1 x 2	87	4	174
6	1 x 1.5	44.17	9	265
1	1 x 2.5	38	2.5	38
6	1.5 x 2	61.5	18	369
1	2 x 2[b]	63	4	63
1	2 x 3	126	6	126
2	2 x 4	68.5	16	137
1	2 x 6[b]	201	12	201
1	3 x 4	74	12	74
1	3 x 6	137	18	137
22	—	—	101.5	1,584

Note: 1 ft = 0.3 m. 1 ft^2 = 0.09 m^2.
[a]Each 2.5-in.-thick (6.4-cm) patch was cured for 8 hours.
[b]Not vibrated.

As given in Table 3, a total of 292.5 ft^2 (27.5 m^2) of precast patches were installed in 5,224 min (88 hours).

Table 5 gives a summary of the data for cast-in-place patching. A total of 101.5 ft^2 (9.43 m^2) in 22 patches were installed. In all of the 2-in.-deep (5.1-cm) patches except two, the wet concrete was vibrated. For cast-in-place concrete, this type of hole preparation is too elaborate and time-consuming.

PROBLEMS ENCOUNTERED

Equipment

In the first 2 weeks of the project, extensive machine failures occurred that extended the job. The smaller machine, which had been stored in the contractor's equipment yard for the winter, malfunctioned after cutting only 1 hole and was out of commission for 4 working days when the manufacturer's representative diagnosed the problem as a stuck valve.

The general purpose machine was worn when it came to the job and did not cut the holes to the proper dimensions. After operating at a reduced capacity for 5 working days, it was taken out of service for 2 working days for overhaul. The overhaul entailed putting all new cutting heads (11) and guide rollers on the hammer carriage. After this maintenance was performed, no more equipment problems were experienced during the project.

Materials

Not enough epoxy was stockpiled at the site to complete the precast patching, and, when it was used up, the operation had to be suspended for several days until a new supply came.

RESULTS

The two Klarcrete machines used to cut the holes functioned well after the previously noted maintenance was performed. All holes were cut to a 2.5-in. (6.4-cm) depth, and the steel mesh in the pavement occurred most often at approximately that depth. The machines would not remove the steel mesh, but it could be removed with a hand tool. The capability of the machines to cut a 4-in. (10.2-cm) depth was not determined. Of the 90 holes cut (68 for precast, 22 for cast-in-place), none required a depth greater than 2.5 in. (6.4 cm), although on a few, less than 10, a small amount of deteriorated concrete below that level was taken out with a hand tool.

The most efficient work combination consisted of one operator for each machine and three men to mix the epoxy and install the patches. One of these three assisted the machine operators when needed. When operating at an optimum, the two machines were barely able to keep ahead of the crew installing the patches.

On this first partial-depth precast concrete patching project in the United States, many pitfalls common to new methods were encountered: (a) casting three or four sizes of precast slabs based on the belief that they would take care of all situations and (b) casting the slabs in even increments of feet and inches (meters and centimeters). These practices sometimes make it necessary to cut the slabs to fit the holes. The slabs were cast at exactly 18 in. (45.7 cm); therefore, they did not fit the 18-in. (45.7-cm) holes cut by the small machine because at least a 0.25-in. (6.25-mm) crack must be left on each side for epoxy. The same thing happened when patching was done with slabs cast 2 ft (0.61 m) in one dimension. When five cutting heads are operating, the general purpose machine cuts a 22.5-in. (57-cm) width, and when six heads are operating, it cuts a 27-in. (69-cm) width. Neither of these matches the 24-in. (61-cm) dimension.

The 22 cast-in-place patches were all vibrated except two. The bottoms and sides of the holes were painted with a slurry of the patching material to enhance bonding between the old and new concrete. A curing membrane was sprayed on the patches, and the finished product was a professional job. However, hole preparation with the Klarcrete machines is too time-consuming and sophisticated to make it practical for this type of patching.

Precast patching was successful, but more field projects are necessary to increase production.

PLANNED EVALUATION

Not enough time has elapsed to gain any meaningful data on the durability of the patches placed during the experiment. However, two precast patches were placed on I-95 in Emporia, Virginia, in the summer of 1973 in a demonstration, and they have proved durable so far.

When the patching operations were under way, a sketch was made of each hole (a) showing all of the dimensions, irregularities, and any other important information and (b) showing the dimensions of the cracks between the slab and surrounding concrete (Figure 14). In addition, a photograph was taken of each hole to show areas next to the joint from which additional bad concrete had been removed and areas that would require backfilling with epoxy grout to bring them up to patching level. A photograph was also taken of the finished patch.

Based on these data and the information on the epoxy, it should be possible to diagnose the causes of any failures that occur. A road log has been prepared showing the exact location of each patch so that surveys may be made at 2-month intervals.

A report setting forth the findings will be written within a 3-year period.

COST COMPARISON

The following figures reflect only the cost for the areas where the contractor removed the deteriorated concrete and supplied the precast slabs. No cost data are given for the Wirand or cast-in-place patching. At a cost of \$25/ft^2 (0.09 m^2), the total cost for precast patching was \$5,900/236 ft^2 (22 m^2). On a cast-in-place project in the eastbound lanes, not included in the experiment, the cost was \$29.80/ft^2 (0.09 m^2). This is probably not a true cost comparison, and it is anticipated that the contractor will have to adjust his cost figures in the future.

CONCLUSIONS

1. Precast concrete patching is feasible.
2. The Klarcrete machines used to cut the holes did a creditable job.
3. Although the installation of partial-depth precast patching was deemed successful, more projects are needed in the 300 to 500-ft^2 (27.9 to 46.5-m^2) range to develop a methodology for increasing output.
4. Although the epoxy obtained from United States sources met AASHTO standards and apparently worked well, the 3-hour curing time was excessive and defeated one of the purposes of the experiment. However, the 4 gal (15.1 liters) shipped from England cured quickly enough to allow traffic on the patches in 30 min. This proves that rapid opening to traffic is possible.
5. The most efficient working arrangement was one operator for each machine and a patching crew of three men, one of whom assisted the machine operators when necessary. The two machines kept one patching crew busy.
6. Precast concrete patching projects should have a bench type of masonry saw on

the job site capable of sawing precast slabs to exact dimensions. It is not practical to try to cast all of the different size slabs that may be needed.

7. The steel mesh in the pavement did not cause a problem in precast patching.

8. Adequate supplies of materials should be stockpiled before beginning the project.

9. To ensure a neat job, a canvas covering should be spread on the road surface where epoxy is being mixed to catch the drippings.

10. Preparation of holes by the Klarcrete machines to exact dimensions for cast-in-place concrete patching is an unnecessary sophistication.

ACKNOWLEDGMENTS

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The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.

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