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Hazardous Materials Transportation, Work-Zone Traffic Control, and Traffic Marking Materials

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Foreword

Papers in this Record address four topics: identification and transportation of hazardous materials, handling traffic through highway work zones, evaluation of traffic marking materials, and optimization of highway maintenance equipment use.

Minimizing risk during the transportation of hazardous materials entails a risk assessment based on available data sources and shipment routings that minimize risk. Abkowitz and List offer several recommendations to improve the quality of hazardous materials transportation incident and accident information. Saccomanno et al. provide an interactive model for routing shipments of dangerous goods through an urban road network. Weck discusses the identification of hazardous waste sites in planning transportation projects and how to either avoid or clean up such areas.

An authority in one state estimates that one-fourth of the highway system will undergo reconstruction, rehabilitation, or pavement maintenance every year and that most of that work will be done while traffic is maintained through the work area. Clearly, traditional approaches to construction traffic control are inadequate to cope with obstructions of such magnitude. Burritt and Guenther offer a comprehensive analysis of traffic operations throughout Colorado's Glenwood Canyon construction program, addressing many issues and suggesting an innovative approach for handling traffic. Krammes et al. report on several applications of a computer model, QUEWZ, developed in 1982 as a tool for planning and scheduling freeway work-zone operations and document two enhancements that have been made to improve the utility and accuracy of the model. Ullman and Levine and Booker et al. discuss methods to improve the process of flagging traffic and to reduce costs at work sites: a portable fixed-time signal system and a temporary stop bar and oversized sign paddle.

Manufacturers and suppliers continuously introduce new materials that purport to offer significant advantages, and the search for objective processes by which to judge the validity of the claims is also a continuing one. A further aim is to establish true requirements. One of the areas in which this process is most obvious is traffic marking materials. Bhavsar's recommended measures of snowplowable raised pavement marker reflector wear are aimed at encouraging the use of objective measures to provide a basis for standardization of wear measures. Bryden and Lorini describe accelerated-wear tests of traffic paints on portland cement concrete and asphalt concrete pavement.

In the last area, Sinha et al. review an optimization procedure for assigning equipment to routine highway maintenance activities so as to minimize total fuel consumption.

Hazardous Materials Transportation Incident-Accident Information Systems

MARK ABKOWITZ AND GEORGE LIST

As concern over the safe transport of hazardous materials continues to grow, public officials are placing greater emphasis on the ability to conduct analyses of present practices and future policy initiatives. The capability to do this effectively is directly dependent on the quality and availability of information on previous transport accidents and incidents involving hazardous materials cargo. The objective of this paper is to explore the reporting requirements of hazardous materials transport incidents and accidents and to determine what use is and can be made of the information that is collected and stored. It is generally concluded that the primary reporting system offers considerable information from which to conduct policy analysis. However, the quality of this information has been subject to considerable criticism. Although the secondary sources of data are, in some cases, quite good, the incongruences among secondary databases and with the primary database are such that significant improvements in the primary information system are necessary. Several recommendations are made to improve the quality of hazardous materials transportation incident-accident information. They are not resource-intensive and deserve serious consideration in light of the health threats posed by hazardous materials releases.

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The objective of this paper is to explore the reporting requirements of hazardous materials transport incidents and accidents and to determine what use is and can be made of the information that is collected and stored. For the purposes of this study, hazardous materials are defined by statute [Hazardous Materials Transportation Act (HMTA)] and by regulation (49 CFR, Part 171.8, 1984) as substances and materials in quantities and forms that the Secretary of Transportation has found may pose an unreasonable risk to health and safety, or to property, when transported in commerce. The approximately 2,400 materials classified as such are listed in 49 CFR, Part 172 *(1)*.

Inclusive in this list are several substances and wastes classified as hazardous in order to coordinate the regulatory program of the U.S. Department of Transportation (DOT) with that of the Environmental Protection Agency (EPA). The primary reason for designating these materials as hazardous is their long-term effects on health and the environment *(2)*. For each substance, EPA has established a "reportable quantity" (RQ) that indicates the quantity and concentration of a chemical that could pose a threat of pollution. RQ's for most substances are 1 lb, although EPA is currently studying the effects of changing the RQ level *(3)*. Packages containing more than the RQ of the hazardous substance are subject to DOT regulation. DOT regulations also apply to hazardous wastes that are subject to EPA's manifest system under the Resource Conservation and Recovery Act (RCRA).

To carry out the regulatory requirements imposed by the HMTA, the Secretary of Transportation established the Office of Hazardous Materials Transport (OHMT), which was formerly known as the Materials Transportation Bureau. OHMT is responsible for regulating hazardous materials transport safety, including bulk transportation by water, which is promulgated by the U.S. Coast Guard [46 USC 170 and 391(a)]. OHMT's responsibilities also include coordination among the various DOT modal administrations and other federal agencies that are involved in the transport of hazardous materials.

The data for analyzing hazardous materials incidents emanate from the reports filed by carriers and others responsible for reporting to various agencies under federal regulations. Each database potentially applicable to the hazardous materials transport problem is described separately in the following discussion. These information sources and their relationship appear in Table 1.

OHMT HAZARDOUS MATERIALS INCIDENT REPORTS (HMIR)

In 1971 this database became the centralized federal system for uniform incident data. Before that time, hazardous materials regulatory authority was divided among the DOT modal administrations. Each agency independently developed criteria reflecting their particular needs for data collection and analysis. A wide range of hazardous materials reporting systems evolved, which resulted in redundant reporting, inconsistencies in definition and coverage, and reporting gaps.

A transportation-related incident is defined as any unintentional release of a hazardous material during transportation, loading or unloading, or temporary storage related to transportation. This includes releases of hazardous wastes and RQ's of hazardous substances discharged during transport *(4)*. Every incident must be reported to OHMT in writing (49 CFR, Parts 171 and 174–177), with the exception of consumer commodities that present only a limited hazard during transportation (ORM-D class), electric storage batteries, and certain

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TABLE 1 INCIDENT/ACCIDENT DATABASES

						Exclusive Focus	
Database	Maintaining Agency	Years	Modes	Accidents	Incidents	Hazardous Materials	Transportation
Hazardous Materials Incident Reports (HMIR)	Research and Special Programs Administration, DOT	1971–present	All	Yes	Yes	Yes	Yes
Commercial Vessel Casualty File (CVCF)	U.S. Coast Guard	1963–present	Marine	Yes	No	No	Yes
Pollution Incident Reporting System (PIRS)	U.S. Coast Guard	—	All	Yes	Yes	Yes	No
Truck Accident File (TAF)	Bureau of Motor Carrier Safety, DOT	1973–present	Highway	Yes	No	No	Yes
Railroad Accident File	Association of American Railroads	1973–present	Rail	Yes	Yes	Yes	Yes
Air Accident File	FAA	—	Air	Yes	Yes	No	Yes
National Accident Sampling System (NASS)	NHTSA	1983[a]	Highway	Yes	No	No	Yes
Fatal Accident Reporting System (FARS)	NHTSA	1983[a]	Highway	Yes	No	No	Yes
National Response Center	U.S. Coast Guard	—	All	Yes	Yes	Yes	No
NTSB File	National Transportation Safety Board, DOT	—	All	Yes	No	No	Yes
Department of Energy database	Sandia National Laboratories	—	All	Yes	Yes	Yes	Yes
Washington State Accident File	Washington State Utilities and Transportation Commission	—	Highway	Yes	No	No	Yes

[a]"Hazardous materials" flag.

paints and related materials. These exceptions were established in 1981 and have decreased the number of reported incidents considerably. The exceptions, however, do not apply to incidents involving aircraft or those involving the transport of hazardous waste. The written response must be prepared by the carrier on DOT Form F5800.1 and must be submitted to OHMT within 15 days of discovery of the release *(5)*. Although carriers are required to report, any interested party may do so.

An additional telephone-reporting requirement is imposed on carriers when an incident has resulted in one or more of the following consequences as a direct result of the hazardous material:

- Fatality;
- Serious injury that requires hospitalization;
- Estimated carrier or other property damage exceeding $50,000;
- Fire, breakage, or suspected radioactive contamination involving shipment of radioactive material;
- Fire, breakage, or suspected contamination involving shipment of etiologic agents; or
- Situation of such a nature that, in the judgment of the carrier, should be reported.

The telephone report must be communicated immediately to the National Response Center (NRC), which is staffed 24 hr a day by the U.S. Coast Guard, but which handles the reporting of all significant hazardous materials spills under agreements with DOT and EPA. NRC, established in 1974, provides facilities, communication, information storage, and other needs for coordinating emergency response. It has two 24-hr toll-free telephone lines to receive the notifications and several other lines to relay the calls to response agencies that may need to know of the release.

The telephone report must include the following information:

- Name of reporter;
- Name and address of carrier represented by the reporter;
- Phone number where the reporter can be contacted;
- Date, time, and location of the incident;
- Extent of injuries, if any;
- Classification, name, and quantities of hazardous materials involved, if such information is available; and
- Type of incident and nature of hazardous materials involvement and whether a continuing danger to life exists at the scene.

This information is transmitted to the Transportation Systems Center every evening, where it is subsequently retained and managed by OHMT.

In many cases, carriers have made their telephone contact with CHEMTREC, a chemical transportation emergency center established in 1971 by the Chemical Manufacturers Association. On request, CHEMTREC provides referrals to those at the site of a transportation emergency involving hazardous materials. Since 1980, CHEMTREC has been officially required to notify the NRC of "significant" hazardous materials transportation incidents, those that cause, or have the potential for causing, considerable harm to the public or the environment. Despite this cooperative arrangement, a call to CHEMTREC only fulfills the NRC telephone reporting requirements, but it does not fulfill the federal written-report requirements.

Although spill reporting is a regulatory requirement, in practice it is handled on a voluntary basis. The incentive for reporting as required is to avoid the possibility of a civil or a criminal penalty; the latter can be imposed if a person knowingly commits an act that violates an HMTA regulation. Civil penalties, which are more common than criminal penalties, can include a liability of up to $10,000 per violation, or one years' imprisonment, or both. Criminal penalties can be a fine of up to $25,000 or five years' imprisonment, or both.

However, because OHMT has very few inspectors to ensure compliance with these reporting requirements, and there is a general shortage of inspectors within the DOT modal administrations, it is basically agreed that the federal enforcement program does not by itself create an adequate deterrent to violations of the reporting requirement. It has also been suggested that even when violators are penalized, the level of the penalty is insufficient to deter future violations. The reason is that the costs of compliance are greater than those of the infrequent penalties. Thus, some operators may consider penalties to be merely an occasional cost of doing business *(2)*.

In support of this claim, it has been estimated by one source that 30 to 40 percent of reportable hazardous materials incidents are never reported (S. W. Ballou, Iowa Department of Water, Air, and Waste Management, May 1985). A recent study conducted by the Office of Technology Assessment (OTA) has found that the nonreporting problem may be even more acute than previously estimated *(6)*. EPA Region 7 officials have independently estimated that only about 10 percent of reportable releases under 100 gal are reported to EPA, the states, or the NRC if the substance released is not extremely hazardous. If 5 gal of an extremely hazardous substance were spilled, it would probably be reported; 90 percent of releases over 100 gal are reported; and 20 percent of all releases of polychlorinated biphenyl (PCB) are reported *(3)*. Transport-related incidents constitute 26 percent of the incident reports compiled by EPA *(7)*.

This information system has also been the subject of considerable criticism from the General Accounting Office (GAO) for the following reasons *(8)*:

1. OHMT is not receiving reports on all incidents because it relies on voluntary reporting from carriers;
2. Companies involved only in the loading, unloading, or storage of hazardous materials (e.g., shippers, freight forwarders) are not required to submit hazardous materials incident reports;
3. Reports are not required by OHMT for incidents involving hazardous materials shipped in bulk by water;
4. DOT has elected not to regulate firms involved only in intrastate transportation or to require them to submit hazardous materials incident reports;
5. OHMT has no systematic procedure for refining reported data that are incomplete or inaccurate; and
6. Because of the time limit on reporting and because only the carrier's perspective is solicited, the total consequence of an incident can be understated significantly.

Each of these factors works to understate the overall impact of hazardous materials transportation incidents in the United States.

Illustrations of these disparities have been noted in studies by GAO and others. GAO selected 30 hazardous materials transport incidents between 1976 and 1979 and requested OHMT data on them. OHMT had received reports for only 12 of the incidents. The 18 unreported incidents, according to news reports, resulted in 18 deaths, 9 missing persons, and at least 187 injuries. Concerning damage estimates, in investigations of five accidents involving the transport of hazardous materials between 1972 and 1979, the National Transportation Safety Board (NTSB) estimated the overall damage to be $42 million as compared to an estimate of $10.1 million from OHMT reports *(9)*. A more detailed study on nonreporting and misreporting conducted by OTA has substantiated these disparities *(6)*.

Despite the objections to the HMIR database, in many respects it serves as the most relevant database for conducting hazardous materials transport incident and safety analysis. The HMIR database is the only one exclusively devoted to hazardous materials transport incidents, and as such, it includes a number of descriptors that can be used to examine issues in packaging, labeling, cause, and public safety that might not otherwise be possible.

If the deficiencies in the database are accepted as stated, the total volume of hazardous materials incidents is underestimated. However, for the purposes of deriving distributions of events, causes, and consequences, and for some multimodal comparative analyses, the HMIR database may still be representative. The approximately 135,000 records that now make up the HMIR database may permit comprehensive analysis on the basis of statistical considerations.

SUPPLEMENTARY DATABASES

Independent of the OHMT incident-reporting system are several accident-reporting systems maintained by various DOT modal administrations. The term "accident" refers to a vehicular accident; most hazardous materials transport incidents are not caused by vehicular accidents. These reporting systems have been designed to cover all transportation accidents under the jurisdiction of the respective modal administrations, not just those involving hazardous materials. In most cases, however, there are special identifiers in the reporting format to permit the designation of an accident that involves hazardous cargo. This may be a particularly important form of secondary data, because the accident reports are usually based on an independent set of reporting procedures from the OHMT procedures, and thus are not subject to the same deficiencies as those noted for the OHMT information system.

Several sources of information outside of DOT also exist that, in some fashion, address the subject of incidents and accidents involving the transportation of hazardous materials.

Modal Administrations

In addition to coordinating activities with OHMT, the DOT modal administrations conduct their own record-keeping procedures for accidents under their purview. In many cases, the capability exists to isolate accidents that involve the transport of hazardous materials.

U.S. Coast Guard

The Coast Guard maintains two databases that include recognition of accidents or incidents, or both, involving hazardous materials: the Commercial Vessel Casualty File (CVCF) and the Pollution Incident Reporting System (PIRS).

CVCF includes vessel accidents (domestic and foreign) occurring in U.S. waters that meet one or more of the following reporting criteria:

- Actual physical damage to property in excess of $25,000;
- Material damage affecting the seaworthiness, maneuverability, or efficiency of a vessel;
- Stranding or grounding (with or without damage);
- Loss of life; or
- Injury causing any person to remain incapacitated for a period in excess of 72 hr, except injury to harbor workers not resulting in death and not resulting from vessel casualty or vessel equipment casualty.

These data have been collected since 1963, and the only major reporting changes have been a move to an alphanumeric format in 1980 and a change in the damage threshold in August 1982 from $1,500 to $25,000. Categories in each record include vessel characteristics, event, cause, fatalities or injuries, and monetary damage. The major deficiency in the file is the lack of a commodity classification in the database. However, there are specific vessel codes that indicate whether the vessel was carrying hazardous cargo *(10)*.

The PIRS database consists of reports generated as required by the Federal Water Pollution Control Act (1965) and the Comprehensive Environmental Response, Compensation, and Liability Act (1980) (CERCLA). It includes all polluting spills into U.S. waters, including those occurring during transport. There is a special identification for transport-related spills, and materials are identified by name, so hazardous substance spills during transport can be tracked. The database also includes the quantity released, cause of the incident, and the date and location. In addition, the file contains potential incidents in which the Coast Guard was informed but a spill did not materialize *(11)*.

According to Coast Guard officials, the PIRS database is rather unreliable because of unedited files in which major errors often appear. Furthermore, only closed cases are available for analysis from the database, so recent cases—those that are tied up in the courts and those for which the Coast Guard district has neglected to update the file to show that a case has been closed—are not available and bias any conclusions reached by using the data. The Coast Guard is in the process of designing methods to address these problems.

The Coast Guard databases may be viewed as filling a rather obvious gap in the HMIR database, which is particularly weak in the marine mode. This is due in part to the lack of OHMT regulatory enforcement of bulk movements shipped by water.

Federal Highway Administration

FHWA's Bureau of Motor Carrier Safety (BMCS) maintains a database on accidents that has been operational since 1973. It includes any motor carrier accident in which a fatality or injury occurred or for which there was at least $2,000 in property damage. Reports are filed on Form 50-T, the format of which has remained relatively stable through the years. The BMCS database includes carrier identification and address, location of the incident, characteristics of the event, cause, information on the cargo, and consequences of the accident. The carrier identification, cargo description, and certain accident characteristics are such that congruence between the HMIR database and BMCS database may be achievable for incidents caused by vehicular accidents.

Federal Railroad Administration

FRA maintains its own accident-incident database from information generated by railroads, inspectors, and OHMT. Although the database includes events earlier than 1974, access to the pre-1974 data is rather difficult. The information included is similar to that described for the Coast Guard and FHWA databases. FRA has its own definition of incidents and accidents. An incident is an event that results in a death, reportable injury, or property damage. If the event results in a death or reportable injury and if damages exceed a threshold of $4,900, the event is classified as an accident. The threshold value has been increased by FRA over the years to approximate constant real value.

FRA performs a number of internal consistency checks to strengthen the validity of the database. These include the elimination of double-counting of events when more than one railroad files a report, spot checks of suspicious events, and occasional audits of railroad internal records.

During the past 10 years, more than 80,000 records have been included in the FRA file. Approximately 1,000 of these have involved releases of hazardous materials.

FRA also maintains an OHMT-enhanced database on hazardous materials incidents. The enhancements include the addition of accident location information, railroad code, and Standard Transportation Commodity Code (STCC) designation.

Federal Aviation Administration

The FAA maintains a computerized accident-incident database at their National Field Office in Oklahoma City. It consists of air accidents officially reported to NTSB and reports filed by FAA field inspectors. FAA makes a distinction between an accident and an incident on the basis of the dollar damage incurred in the reported event. The FAA database includes the pilot involved, the carrier, time of day, and other descriptors such as contributing circumstances and accident (incident) severity. Apparently it is possible to identify hazardous materials accidents and incidents in this database, because, according to FAA officials, 11 accidents and incidents involving hazardous materials have been reported in the past 5 years.

National Highway Traffic Safety Administration

NHTSA's National Center for Statistics and Analysis maintains accident data on police-reported accidents, including those that resulted in nonfatal injury or property damage, or both. The data are typically collected by each state under contractual agreement with NHTSA.

The file of reported accidents, called the National Accident Sampling System (NASS), was developed to provide an automated, comprehensive national traffic accident database. The accidents investigated and recorded in NASS are a probability sample of all police-reported accidents in the United States

(12). The data collection for a NASS-selected accident is very involved and includes characteristics of the accident, driver, occupants, and vehicle. Although the specific commodity being carried is not described, sufficient information exists to track accidents that are likely to have contained hazardous materials cargo. In fact, recently a hazardous materials "flag" has been added to the record description. However, outside of the date and location of the accident, there appears to be little or no congruence with the data collected by OHMT. Even so, the characteristics of the driver, road, and traffic may be important determinants of hazardous materials accidents for which OHMT does not have the appropriate information.

Those accidents that result in loss of human life are classified separately in the Fatal Accident Reporting System (FARS). The FARS file contains data on vehicles and persons involved in fatal accidents, defined as an event in which an accident-related death occurs within 30 days of the accident *(13)*. FARS is not a national sample; rather, it includes all fatal traffic accidents that are reported in the United States. Other than this distinction, however, the information collected parallels the NASS data and is subject to the same critique as that noted previously.

Other Useful Databases

The following information systems may also be useful in analyzing hazardous-materials transport safety. They are maintained by other federal agencies, state and local agencies, carriers, and trade organizations.

National Response Center

Although telephone reports to NRC are primarily intended to stimulate a response, the information provided in these reports can be used for policy analysis. Data items include the location of the incident, mode of transportation involved, material involved, and quantity released. The material definitions are coded differently than those in the HMIR, and causal factors are not considered in any fashion. However, the NRC database does provide a more balanced portfolio of incidents by various modes, particularly with regard to marine transport.

Environmental Protection Agency

EPA regional offices have personnel to receive notifications of releases of hazardous substances. These notifications are integrated into a regional incident-reporting system. Typical reports include the incident date, company involved, spill location, nature of the emergency, material spilled and volume, source of the spill, responding agency, nature of the response, and resolution. In the case of EPA Region 7, this information is in a computerized file.

EPA also receives the NRC reports and uses this information in concert with incidents reported to EPA regional offices, states, and local governments to formulate regulatory policy. Attempts are now being made to use the NRC reports as a management information system to support EPA initiatives.

National Transportation Safety Board

NTSB receives the NRC telephone reports, which are used to determine whether to proceed with an investigation. NTSB's investigation of transportation accidents is a multimodal activity. Their jurisdiction for conducting an investigation is based on the definition of a major vehicular accident as given for each mode in CFR 49.

An NTSB investigation begins with a multiple-day field investigation involving the shipper, carrier, government agencies, associations, and other interested parties. A report is subsequently generated that goes through several cycles of review and comment before it is finalized. The primary purpose of the report is to make recommendations to improve transportation safety on the basis of findings from the accident investigation.

A major advantage of the NTSB process is that the investigations involve other participants besides the carrier, are extremely thorough, and take place over a longer time frame, so that the full impact of the accident can be more accurately identified. As noted by GAO in their critique of the HMIR database, the damages reported by the carrier to OHMT often substantially underestimate those reported by NTSB *(8)*.

NTSB does maintain a database on the vital statistics of each investigated accident. Railroad and aviation accidents are stored in computer files. Highway and marine accidents are stored on coding sheets but have not as yet been logged into the computer system.

Department of Energy

The Department of Energy (DOE) maintains a database on all radioactive materials incidents based on the HMIR file and information from the Nuclear Regulatory Commission on the loss of control of radioactive materials. The database consists of approximately 70 percent HMIR records and 30 percent Nuclear Regulatory Commission records. It is on line, and is maintained by Sandia National Laboratories.

Nuclear Regulatory Commission

Besides the aforementioned activity, the Nuclear Regulatory Commission is the lead agency in conducting investigations of transport accidents involving radioactive materials. These investigations have focused on mechanical analyses of the containers involved in the accident for the purpose of improving their safe use in transporting radioactive materials *(14–17)*.

State and Local Agencies

Accident-incident databases maintained by state and local agencies vary considerably depending on the authorities involved and the level of commitment that has been made to managing the hazardous materials transport problem.

On the basis of limited observation, state and local agencies appear to be more directly involved in accident-reporting systems than in incident-reporting systems and focus much of their attention on the highway mode. This likely is due to the role of the state and local police in reporting traffic accidents and a more established and coordinated network of accident management. Some states do, however, have mandatory reporting of hazardous substance releases similar to CERCLA requirements, although many local agencies are unaware of these reporting requirements *(2)*.

However, there have been state and local attempts to focus on hazardous materials incidents. Much of this activity has been funded by OHMT in the form of demonstration projects to examine capabilities for hazardous materials accident prevention and emergency response.

The first of these projects, completed in 1981, was conducted by the Puget Sound Council of Governments (PSCOG). As part of its study, PSCOG examined hazardous materials movements and incidents within the region. Subsequent projects have been conducted by the state of Massachusetts; the cities of New Orleans, Memphis, and Indianapolis; the Association of Bay Area Governments (San Francisco); and Niagara County, New York. Although the grantees have, in some cases, made efforts to collect incident data from local sources, often the HMIR database has been accessed to identify incidents that have occurred in the study region *(18)*.

Other state and regional projects have explicitly examined hazardous materials incidents, but have relied heavily or exclusively on HMIR for their data. These include an analysis of hazardous materials transport by rail conducted by the state of New Jersey *(19)* and a multimodal study of the transportation of hazardous materials in the New York–New Jersey region *(9)*.

At the state level more-sophisticated applications center around the use of computerized accident record-keeping systems used in concert with flow data to determine accident rates and high-risk locations in the highway network. In the states of Utah, Washington, and New York, for example, computerized accident record-keeping databases are maintained that contain police accident investigation reports. Typically, these reports include, when a heavy truck is involved, the carrier name, vehicle type, contributing circumstances, accident severity, and so on. In the case of the state of Washington, the type of cargo (United Nations Code) is also included.

This type of database permits the extraction of heavy-vehicle accidents in which hazardous cargo was involved (or was likely to have been involved). This information can be portrayed against movement data to determine accident rates of vehicles transporting hazardous cargo, which can subsequently be used in the computation of transport risk profiles and the identification of safer procedures for routing hazardous materials. Although the capability to do this exists in the states of Washington and New York, the fragmented location of accident and movement data and their relationship with the offices responsible for policy analysis have served as constraints. These states are, however, moving in the direction of conducting improved analyses with those data that they collect and maintain.

The state of Maryland has largely overcome these problems. Several years ago, Maryland began a surveillance system of hazardous cargo movements at multiple checkpoints and different times of the day. It also instituted a state incident-reporting system by which any hazardous materials incident resulting in a reported spill is entered into the database. These two sources of information are subsequently compared to determine the level of hazardous materials transport safety in the state. This information has been used to successfully demonstrate a preferred nuclear materials routing system in Maryland. It should be noted that the accomplishments in Maryland have come after 10 years of activity and significant coordination among state agencies.

Carriers

Virtually all carriers retain copies of reports on accidents and incidents that they have filed with the appropriate authorities. However, personal contact with a few carriers has shown that the method used for reporting information on Form F5800.1 is rather arbitrary. For example, there was a consensus among carriers that the primary purpose of the form was to record an incident, but not to establish the accuracy of the details involved in the incident. For example, if the damage is rather small, it is often reported as no damage. Furthermore, when the damage is measurable, the carriers usually report the out-of-pocket cost and often include only the loss of cargo and not the cleanup cost.

In fact, beyond the reporting requirement to OHMT, there is little evidence that the incident reports are usually internally for any analysis purposes, not even for safety of operations. The carriers who were contacted also indicated that the 15-day reporting requirement is too short and that it is inappropriate for the carrier to assume the reporting requirement for loading and unloading incidents because they do not perform this function and often are unaware that an incident has occurred or do not know the details concerning it.

Association of American Railroads

The Association of American Railroads maintains its own hazardous materials incident database; the sources used are the inspector, the railroad, Form 5800.1, CHEMTREC, and telephone reports. Information includes date, incident location, incident type, source of the data, deaths and injuries, and estimated damage. The damage estimates can be segmented by equipment, lading, and fire and other damage. This database dates back to 1973.

REGULATORY USES OF DATABASES

The previously described databases serve a very important purpose for DOT, its modal administrations, and other agencies in terms of inspection, enforcement, and equipment requirements.

The size of the community involved with hazardous materials regulation is such that inspection of every facility, manufacturer, shipper, carrier, and so on, is infeasible, and modal administrations are required to use a variety of criteria to determine how best to deploy their finite inspection resources. As a rule, violation and incident experience are the indicators most frequently used to identify areas on which to concentrate their inspection efforts. The Coast Guard, for example, has redirected its inspection efforts toward "high-priority" vessels, the definition of which includes a vessel with a previously reported hazardous materials incident. BMCS and FRA also use selection criteria to determine inspection priorities, which are based in part on incident experience *(5)*.

Statistics generated by the hazardous materials incident databases are also used internally to measure program effectiveness, to improve prevention by identifying and analyzing causes and events, and for general regulatory and enforcement analysis. For example, OHMT is interested in the data for regulatory evaluation concerning packaging requirements.

BMCS uses its database for cargo container analyses. In the case of the railroad industry, DOT has used incident-accident data to examine container specifications for tank cars. This resulted in amendments to CFR 49 requiring thermal protection or insulation against external fire sources, tank-head protection against punctures, coupler modifications to resist disengagement, and other improvements to new cars or to existing equipment used to transport hazardous chemicals under pressure *(20)*.

There is reason to believe that incident-accident databases can be used to improve emergency response and disaster preparedness. For example, knowledge of locations with high accident frequency and of the flow of hazardous materials provides communities with a better understanding of the probability of an incident and the materials likely to be involved.

There has also been a broad set of requests for both accident and incident data from the private sector, including the legal profession, industry analysts, private citizens, consultants, and university researchers. In most cases, these are handled through distribution of a hard copy of the requested materials. Some databases are also accessible through on-line query by telephone access.

CONCLUSIONS AND RECOMMENDATIONS

This paper has focused on the reporting and data collection of accidents and incidents involving hazardous materials transport. As noted, the regulatory environment has evolved to a point at which OHMT should be the repository of information on hazardous materials transport incidents. Data collected by DOT modal administrations focus more generally on vehicular accidents, yet permit the identification of accidents that involve hazardous materials. Other databases serve to identify accidents and incidents involving hazardous materials. Because of this connectivity capability, the availability of these secondary databases in a supporting role is invaluable.

The HMIR database maintained by OHMT has become the best source of data on the causes, events, and consequences surrounding hazardous materials incidents. However, several reporting and data collection deficiencies exist that make it difficult to conduct unbiased analyses of hazardous materials transport incidents and safety without additional verification. The most useful sources of additional verification appear to be the NRC telephone reports, NTSB investigations database, state and federal agency accident files, and other related databases.

The NTSB damage estimates and probable causes are likely to be more accurate than those reported to OHMT within 15 days by the carrier. The number of incidents and accidents involving hazardous materials that go unreported to OHMT can be identified, in some respects, by examining accident reports filed with the modal administrations, state agencies, and NHTSA and incident reports filed with NRC, and comparing them with incidents reported in the HMIR file (even after this process, the number of unreported events may still be significant). This is particularly important in the case of the marine mode, for which reports on incidents involving hazardous materials transported in bulk are not requested by OHMT.

Although the additional sources of information are extremely important, in practice it is quite difficult to establish congruence among any of the databases. There are several reasons for this, the most important of which are different definitions of accidents and incidents, criteria for a reportable event, ability to track a hazardous cargo movement, and level of detail concerning specific commodity, contributing factors, consequences, and so on. Thus, the secondary data are not an adequate substitute for an improved primary information system.

A number of suggestions have been made to improve the accuracy and completeness of hazardous materials incident reporting. These recommendations focus on the contents of the incident report form, criteria and procedures for incident notification, and internal management of reported information *(6)*.

For example, the format of Form F5800.1 could be modified so that it is more standardized and does not allow too much flexibility in response, which has led in the past to incomplete reports and subjective judgments by OHMT data entry clerks. This would also simplify the data entry process and diminish the likelihood of redundant codes for the same data entry field. The amount of information required on Form F5800.1 does not appear to be excessive when contrasted with other incident-accident reporting systems, and could actually be expanded to include a few additional characteristics of the incident, if desired.

OHMT should work to change the idea that incident reporting is voluntary by policy initiative or by new legislation requiring mandatory reporting of incidents meeting the reporting criteria. In order to enforce more stringent requirements, the severity of penalties for noncompliance must be increased substantially. In response to issues raised by carriers, it would be beneficial to extend the reporting limit beyond 15 days, and perhaps also require shippers and receivers to file written reports when incidents involve loading or unloading operations.

Finally, OHMT management should focus internally on improving the completeness of filed reports, identifying and mediating misreporting, and identifying and prosecuting unreported incidents that meet the OHMT reporting criteria. This requires the cooperation of other government agencies in the form of data sharing and perhaps minor modification to their own reporting practices.

None of these recommendations are resource-intensive; in some cases, only one-time developmental expenses would be incurred. In light of the inadequacies in the current information system, this is a relatively inexpensive program for establishing a comprehensive basis for monitoring and regulating safety in the hazardous materials transport industry.

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Interactive Selection of Minimum-Risk Routes for Dangerous Goods Shipments

F. F. SACCOMANNO, M. VAN AERDE, AND D. QUEEN

An interactive model for routing shipments of dangerous goods through an urban road network is presented and demonstrated. The model computes minimum-risk routes based on each shipment's origin and destination, and graphically illustrates the selected paths. Alternative approximations for estimating risk are considered. The consequences of these differences are compared against routings based on objective risk exposure. Objective risk exposure is predicted by using observed accident rates, a fault-tree analysis for estimating damage potential, and various damage propagation relationships. The resultant risk estimates in this model are responsive to various environmental conditions, material properties, and location-specific parameters. An application of the model to the routing of chlorine shipments within the metropolitan Toronto road network is presented. The application illustrates the sensitivity of minimum-risk routes to a range of external contextual variables and relationships. Route patterns appear to be strongly influenced by the nature of the risk measures applied to candidate links and nodes.

In recent years the risks associated with the shipping of dangerous goods have received increasing attention from the government, the public, and the industries involved. These concerns have prompted several jurisdictions to consider a range of strategies for controlling dangerous goods shipments within large urban areas. In general, the intent of these strategies is to minimize potential damage to nearby population and properties from accidental spills of dangerous goods.

BACKGROUND

Current strategies for restricting dangerous goods shipments along an extensive road network are based essentially on two measures of potential damage *(1–3)*:

1. Truck accident rates or
2. Objective risk exposure.

Although the former only considers the probability of occurrence of dangerous goods incidents, the latter also attempts to incorporate directly some measure of their consequent damages.

In most cases damages are estimated by multiplying the accident rate by the number of people (or properties) affected along each affected route within the network. However, frequently there is no provision for the variability in spill probabilities for different accident conditions. Similarly, estimates of the impact area associated with materials spills may fail to account for variabilities in environment and material properties. This variability is a significant factor, because the results of a given accident may range from a virtually negligible impact to a major disaster.

A model is presented that integrates the consideration of the foregoing variabilities into the process of selecting minimum-risk routes. Variations in risk exposure for different links and nodes of the network are estimated through a fault-tree framework, a family of damage propagation relationships, and truck accident statistics. These estimates are employed to compute minimum-risk routes for specific types of dangerous goods shipments.

The objectives of the paper are threefold:

1. To present the basic features of an interactive model for dangerous goods routing,
2. To demonstrate the feasibility and use of the model for a typical application, and
3. To illustrate the route pattern sensitivity in terms of alternative routing strategies or contextual factors, or both.

MODELING APPROACH

The modeling approach estimates risk exposure for each link in terms of four components:

- Accident rates per movement
- Probabilities of spill damage occurrence per accident
- Spill impact area
- Population exposed within impact area

Accident rates reflect the likelihood that a given shipment will be involved in an accident on each link and node in the network. For each accident, the fault-tree analysis estimates the probability of spill damage occurrence. Finally, for each potential such occurrence, the impact propagation models estimate the impact area involved and the number of people exposed. Details of each stage of this process will be provided.

Accident Rates

The accident rate component of the risk exposure is separated into two subcomponents. On roadways, it is expressed as the number of truck accidents per truck vehicle kilometer on each

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discrete 0.5-km section. For intersections, the accident rate is expressed on the basis of per-truck movement for all constituent approaches.

Two contextual factors were found to significantly influence truck accident rates, namely, geometric design and weather. The specific categories considered are summarized in Table 1. For each category, a separate "conditional probability" is estimated based on observed accident profiles for 1,400 truck accidents in Toronto during 1981 *(4)*. These conditional probabilities are applied to all network links and nodes with similar contextual restrictions.

TABLE 1 CONDITIONAL TRUCK ACCIDENT RATES PER TRUCK KILOMETER *(4)*

	Dry Pavement		Wet Pavement	
	Unrestricted Visibility	Restricted Visibility	Unrestricted Visibility	Restricted Visibility
Arterials and collectors				
50 km/hr	3.72	3.96	1.82	0.96
> 50 km/hr	2.74	1.78	1.89	1.74
Expressways				
< 100 km/hr	0.88	1.67	0.96	0.53
100 km/hr	1.48	2.52	1.73	2.74
Junctions				
Ramps	2.22	5.22	2.58	8.28
Major intersections	0.83	0.94	0.88	0.59

NOTE: Accident rates are expressed in accidents per million vehicle kilometers.

Probability of Spill Damage Occurrence

Several methods are available for estimating the probabilities associated with system failures. A fault-tree analysis was selected for this study because it permits the contextual relationships associated with the handling and transportation of dangerous goods to be internalized *(5–7)*.

In general, a fault tree represents a deductive failure mechanism. An undesirable state is specified, and the system is analyzed in terms of the inherent environmental and operational characteristics that influence the failure likelihood *(6)*. The ultimate objective of the analysis is to estimate the probability of occurrence of a system failure subject to a sequence of preconditioning or prior events. In each case, the logical cause-and-effect relationships between lower- and higher-order occurrences in the failure sequence are represented by using logic gates.

The general fault-tree approach was adapted to the dangerous goods routing problem by specifying four distinctive failure mechanisms related to spill damage occurrence:

1. Airborne release of toxic vapor outside containment,
2. Explosion of unstable liquid or solid,
3. Explosion of confined or unconfined vapor cloud, and
4. Flash fire accompanying the spill of a flammable liquid.

As an example, a simplified representation of the fault tree for item 1 is shown in Figures 1–3. In Figure 1 two conditions need to be satisfied to permit a toxic vapor release:

1. A vapor plume must be present outside containment, and
2. The material released must be toxic.

Vapor is present outside containment if there is a direct vapor release from the tanker or if the material is spilled in the form of a liquid or solid solution with subsequent evaporation. Breach of containment (direct vapor release from the tanker) is broken down further into causes, for example, because of load-induced failure in the container or heat-induced internal pressure build-up (Figures 2 and 3, respectively).

The material is considered to be toxic if it is toxic in transport or if the material becomes toxic in reaction because of the presence of a catalyst.

Spill Impact Area

For each spill, the consequent damages are estimated in terms of several impact propagation relationships. These relationships estimate the magnitude of the affected area as a function of release rate, duration of release, wind speed, material toxicity, and concentration. An estimate of the number of people exposed is derived by multiplying this estimated impact area by the relevant population density.

The population density employed within the model is a weighted sum of the residential and employment population in an area for a complete 24-hr day. These population estimates are highly correlated with property distribution, so that separate data for property distribution and damage are not explicitly included.

Consequent damages are expressed only in terms of immediate impacts to nearby population. Immediacy here refers to damages that are sustained during the duration of the spill before any recontainment or cleanup action. Essentially, in this aspect the long-term effects of dangerous goods spills, such as any carcinogenic effects, are ignored. Exposure to long-term effects is frequently correlated with immediate population impacts.

The size of any impact area is determined from physical relationships associated with each spill. Four types of impact-range relationships are considered:

1. Dispersal of toxic airborne contaminants,
2. Fireball from ignition of vapor cloud,
3. Blast effect of vapor cloud explosion, and
4. Ignition of flammable liquid.

These damage relationships are as follows:

Dispersal of toxic airborne contaminants (*8*, pp. 10–13):

$$r = \left(\frac{W * e * Kt}{3.14 * u * p * a}\right)^{1/b}$$

where

W = weight per unit volume (g/m^3),
e = volume of material released (m^3/sec),
Kt = duration factor (dimensionless),
u = wind speed (m/sec),
p = ppm equivalent (g/m^3), and
a, b = coefficients dependent on air stability.

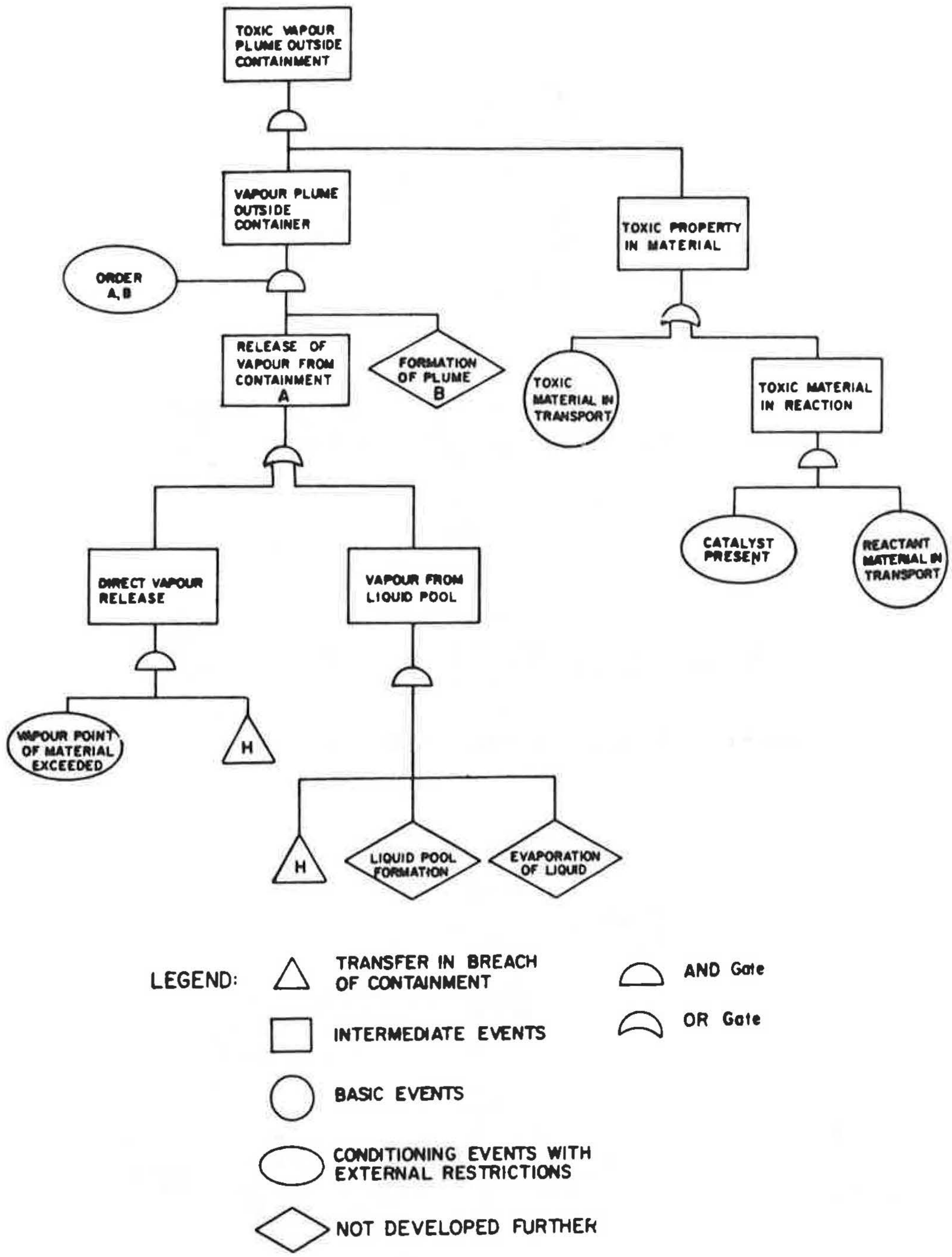

FIGURE 1 Fault tree for airborne release of a toxic vapor.

Fireball from ignition of vapor cloud (*9*, pp. 5–11):

$$r = 27.5\ (M)^{1/3}$$

where r is the range of the fireball (m) and M is the mass of hydrocarbon in the material (tonnes).

Blast effect of vapor cloud explosion:

$$r = R(B)\ (M)^{1/3}$$

where

r = range of blast impact zone (m),
M = mass of TNT equivalent of material (kg), and
$R(B)$ = distance factor for specified damage class (for example, Class B damage: $R = 7.0$).

Ignition of flammable liquid:

$$r = f(R)$$

where r is the range of the flash fire and R is the radius of the pool of contaminated area.

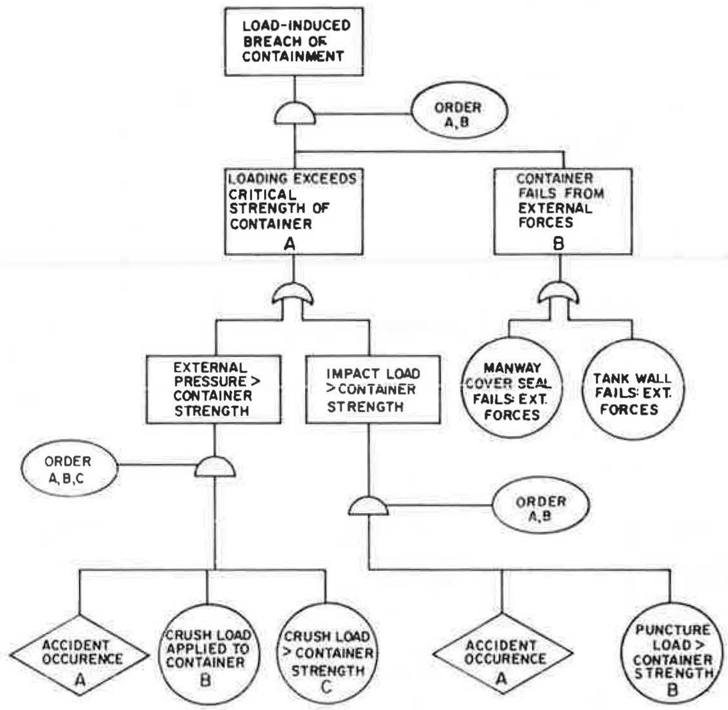

FIGURE 2 Load-induced breach of containment.

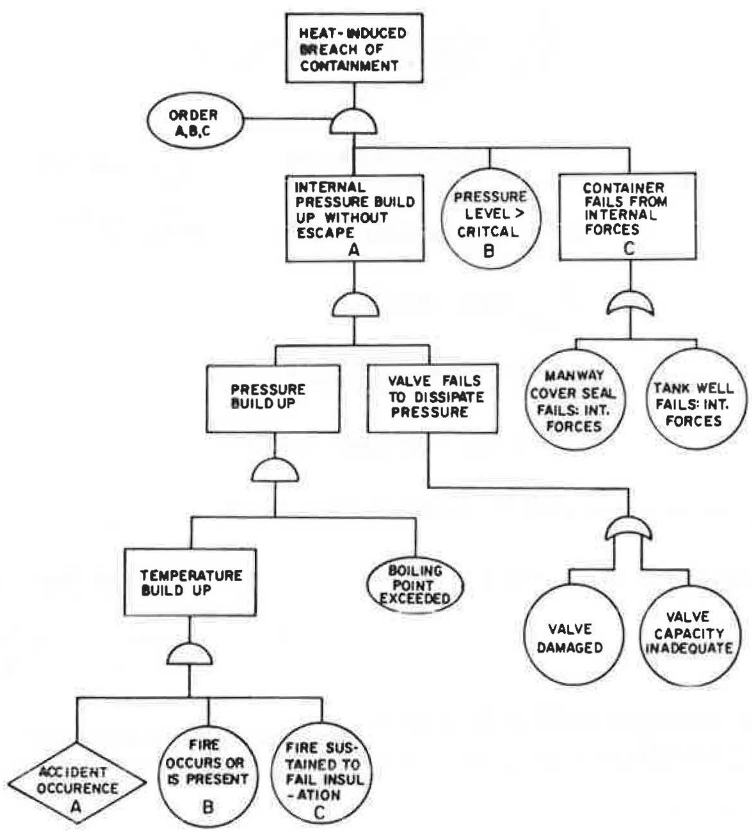

FIGURE 3 Heat-induced breach of containment.

Population Exposed Within Impact Area

The number of people affected by each dangerous goods spill is obtained from the cumulative effects of all relevant damage modes within a designated impact area.

For each road section k (link and intersection) the number of persons exposed to damage mode m is estimated as the following product:

Persons
exposed = (link accident rate + intersection accident rate)
* (release/fire/explosion probability per accident)
* (impact area for damage mode m)
* (population density along road section k)

The model emphasizes the derivation of dangerous goods routes based on the foregoing estimate of objective risk exposure. However, from an operational standpoint, accident rates and spill damage potential may also be considered as simpler surrogates for objective risk exposure. The model can employ these partial indexes for suggesting dangerous goods routes and allows them to be compared with the more comprehensive risk estimate, as calculated earlier. In addition, routes based on minimum truck operating costs may also be generated.

The various options for computing alternative routings permit a true evaluation of the cost-effectiveness of minimum-risk routes. Comparisons against minimum-operating-cost routes indicate the trade-offs between the benefits to society and the costs to the trucking industry. Similarly, comparisons against simpler risk surrogates indicate the relative merits of using more sophisticated risk measures.

Model Implementation

The procedure is implemented in terms of an interactive program for a microcomputer. The model logic is coded in compiled BASIC to illustrate the approach and demonstrate the sensitivity of routes to different contextual factors. The core program structure consists of four distinct phases, as shown in Figure 4. In addition, a set of graphical routines is available to plot the routes being selected for any number of origin-destination (O/D) pairs in the network. The program phases are described in the following paragraphs.

Specification of Routing Strategy

In the initial phase, the user selects the routing strategy to be considered from the four alternatives:

- Minimum truck operating cost
- Minimum truck accident rate
- Minimum spill damage potential
- Minimum objective risk exposure

Specification of Contextual Factors

In the next phase a range of specification factors is determined for each routing strategy, for example:

- Accident environment
- Material properties
- Spill relationships
- Containment factors
- Location characteristics

From these contextual factors, impedance measures per individual link movement are calculated for each link and node in the network.

Route Estimation

In the third phase the minimum-path tree for a specified origin node is calculated. This optimization finds routes that minimize the cumulative link impedances between a given origin and all destinations. Given a destination, the desirable minimum path can be selected.

Evaluation

In the final phase, a specific route is evaluated and the cumulative route impedance for all strategies is computed subject to the underlying contextual factors. At this stage the selected route can be stored for plotting and a feedback loop can be entered. The latter permits a variety of model parameters to be reselected, so that sensitivity analyses are possible. All route files are stored as external permanent files for later reference.

MODEL APPLICATION

The model was validated on the basis of an application to the metropolitan Toronto road network. Details are provided in the following paragraphs.

Background

Metropolitan Toronto has a total population of nearly 2.5 million. An abstraction of the Toronto road network used in this analysis is shown in Figure 5. The abstracted network involves the use of 255 nodes and 457 links, reflecting the network's major traffic arteries, which also serve the bulk of the truck movements within the area.

The primary objectives of model application are

1. To assess the sensitivity of route patterns to different routing strategies for a given set of contextual factors, and
2. To assess the sensitivity of route patterns to different contextual factors for a given routing strategy and material.

The first objective attempts to capture the differences in routes that arise when different strategies are used. The second objective addresses the extent to which different environmental conditions affect the resultant route patterns.

Chlorine was selected for testing the algorithm subject to certain contextual restrictions. In addition, the analysis was concentrated on trips starting from the downtown area (Node 66) and proceeding to four external areas (Nodes 8, 142, 200, and 253), as shown in Figure 5. The contextual restrictions used were

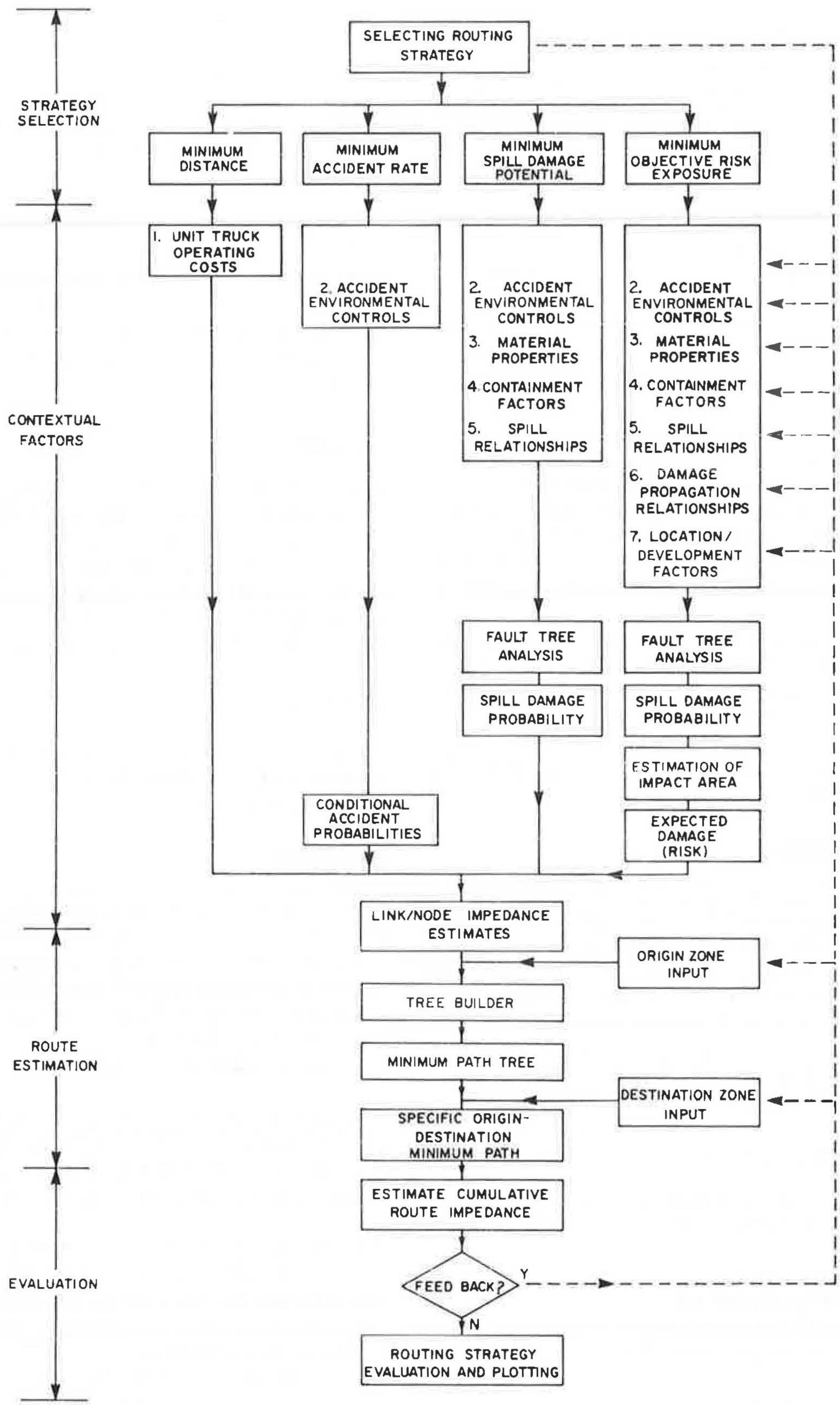

FIGURE 4 Program structure of routing-model implementation.

1. Density of chlorine at standard temperature and pressure (STP) = 320 g/m^3,
2. Critical toxic concentration 60 min from spill = 20 ppm,
3. Spill rate for spill damage occurrence = 0.5 m^3/sec,
4. Volume in container at STP = 320 m^3,
5. Prevailing wind speed at spill site = 0.50 m/sec (negligible wind), and
6. Atmospheric conditions = unstable.

Results

Table 2 gives the results of the model application for four representative O/D pairs in the Toronto network. For each pair the relevant routing criterion impedance measure and the corresponding trip distance are listed.

A graphical comparison between the results for the four alternative routing strategies is provided in Figure 6. Similarly, Figure 7 provides a comparison of the routes that were selected for each combination of the two different types of environmental conditions that were assessed for each routing strategy. The significance of both these comparisons is discussed next.

DISCUSSION OF MODEL APPLICATION

A comparison of routings between alternative strategies and different environmental conditions reveals a number of interesting findings.

Alternative Routing Strategies

Figure 6 shows the sensitivity of routes to the use of different routing strategies. This sensitivity, however, is not ubiquitous

TABLE 2 SUMMARY OF ROUTING CRITERIA FOR EACH O/D PAIR

a. Minimum Truck Operating Costs

Conditions	Destination 008 Imp.	Destination 008 Dist.	Destination 142 Imp.	Destination 142 Dist.	Destination 200 Imp.	Destination 200 Dist.	Destination 253 Imp.	Destination 253 Dist.
All		16.3		18.1		19.9		23.4

b. Minimum Truck Accident Rate

Conditions	Destination 008 Imp.	Destination 008 Dist.	Destination 142 Imp.	Destination 142 Dist.	Destination 200 Imp.	Destination 200 Dist.	Destination 253 Imp.	Destination 253 Dist.
U - D	44.8	18.6	74.3	27.2	56.0	19.9	85.0	27.3
U - W	61.7	18.9	72.2	19.5	62.0	20.5	85.1	27.3
R - D	41.8	18.7	49.9	18.1	47.2	20.6	62.8	23.4
R - W	42.6	17.1	36.5	26.0	32.6	20.9	60.4	28.0

c. Minimum Spill Damage Potential

Conditions	Destination 008 Imp.	Destination 008 Dist.	Destination 142 Imp.	Destination 142 Dist.	Destination 200 Imp.	Destination 200 Dist.	Destination 253 Imp.	Destination 253 Dist.
U - D	1.1	18.6	1.8	27.2	1.4	19.9	2.1	27.3
U - W	1.5	18.9	1.9	19.5	1.5	20.5	2.1	27.3
R - D	1.0	18.7	1.2	18.1	1.2	20.6	1.6	23.4
R - W	1.0	17.1	0.9	26.0	0.8	20.9	1.5	28.0

d. Minimum Objective Risk Exposure

Conditions	Destination 008 Imp.	Destination 008 Dist.	Destination 142 Imp.	Destination 142 Dist.	Destination 200 Imp.	Destination 200 Dist.	Destination 253 Imp.	Destination 253 Dist.
U - D	356.0	23.4	433.0	29.5	370.0	22.1	451.0	34.6
U - W	1386.0	23.5	1358.0	32.3	1091.0	21.4	1304.0	37.3
R - D	4264.0	19.6	4526.0	22.4	3982.0	21.4	4663.0	25.0
R - W	703.0	17.1	591.0	26.0	693.0	25.0	906.0	40.8

Notes:
Conditions: Visibility (U = Unrestricted, R = Restricted)
Pavement (D = Dry , W = Wet)
Impedance : Expressed as E-06: b. number of accidents
c. number of releases
d. number of people affected
Distance : Expressed in kilometers

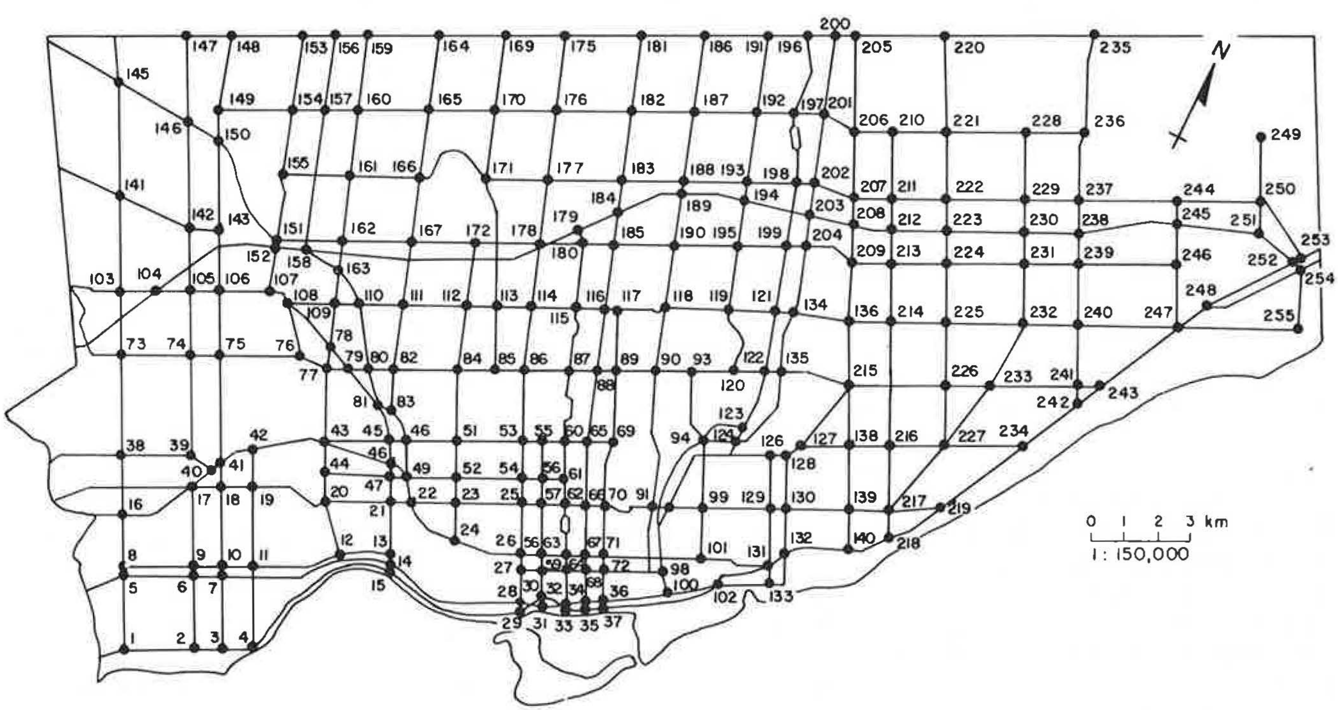

FIGURE 5 Abstracted Toronto link-node road network.

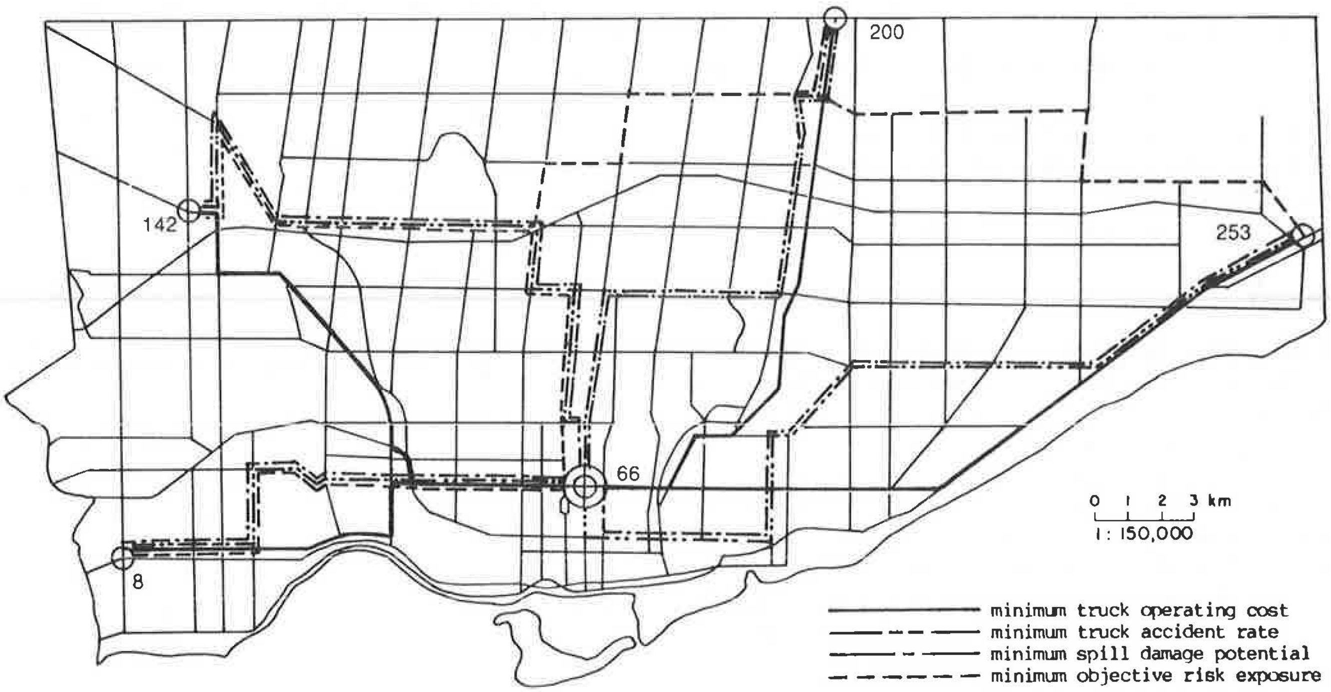

FIGURE 6 Alternative routing strategies for sample O/D pairs.

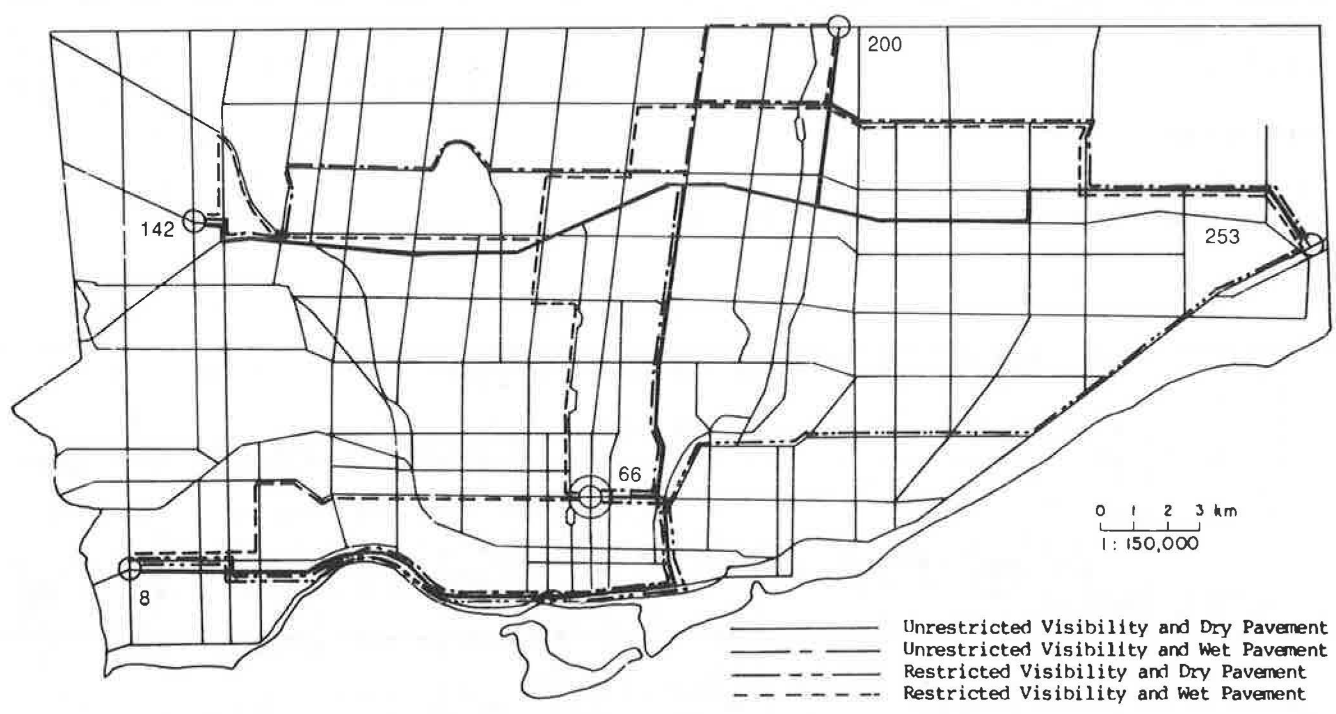

FIGURE 7 Minimum-risk routes for alternative weather conditions.

for all O/D pairs in the network. For example, O/D pair 66–8 suggests the same route regardless of the underlying strategy. This is expected, given the lack of alternative routes. O/D pair 66–253, on the other hand, suggests a range of routes unique to each routing strategy. Other O/D pairs in the network yield route options that are moderately sensitive to these strategies.

For the contextual restrictions used in the analysis, both the accident rate and the spill damage potential strategies yield essentially the same route pattern. This indicates that enhancements to the accident rate measure, by means of supplementary fault-tree analyses, have not affected the resultant route options to an appreciable extent. This implies that from a routing standpoint, the two measures yield essentially the same patterns regardless of context.

Different Environmental Conditions

Figure 7 shows the differences in route patterns for the minimum-risk strategy under two different meteorological conditions (favorable and adverse). Although in some cases routes appear to be highly sensitive to these conditions, again the extent of sensitivity is not ubiquitous for all O/D pairs in the network. For example, O/D pair 66–200 indicates negligible change for the two environmental extremes, whereas routes for O/D pairs 66–142, 66–200, and 66–253 are significantly affected.

The cumulative route impedances in Table 2 indicate that risk levels may be higher under favorable weather conditions than under adverse weather conditions. This apparent contradiction may be due to lower observed truck accident rates in Toronto for adverse weather conditions on certain classes of roads, which may indicate that, all factors assumed constant, truck drivers are much more careful during adverse weather. This aspect was observed to be true in the case of the 1981 truck accident statistics used in this application. Furthermore, during adverse versus favorable weather, the differences in dispersal conditions result in a more confined critical concentration isoline for the spill area. Adverse weather causes a greater dispersal of contaminants and a further dilution of the material in the plume. Consequently, damages under adverse conditions are correspondingly reduced.

Cumulative Truck Accident and Damage Rates

The probability of dangerous goods incidents appears to be relatively low on a per-shipment basis, regardless of whether accident rate or spill damage potential is considered. The low values obtained in this study may suggest that the possibility of negative impacts on population from dangerous goods shipments is too rare to warrant any remedial action. Although this argument has been made in the past to justify lack of action, it may lack validity when total shipments are considered for an entire network and for an extended period of time.

Saccomanno and Chan *(4)* indicated that the restriction of dangerous goods movements to designated risk routes can yield approximately $20.7 million in savings in risk costs over the route option that strictly minimizes operating cost. This would result in an increased operating cost to the trucking industry of approximately $11.8 million per year.

CONCLUSIONS

The safety of transporting dangerous goods in large urban areas can be enhanced through the application of effective strategies. The methodology and model presented in this paper have provided a basis for evaluating and comparing such strategies.

The application of the model also demonstrated that routing patterns may be sensitive to the specific strategy that is selected and, within each specific strategy, to varying environmental conditions. To the extent that these latter conditions vary over time and space, safe routes must be viewed in dynamic terms. In general terms, this analysis has demonstrated the value of developing a systematic framework for risk assessment that is sensitive to these dynamics.

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Dave Hudson assisted in preparing the computer programs used in this study, and members of the Institute for Risk Research provided helpful comments in the preparation of the model and the paper. Part of the research project was sponsored by the Dangerous Goods Directorate of Transport Canada and the Natural Sciences and Engineering Research Council. The model was developed and tested on computing equipment provided as part of the WATDEC Project (DEC, Canada Ltd./ University of Waterloo Research Program).

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Computer Model for Evaluating and Scheduling Freeway Work-Zone Lane Closures

Raymond A. Krammes, Conrad L. Dudek, and Jeffrey L. Memmott

QUEWZ is a computer model that was developed in 1982 as a tool for planning and scheduling freeway work-zone operations. The model analyzes traffic flow through lane closures in freeway work zones and estimates the queue lengths and additional road user costs that would result. Several applications of the model are reported and two enhancements that have been made to improve its utility and accuracy are documented. One enhancement is an analysis option to determine acceptable schedules for alternative lane-closure configurations based on a motorist-specified maximum acceptable length of queue or delay. The second enhancement is an algorithm to account for the natural diversion of traffic away from the freeway work zone to unspecified alternative routes.

Most maintenance and reconstruction operations on existing freeways are conducted in work zones through which traffic operates on a restricted cross section adjacent to the work area. The work zone itself must be planned and scheduled with three objectives in mind: *(a)* to protect the safety of both the workers in the work area and the motorists traveling through the work zone, *(b)* to maximize the efficiency with which the work is performed, and *(c)* to minimize the inconvenience and delay to motorists.

In 1984 Memmott and Dudek *(1)* reported the development of a computer model to perform a queue and user cost evaluation of work zones (hence the name QUEWZ). The model analyzes traffic flows through freeway work zones and estimates the queue lengths and additional road user costs caused by the work zone. It was designed to evaluate the effects on road users of alternative work-zone configurations and schedules. Several applications of the model are discussed and two recent enhancements that have been made to improve its utility and accuracy for planning and scheduling freeway work-zone operations are described. The two enhancements are *(a)* an analysis option that provides a preliminary assessment of acceptable schedules for alternative work-zone lane-closure configurations and *(b)* an algorithm that accounts for the natural diversion of traffic away from the freeway work zone to unspecified alternative routes.

BACKGROUND

QUEWZ is one of several models of freeway work zones that have been developed in recent years. In this section, the several models are briefly reviewed in order to clarify the differences among them.

Lytton et al. *(2)*, St. John et al. *(3)*, and Butler *(4)* developed algorithms to estimate the additional costs to road users per day of construction activity as part of broader economic evaluations of highway improvement alternatives. The methodologies of these models are consistent with standard procedures for calculating road user costs *(5)*, but the aggregate estimates, although appropriate for the purposes for which they were developed, are not at a sufficient level of detail to be useful in work-zone planning and scheduling.

Nemeth and Rouphail *(6)* and Rathi and Nemeth *(7)* developed a pair of microscopic models that simulate the movement of vehicles through lane closures in freeway work zones on the basis of drivers' responses to the stimuli presented at the lane closure. The main application of these models is the evaluation of the effect on traffic performance of different traffic control schemes at freeway lane closures.

The traditional input-output approach for estimating delays and queue lengths resulting from restricted capacities in work zones is described in Chapter 6 of the 1985 *Highway Capacity Manual* (HCM) *(8)*. Delay and queue-length estimates are based on the difference between cumulative arrivals at and cumulative departures from the work zone. Abrams and Wang *(9)* used this procedure to estimate the additional travel-time costs associated with these delays. Plummer et al. *(10)* used the input-output approach in estimating the fuel-consumption-related effect of freeway work zones. The procedure is a theoretically sound, macroscopic approach to delay and queue-length estimation, but the manual nature of the calculations limits its practicality for evaluating large numbers of alternative work-zone configurations and schedules.

DEVELOPMENT AND APPLICATIONS OF QUEWZ

QUEWZ was designed to evaluate traffic flows through lane closures in freeway work zones and to provide estimates of the queue lengths and additional road user costs associated with alternative closure configurations. In this section the methodology and applications of the model are summarized. More detailed descriptions of the computational procedures have been presented elsewhere *(1, 11)*.

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Methodology

The model can be applied to freeway facilities with as many as six lanes in each direction and can analyze any number of lanes closed in one or both directions. The model analyzes traffic flows through the work zone on an hourly basis to estimate the normal approach speeds and the average and minimum speeds through the work zone and, if demand exceeds capacity, the queue lengths, associated vehicle hours of delay, and average and minimum speeds through the queue. The additional road user costs due to the work zone are then estimated from these speeds and queueing characteristics by using the standard procedures presented in AASHTO's *Manual on User Benefit Analysis of Highway and Bus-Transit Improvements (5)*.

The normal approach speed and average speed through the work zone are computed from a relationship between speed and volume-to-capacity ratio similar to that presented in the 1965 HCM *(12)*. However, the user has the option of modifying the parameters to more accurately reflect the speed-volume relationship on the freeway of interest.

The minimum speed through the work zone was predicted from the average speed through the work zone and the square of the volume-to-capacity ratio through the work zone by using a linear regression model whose parameters were estimated from available work-zone data.

The minimum speed in a queue preceding a work zone is assumed to be zero. The average speed through the queue is estimated by using a kinematic wave model developed by Messer et al. *(13)* for predicting travel time on an urban freeway. The equation was derived directly from the Greenshields *(14)* speed-flow-density model, which assumes that space mean speed is a linear function of density.

Vehicle hours of delay and the length of queue when the approach volume exceeds the work-zone capacity are computed with an algorithm that replicates the traditional input-output approach presented in Chapter 6 of the 1985 HCM *(8)*.

The additional road user costs per hour of restricted work-zone capacity include *(a)* the additional travel-time costs due to delays in the queue, reduced speeds through the work zone, and the deceleration and acceleration between the normal approach speed and the minimum speed through the work zone; *(b)* the additional operating costs due to the speed-change cycle from the approach speed to the minimum speed in the work zone and due to the speed-change cycles in the queue; and *(c)* the differences among the operating costs at normal approach speeds, at the average speed through the work zone, and at the average speed through the queue.

Critical to the estimation of speeds and queue lengths and of the associated additional road user costs are the assumed speed-volume relationship and the assumed capacity of the work zone. There is some question whether the speed-volume relationship for a work zone is the same as that for a normal freeway segment. Butler *(4)* concluded that the speed-volume relationship for work zones did correspond to the typical relationship for normal freeway sections in the 1965 HCM *(12)*. Abrams and Wang *(9)* also used the typical relationships as the basis for their estimation of speeds through work zones. However, Rouphail and Tiwari *(15)* concluded that the speed-volume relationships at lane closures on four-lane freeways in Illinois were considerably different from those in the 1965 HCM *(12)*. Additional research will be necessary to determine which conclusion is the most accurate.

The work-zone capacities used in QUEWZ are those observed by Dudek and Richards *(16)* in Texas and by Kermode and Myyra *(17)* in California and reported in the 1985 HCM *(8)*. Dudash and Bullen *(18)* observed single-lane capacities at a reconstruction site in Pennsylvania that agreed well with the capacities observed by Dudek and Richards *(16)* for a similar lane-closure configuration. These capacity estimates are the best currently available. However, additional data will be necessary to quantify the effect on work-zone capacity of several factors, including the lane-closure configuration, the geometry of the work zone, the percentage of trucks, and the type and intensity of work activity.

Applications

QUEWZ has been used in several Texas cities, including Houston and Fort Worth. In Fort Worth, for example, maintenance engineers with the Texas State Department of Highways and Public Transportation (SDHPT) used the model to estimate queue lengths in order to determine the distance upstream of a lane closure at which supplemental advance-warning signs should be placed. Results, which have been reported on an informal basis, have been favorable.

Denney and Levine *(19)* have provided a more formal discussion of the use of the model for evaluating active traffic management strategies during work-zone activity on the Southwest Freeway in Houston. First, they divided the 4.2-mi work zone into 10 subsections that were homogeneous in terms of geometry and demand, and then they used QUEWZ to estimate the queue lengths that would result from closing one lane in each subsection between 9:00 a.m. and 4:00 p.m. They found that closing one lane in the five-lane subsections of the freeway segment would not cause significant queues but that in the four-lane subsections queues would exceed 2 mi, which they considered to be the boundary of acceptability. Next, they adjusted the model inputs to evaluate the effect of two active traffic management strategies on estimated queue lengths in the four-lane subsections. The first strategy was to use the right shoulder for carrying traffic in these subsections, which they estimated would increase the capacity of the work zone by 750 vehicles/hr. The second strategy was to close several entrance ramps and to divert ramp traffic to the parallel frontage road, which was evaluated by modifying the approach volumes for the affected subsections. Denney and Levine *(19)* concluded that "the QUEWZ computer model has been shown to provide reasonable evaluations of the effectiveness of these strategies."

Users of the model have generally been pleased with model results. However, they recommended some alternative forms of analysis and model output to correspond more closely to specific applications of the model for planning and scheduling work zones on urban freeways.

Field applications and additional validation of the model have suggested that the model performs well under many conditions. However, when demands greatly exceed work-zone capacity, the model's estimates of queue lengths are often much longer than those actually observed in the field. The model computes queue lengths by using the traditional input-output approach. With accurate inputs (approach volumes) and outputs (work-zone capacities), the model yields accurate queue-length estimates. In most cases, the approach volumes provided are based on historical data representing normal operating conditions. However, in Texas, where most urban freeways have parallel frontage roads, natural diversion commonly occurs and actual approach volumes during periods of work activity are less than normal approach volumes. Therefore, the problem is not with the methodology of the model but rather with the inputs to the model.

ENHANCEMENTS TO QUEWZ

Two major enhancements to the original QUEWZ model were made in response to the field applications and validation of the model. The first was the addition of an analysis option that determines acceptable schedules for alternative lane-closure configurations based on a motorist-specified maximum acceptable queue length or delay. The second enhancement was an algorithm that accounts for the natural diversion of traffic away from the freeway to unspecified alternative routes. Figure 1 is a flowchart that shows how these enhancements have been incorporated into the structure of the model.

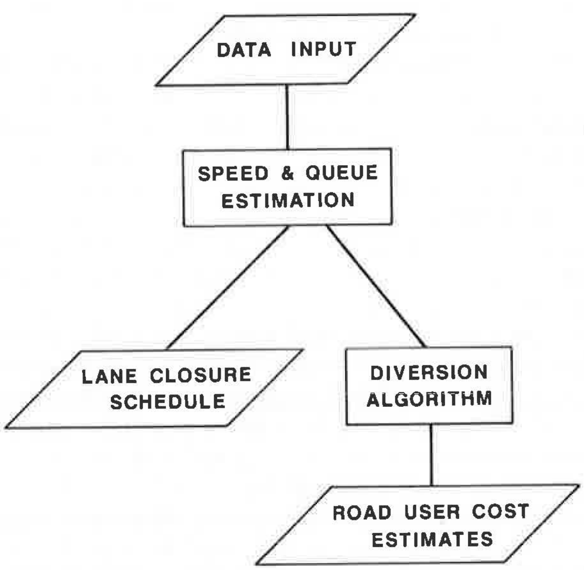

FIGURE 1 Flowchart of QUEWZ.

Lane-Closure Scheduling Option

As one part of an effort to improve the safety of freeway work zones and to minimize their impact on motorists, the Houston District Office of the SDHPT developed a set of guidelines to determine the optimum time for conducting short-term maintenance operations. The guidelines, which were reported by Levine and Kabat *(20)*, specify *(a)* that the delay to the traveling public should not exceed 20 min and *(b)* that the number of lanes that can be closed along a particular freeway section should be determined on a site-specific basis. This determination was to be based on a comparison of hourly flow rates and estimated capacities and on consideration of factors including the availability of shoulders, the existence of parallel frontage roads, and the volumes on entrance and exit ramps.

The Houston Urban Office of the SDHPT requested that QUEWZ be adapted to identify the proper times of day for closing freeway lanes. The algorithm that was developed to determine acceptable schedules for alternative lane-closure configurations at freeway work zones allows the user to define "excessive queuing" in terms of either the maximum acceptable length of queue in miles or the maximum acceptable delay to motorists in minutes *(21)*. When the lane-closure scheduling option is requested, QUEWZ evaluates all possible lane-closure configurations for the freeway facility described by the user. For example, if the user specifies a work zone that will affect both directions of an eight-lane freeway, the model evaluates the effect of closing one, two, and three lanes in each direction. For each lane-closure configuration, the model considers each hour of the day as a possible starting time and determines how many hours the lane closure could continue before queue lengths or delays to motorists became excessive.

If the user defines a critical length as the criterion for defining excessive queues, QUEWZ uses the user-supplied data on approach volumes to estimate the queue lengths that would develop during each hour of the day from each starting hour for each possible lane-closure configuration. These estimated queue lengths are compared with the critical length of queue to determine the number of hours, if any, that the lane closure could remain in place before queue lengths would become excessive.

The user may also specify a maximum acceptable delay to motorists as the criterion for determining acceptable lane-closure schedules. Dudek et al. *(22)* reported driver delay tolerances (the minutes of delay before a driver would divert from a freeway to a service road) of 15 to 20 min on the basis of a survey of drivers in College Station, Texas; Los Angeles; and St. Paul. Denney and Levine *(19)*, Levine and Kabat *(20)*, and Roper et al. *(23)* used 20 min as a maximum acceptable delay to motorists in their work-zone planning efforts. The user is given the option of either accepting a default value of 20 min or specifying another value.

Delay is defined as the difference between travel times on the section of freeway in question with and without the work zone. For each lane-closure configuration, delays are computed for each hour following each possible starting time. The travel time through the work zone is computed as the sum of the travel time through the work zone at the average work-zone speed plus, if applicable, the travel time through the queue at the average queue speed. The comparable travel time without the work zone is computed by dividing the sum of the queue length and work-zone length by the normal approach speed on the freeway. The acceptable lane-closure schedule for each configuration is determined by comparing the estimated delays with the user-specified criterion for maximum acceptable delays.

To illustrate the use of the lane-closure scheduling option, an example is provided. The example involves the evaluation of alternative lane-closure configurations for the inbound direction of a six-lane freeway. Required data for this option include directional hourly volumes for each hour of the day and work-zone capacities for each lane-closure configuration. The hourly volumes used in this example are shown in Table 1. The work-zone capacities, which correspond to the average values observed by Dudek and Richards *(16)*, are as follows:

TABLE 1 DIRECTIONAL HOURLY VOLUMES FOR EXAMPLE PROBLEM

Military Time (begin - end)	Approach Volume (vph)	Military Time (begin - end)	Approach Volume (vph)
0 - 1	340	12 - 13	2200
1 - 2	230	13 - 14	2230
2 - 3	240	14 - 15	2270
3 - 4	170	15 - 16	2330
4 - 5	320	16 - 17	2310
5 - 6	960	17 - 18	2480
6 - 7	4060	18 - 19	1920
7 - 8	4970	19 - 20	1630
8 - 9	3340	20 - 21	1220
9 - 10	2260	21 - 22	1100
10 - 11	2130	22 - 23	950
11 - 12	2130	23 - 24	590

Lane-Closure Configuration	*Work-Zone Capacity (vph)*
One of three lanes closed	2,983
Two of four lanes closed	1,127

A maximum acceptable delay to motorists of 20 min is specified as the criterion for determining acceptable lane-closure schedules. The model output identifying acceptable schedules in military time for each lane-closure configuration is presented in Table 2. The model also provides as output a matrix of estimated average queue lengths by hour of the day for each lane-closure configuration.

The results presented in Table 2 suggest that it would be acceptable to close one of three lanes either before 7:00 a.m. or after 8:00 a.m. A closure beginning at 7:00 a.m. could remain in effect only 1 hr, after which delays to motorists would exceed the 20-min criterion. Two of three lanes could be closed for more than 1 hr only before 6:00 a.m. and after 7:00 p.m. (hour 19 in military time). Delays to motorists would exceed 20 min in less than an hour if two of three lanes were closed at any other time.

The queue-length estimates for the lane-closure scheduling option are based on the assumption that none of the approach volume diverts from the freeway in response to the presence of the work zone. This assumption is appropriate for predicting whether a lane closure during a particular hour would have an unacceptable impact on the traveling public. However, the queue lengths that are predicted may be longer than would actually be observed if some traffic does divert. Therefore, diverting traffic must be taken into account to provide more accurate predictions of traffic patterns and additional costs to motorists.

Algorithm to Estimate Diverting Traffic

As shown in Figure 1, the diversion algorithm is used with the output option that provides road-user cost estimates.

Most urban freeways in Texas have parallel frontage roads. When queues develop upstream of a work zone on the main lanes of the freeway, some proportion of the approaching traffic may choose to divert to the frontage road or to another alternative parallel route, even though the traffic control for the work zone neither encourages nor requires them to do so. Such diversion is termed "natural diversion." When it occurs, the actual traffic volumes through the work zone are less than normal approach volumes. Therefore, queue lengths based on normal approach volumes overstate the queue lengths that are actually observed.

Very little quantitative data exist either on the proportion of traffic that "naturally" diverts or on the roadway or traffic conditions, or both, that influence the volume of diverting traffic. Research to address these questions is under way. However, as an interim approach to be used until additional data are collected, an algorithm that makes use of currently available data has been developed and is presented here for consideration of its theoretical approach.

One would expect diversion to occur when motorists perceive *(a)* that the delays they would experience by remaining on the freeway would be greater than they are willing to

TABLE 2 ACCEPTABLE LANE-CLOSURE SCHEDULES FOR ALTERNATIVE WORK-ZONE CONFIGURATIONS

	Hour of Maximum Lane Closure[a] by Closure Configuration	
Work Starting Hour	One of Three Lanes	Two of Three Lanes
0	7	6
1	7	6
2	7	6
3	7	6
4	7	6
5	7	6
6	7	6
7	8	7
8	24	8
9	24	9
10	24	10
11	24	11
12	24	12
13	24	13
14	24	14
15	24	15
16	24	16
17	24	17
18	24	18
19	24	20
20	24	24
21	24	24
22	24	24
23	24	24

[a]If work continues beyond this hour, the delay through the work zone will exceed 20 min.

tolerate and *(b)* that the travel time they would experience on an alternative route would be less than that on the freeway. The algorithm that has been incorporated into the cost-estimating option of QUEWZ assumes that diversion will occur so that no motorist experiences delays greater than some maximum acceptable level. This level may be specified as 20 min, which has been suggested by some researchers *(19, 20, 22, 23)*, or as another value. For freeway corridors where frontage roads or other alternative parallel routes are not available—and therefore diversion is unlikely to occur regardless of the magnitude of delay—the user may specify a large value for maximum acceptable delay (up to 99 min) to ensure that the model will not divert any traffic.

The first step in the diversion algorithm is to determine the critical length of queue at which delays to the last vehicle in the queue would equal the maximum acceptable delay. Then queue lengths that are estimated assuming that no traffic diverts are compared with this critical queue length. If queues do not exceed the critical length, it is assumed that no traffic diverts. If, in the absence of diversion, queue lengths exceed the critical queue length, it is assumed that enough traffic will divert so that queues never exceed the critical length.

The additional costs for diverting traffic are estimated by assuming that *(a)* the length of diversion equals the length of the work zone plus the critical length of queue, *(b)* the travel time for diverting traffic equals the time for a vehicle at the end of the critical queue to travel through the queue and the work zone, *(c)* the diverting traffic maintains a uniform speed equal to the length of the diversion divided by the travel time, and *(d)* trucks do not divert. The additional costs for diverting traffic are included in the total additional costs to road users that would result from the lane closure.

The algorithm produces queue-length estimates that more accurately reflect the queue lengths observed when diversion occurs and therefore is deemed an acceptable interim approach. When sufficient results from the current research concerning natural diversion become available, the assumptions in the algorithm will be evaluated and the algorithm will be refined to more accurately reflect the range of factors that influence under what conditions and to what extent natural diversion occurs.

The algorithm to estimate diverting traffic is used in conjunction with the cost-estimating option. The output provided by this option is illustrated by an example. A typical application of QUEWZ would be, first, to evaluate alternative lane-closure configurations on a freeway segment by using the lane-closure scheduling option and then to analyze in more detail a specific lane-closure configuration and schedule by using the cost-estimating option.

Suppose that on the freeway segment described in the previous example it was necessary to close one lane for 9 hr. Table 2 indicates that it would be acceptable to close one lane from 8:00 a.m. to 5:00 p.m. An analysis of this lane-closure schedule and configuration using the cost-estimating option yields the results in Table 3. The criterion specified for diverting traffic was a 20-min delay to motorists. The output provides hourly estimates for the volume and capacity through the work zone, the normal approach speed to the work zone, the average speed through the work zone, the average length of queue preceding the work zone, and the additional user costs. A comparison of the volumes through the work zone in Table 3 with the normal approach volumes in Table 1 indicates that no traffic diverts from the freeway. This result should be expected because a schedule was selected so that delays would not exceed 20 min. The estimated total additional daily user costs due to the lane closure are approximately $6,300.

CONCLUSIONS

QUEWZ is a computer model that has proved to be a useful tool for freeway work-zone planning and scheduling. A recent enhancement to the model has increased the utility of the model in identifying acceptable schedules for alternative lane-closure configurations. Another enhancement, the addition of an algorithm to account for the natural diversion of traffic away from the work zone, has improved the accuracy of the model's estimates of queue lengths at sites where natural diversion occurs.

In its present form, QUEWZ has two analysis options. The lane-closure scheduling option identifies acceptable schedules for all possible lane-closure configurations on a freeway segment based on a motorist-specified maximum acceptable length of queue or maximum acceptable delay. The second option provides estimates on an hourly basis of the additional road user costs that would result from a user-defined lane-closure configuration and schedule. The user cost-estimating option employs an algorithm that estimates the magnitude of diverting traffic based on the assumption that traffic will divert so that delays to motorists never exceed a user-specified maximum value. The additional costs to the diverting traffic are computed and included in the total additional road user costs that would result from the lane closure.

TABLE 3 SUMMARY OF ROAD USER COSTS

Military Time (begin - end)	Approach Volume (vph)	Work Zone Capacity (vph)	Approach Speed (mph)	Work Zone Speed (mph)	Queue Length (mi)	Additional User Costs ($)
8 - 9	3340	2983	52	30	0.5	3434
9 - 10	2260	2983	54	39	0.5	1500
10 - 11	2130	2983	55	49	0.0	164
11 - 12	2130	2983	55	49	0.0	164
12 - 13	2200	2983	54	49	0.0	181
13 - 14	2230	2983	54	49	0.0	189
14 - 15	2270	2983	54	48	0.0	201
15 - 16	2330	2983	54	48	0.0	218
16 - 17	2310	2983	54	48	0.0	212
Total Additional Daily User Costs Due to Lane Closure						6263

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Traffic Control Management Through Construction Zones

BENJAMIN E. BURRITT AND HERMANN A. GUENTHER

As I-70 construction activities in Colorado's Glenwood Canyon intensified, it became increasingly clear that traditional approaches to construction traffic control could neither efficiently nor safely accommodate existing traffic volumes under the number of active construction projects that would be required to complete the canyon project on schedule. In 1984 and early 1985, traffic-handling conditions had deteriorated to the point where total loss of control was imminent and there was growing public dissatisfaction with the frequently unnecessary and indiscriminate delays. In response, the Colorado Department of Highways (CDOH) authorized its management consultant, Daniel, Mann, Johnson, & Mendenhall (DMJM), to conduct a comprehensive analysis of traffic operations and safety throughout the canyon. The comprehensive study addressed many issues and suggested an innovative approach for handling traffic that would minimize delays, decrease the potential for a complete stoppage in the canyon, and allow control to be regained. Key elements of the proposed traffic management plan included a pilot-car operation, a sophisticated communications network, a systems approach to coordinating all flagging operations, and an umbrella contract that would combine all traffic control functions in the canyon under one separate authority. CDOH authorized a test of the pilot-car operation in late April 1985, which was to continue for an indefinite period of time. Operating through three active construction projects, with combined project limits of 3.6 mi, the pilot-car operation was highly successful and the benefits became immediately obvious. Because the test was conducted initially during a month with a relatively low traffic volume, it was necessary to gain a complete understanding of the dynamics of the pilot-car operation in order to assess its ability to cope with peak summer traffic volumes. Consequently, during the initial test and in subsequent periods, a large amount of operational data was collected. After data reduction and analysis, a complete understanding was gained of the traffic flow characteristics through the construction zones.

As I-70 construction activities intensified in Colorado's Glenwood Canyon, it became increasingly clear that traditional approaches to construction traffic control could neither efficiently nor safely accommodate existing traffic volumes under the number of active construction projects that would be required to complete the canyon project on schedule. The need for an overall coordinated traffic management plan had been discussed for several years. However, in 1984 and early 1985, traffic-handling conditions had deteriorated to the point where total loss of control was imminent and there was growing public dissatisfaction with the frequently unnecessary and indiscriminate delays. In response, the Colorado Department of Highways (CDOH) authorized its management consultant, Daniel, Mann, Johnson, & Mendenhall (DMJM), to conduct a comprehensive analysis of traffic operations and safety throughout the canyon. The resultant report *(1)* was submitted to CDOH early in 1985.

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The comprehensive study addressed many issues and suggested an innovative approach for handling traffic that would minimize delay, decrease the potential for a complete stoppage in the canyon, and allow control to be regained. Key elements of the proposed traffic management plan included

- A pilot-car operation (PCO),
- A sophisticated communications network,
- A systems approach to coordinating all flagging operations, and
- An umbrella contract that would combine all traffic control functions in the canyon under one separate authority.

CDOH authorized a test of the PCO to proceed in late April 1985 and to continue for an indefinite period of time. Operating through three active construction projects with combined project limits of 3.6 mi, the PCO was successful and the benefits became obvious immediately. The chaotic operational conditions existing before the test were highly variable and unfortunately did not allow for the collection of a statistically valid sample of data. Consequently, a quantitative assessment of the impact of the PCO on previous conditions was not possible. However, a qualitative review revealed that travel time through the construction zone was significantly reduced, overall delay was significantly reduced, motorists were stopped less frequently (usually only once), emergency trips through the canyon were more efficiently accommodated, public response was quite favorable, and contractors' operations benefited significantly in numerous ways.

Because the test was conducted initially during a month with a relatively low traffic volume, it was necessary to gain a complete understanding of the dynamics of the PCO in order to assess its ability to cope with peak summer traffic volumes. Consequently, during the initial test and in subsequent periods, a large amount of operational data was collected. After data reduction and analysis, a complete understanding was gained of the following traffic flow characteristics:

- Delay
- Travel time
- Headway

- Discharge time
- Queue length
- Approach volume

In this paper the current operation is discussed, the findings of the operational analysis are presented, and the basis for further refinements aimed at accommodating increased traffic volumes is provided.

PILOT-CAR OPERATION

The PCO requires the establishment of two control points at either end of the controlled section. At those points, controllers hold queues until the opposing queues negotiate the canyon and pass the control point. Once that has occurred, the stopped queue is released and led through the canyon by Pilot Car A. A trailing pilot car, designated Pilot Car B, ensures that vehicles do not straggle or stop and advises the operator of Pilot Car A when gaps develop in the queue that warrant a reduction in speed to reduce the gaps. Pilot Car B also has the responsibility of "fitting in" the contractors' equipment at the end of a queue. Under field conditions, it was determined that the vehicle used as Pilot Car A in one direction would become Pilot Car B for the movement in the opposite direction. This practice evolved when it became apparent that considerable efficiency results from having Pilot Car A proceed past the control point to the end of the stopped queue, turn around, and take up position as the trailing pilot car. Similarly, when Pilot Car B reaches the control point, it can easily turn around, take up position at the head of the stopped queue, and almost immediately lead off as the new Pilot Car A.

The controlled section was divided into 10 equal segments, with signs installed to clearly identify the checkpoints. As a queue proceeds through the canyon, Pilot Cars A and B report their location by radio each time they reach a checkpoint. In this manner, all individuals in the radio network clearly understand the location of the head and the tail of the queue as it proceeds through the canyon. The pilot-car operators also record their departure and arrival times as they cross the respective checkpoints.

Communications

Because of the terrain constraints on radio transmissions, it was decided to equip all members of the PCO with UHF radios. Radios were also supplied to each project traffic control supervisor (TCS), because it is essential that they know exactly where and in what direction the queues are moving. In communicating with their individual project flaggers, the TCSs use UHF radios, but on different frequencies from those used in the PCO. Selected CDOH project personnel have had their state radios modified to be capable of receiving and transmitting over the PCO radio network.

Flagging

The implementation of the PCO required a complete reversal in the role and duties of the project flaggers. Before the PCO, flaggers and TCSs were controlling traffic to provide for the passage of construction equipment and the performance of some construction tasks. In effect, the public was at the mercy of the flagging personnel on each project that they passed through. Because there was no coordination between projects, the public was simply forced to work its way through the canyon from project to project. In effect, motorists were faced with running a gauntlet each time they traversed the canyon. Driver expectancy was continually violated and motorists had to respond to a bewildering array of varying conditions. Uniformity of controls and procedures was almost totally absent. It was not uncommon to see contractors' equipment intermixed with the traffic stream. The potential for a disastrous emergency situation was becoming ever more apparent.

Under the PCO, the role of the project flagger is to control contractors' equipment, not the public. Flaggers are stationed at points of contractor equipment operation to control their entry onto the highway and ensure a clear passage for the arriving queue.

Staffing

The following is a listing of the key parties involved in the PCO and a description of their responsibilities:

1. Colorado Department of Highways
   a. Overall administration of the program
   b. Evaluation of the program's success
   c. Enforcement of regulations governing the operation
2. Daniel, Mann, Johnson, & Mendenhall
   a. Assistance in implementing the program
   b. Expert advice to CDOH
   c. Monitoring of operations and analysis of findings
3. Traffic coordinator (TC)
   a. Overall coordination of all participants
   b. Management of emergencies as well as priority delivery of construction materials
   c. Placement and removal of cones, folding and unfolding of traffic signs
   d. Maintenance of all equipment used by pilot-car operators and pilot-car controllers
   e. Maintenance of official diary
   f. Maintenance of daily dialogue with project TCSs
4. Project traffic control supervisor
   a. Supervision and direction of project flaggers
   b. Maintenance of project flaggers' equipment
   c. Coordination of individual contractor's operation through TC
5. Pilot-car operator
   a. Guidance of traffic through one-way zone
   b. Reporting on position of traffic queue
   c. Assurance of compliance with no-stopping and no-passing requirements
6. Pilot-car controller
   a. Control of traffic approaching one-way zone
   b. Provision of advance warning at rear of queue
   c. Management of lead pilot car based on instructions from TC
7. Project flagger
   a. Direction of contractor equipment operators
   b. Communication with project TCSs

Equipment

The pilot cars used in the test operation were actually mini-pickup trucks equipped with manual transmissions. Four pickups were originally acquired: two for the actual PCO, one for the TC, and one as a spare. They have proved to be durable under the stress of operating some 200 mi a day. However, this use equates to some 50,000 mi/year. Because of the intensive use, rotation of the four vehicles is necessary to avoid premature aging of half the fleet. Also, experience has shown that in the future, vehicles for this operation should be equipped with automatic transmissions. The pilot-car operators are burdened with numerous duties as they traverse the canyon. In addition to the obvious requirements for judgment, attentiveness, and the ability to operate the vehicle, the operators are continually using the radio to report arrival times at checkpoints, to coordinate the smooth movement of contractor equipment that needs to move with the queue, and to maintain the maximum density attainable in a given queue. For these reasons, the additional burden of operating the manual transmission is an unnecessary distraction.

Folding signs and portable sign brackets were fabricated by CDOH personnel for the tailgates of both pickups that read Pilot Car/Follow Me. The signs are closed when a vehicle is operating as Pilot Car B and opened when its role changes to that of Pilot Car A.

A sequence of warning signs was installed at the approach to each checkpoint to alert motorists of the PCO. Within the controlled section, equally spaced (0.36-mi) No Stopping signs were installed on either side of the road. On top of each signpost, normal street name sign brackets hold black-on-yellow checkpoint numerals, to which the pilot car operators refer when announcing their position.

OPERATIONAL CHARACTERISTICS

Once the coordinated PCO was implemented, it became immediately apparent that there was an improvement in the quality of service to the traveling public. To quantify the results of the operation and develop a basis for predicting when traffic flow conditions could not be accommodated by the PCO, a comprehensive data collection and recording program was begun during the first week of the operation. Concurrently, a computerized queuing model was run in an attempt to determine whether traffic characteristics in the canyon could be predicted according to traditional queuing theory. The data collection program was designed to be carried out periodically throughout the year so that the effects of varying traffic volumes could be analyzed.

The types of data collected included the following:

- Traffic approach volumes—Manual counts along with vehicle classifications were made in order to obtain the arrival rates of vehicles throughout the time period of the PCO. The counts were taken at distances sufficiently removed from the construction so that the random-arrival pattern of vehicles was not affected.
- Travel times—The travel time of each queue was calculated on the basis of the pilot-car operators' radio transmissions of departure and arrival times at the respective checkpoints.
- Discharge and passage times—The elapsed time for each queue of traffic to pass a given point was determined by radio transmission and was used along with queue volumes to determine vehicle densities and headways.
- Queue volumes—The number of vehicles in each queue was recorded manually at a point midway through the controlled section.

With the collected data, it was possible to calculate the speed of each queue, the average speeds of all vehicles, the average delay times for vehicles in each queue, and the overall average delay times per day for each direction. The information presented in this paper is based on data recorded between 7:00 a.m. and 5:00 p.m. on April 24 and 25, 1985, and on June 3 and 4, 1985.

Observations

The information gathered in the field was tabulated in a computer spreadsheet program from which it was then reduced to give the various calculated traffic parameters. The key operational parameters are summarized in Table 1.

TABLE 1 SUMMARY OF OPERATIONAL PARAMETERS

Parameter	April	June	Percent Change
Combined approach volume (vph)	3,402	4,114	+21
Combined queue volume (vph)	3,169	3,839	+21
Average queue volume (vph)	80	96	+20
Average no. of queues per day	35	40	N/A
Average speed (mph)	25.2	26.9	7
Average delays (min)	12.7	12.4	–2.5
Headway (sec)	4.44	4.10	–8
Travel time (min)	8	8	N/A
Passage time (min)	5.15	6.21	+20

The difference between the combined approach volume and that actually carried in the queues was attributable to the high number of construction-related vehicles that either did not go as far as the location of the PCO or were allowed to bypass a stopped queue and therefore were not counted. The average number of vehicles per queue increased 20 percent, which was consistent with the overall traffic volume increases. It was found, in fact, that the length of the queue was directly proportional to the amount of approach traffic.

Although average speeds increased 7 percent from April to June, it could not be assumed that speeds would continue to increase in direct relationship to increases in traffic volumes. The lower average speeds in April were mostly attributable to the novelty of the PCO and are evidence of the motorists', as well as contractors', lack of familiarity with this type of operation. Observations indicated that the average travel time through the one-way section and the average speed stabilized at about 8 min and 27 mph, respectively. It is unlikely that these two parameters will change significantly from this point on (unless, of course, the length of the one-way section is changed).

The 2.5 percent reduction in average delay time was attributable to the improved efficiency of the operation and must not be interpreted as a trend. In fact, as traffic volumes increase substantially (without considering unusual events), delays can be expected to increase accordingly.

The headway is the calculated time difference between adjacent vehicles passing a given point. The 8 percent reduction in headway was related to the improved efficiency and confidence level. Again, it is not expected that headway will decrease significantly, because of the level of activity in the construction zone, the traffic mix, and the "interest factor."

Passage time— the time required for the entire queue to pass a given point—was recorded at three locations: the beginning and mid- and endpoints. The passage times given in Table 1 were taken at the endpoint, which was found to be the critical, and therefore the most meaningful, location.

Unusual Events

The information contained in Table 1 was utilized in preparing the derivation of the DMJM projection model (available from the authors). It should be noted that the discussions pertaining to the operational parameters are based on "normal" operations; that is, they do not take into account unscheduled or unusual events, such as those that have already occurred on several occasions during the PCO. For example, a natural rockfall occurred on June 5, 1985, in the vicinity of a stopped queue, resulting in vehicle damage and bodily injury. This necessitated stopping all traffic in the canyon until the emergency was cleared. There have been several instances in which rock cuts resulted in unusually larger-than-expected volumes of material landing on the road, which also required temporary closing of the canyon.

These events are unusual, yet they can be expected to occur periodically for some time to come. The possible responses to these events have been discussed elsewhere *(1)*. The frequent passage of an emergency vehicle through the canyon in response to some need outside the canyon has become almost routine. These events have been successfully handled through the coordinated communications network. Although all vehicular movement in the canyon is temporarily halted to allow passage of the emergency vehicle, these stoppages are short enough not to adversely affect the PCO.

Coordination with Other Projects

The PCO as described encompasses several projects at the west end of Glenwood Canyon. There is additional construction activity several miles to the east of this operation that also requires frequent traffic stoppages. Although it is impractical to include the eastern area as part of the PCO, the importance of coordinating these traffic stoppages with the PCO cannot be overstated. The effects that uncoordinated traffic control on the east end project can have on the PCO, or vice versa, can be dramatic and very detrimental to achieving the goal of minimal delay to motorists.

Because the foregoing phenomenon is difficult to quantify in understandable terms, it is best shown graphically. Figure 1 shows a plot of actual westbound approach volumes by time of day superimposed on a plot of westbound queue volumes corresponding to the same period of time. It is readily apparent that the queue volumes do not follow the more orderly arrival pattern of approach traffic unimpeded by construction. The alternating high and low queue volumes clearly illustrate the regulated but uncoordinated release of westbound traffic from the east-end project. By contrast, Figure 2 shows the same type of information for the eastbound direction in which the queue traffic has not been subjected to previous construction-related stoppages. Figure 2 shows what the westbound plot could, and should, look like if the east-end traffic stoppages and releases were fully coordinated with the PCO. In both Figures 1 and 2, the bands of shading show the general variation of approach volumes and queue volumes throughout the day. Note the parallel relationship between approach volumes and queue volumes, which clearly substantiates the correlation between the two.

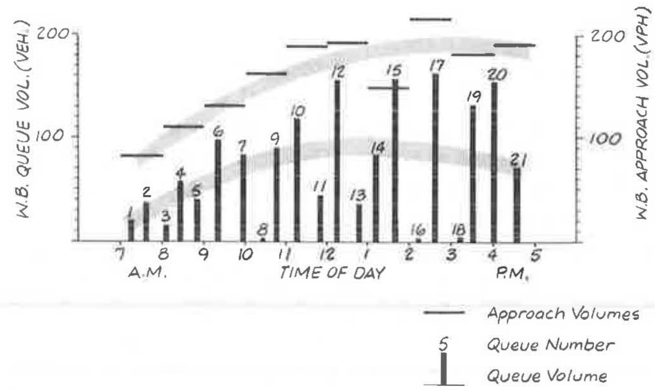

FIGURE 1 Westbound approach and queue volumes, Glenwood Canyon pilot-car operation, April 24, 1985.

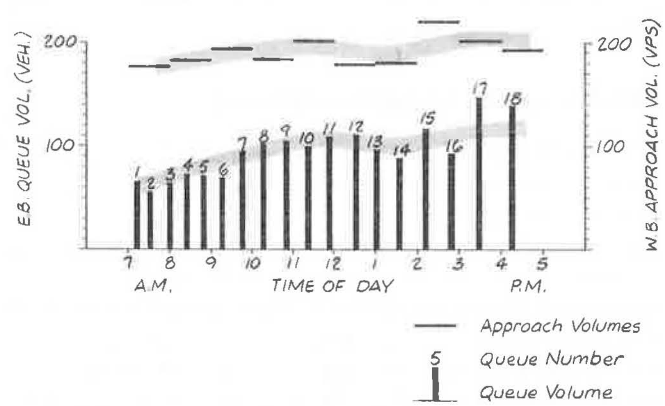

FIGURE 2 Eastbound approach and queue volumes, Glenwood Canyon pilot-car operation, April 25, 1985.

What these figures do not show directly but illustrate by implication is the effect that the east-end project has on eastbound traffic that has just passed through the one-way section as part of a queue. This traffic should ideally not have to stop again but is frequently required to do so because of a lack of total coordination. Actual field observations have proved this to be the case. An attempt has been made to coordinate the stoppages and releases of traffic at the east end with the PCO at the west end. This has met with limited success, mainly because of the lack of a central authority over all traffic control operations in the canyon.

CONCLUSIONS AND RECOMMENDATIONS

The data collected from the PCO quantified operational parameters only under relatively low approach volume conditions. However, detailed analysis of the data resulted in a clear understanding of the dynamics of the PCO under all approach volume conditions. The empirical data were used in logical relationships of traffic flow to develop a predictive equation for determining maximum service rates under varying approach volumes. A complete description of the mathematical derivation of the equation is available from the authors.

In the early stages of implementing the PCO, there was hope that a modified signalized intersection queueing model would be capable of predicting actual operations. However, the results were disappointing. The model did not reflect actual conditions and could not be calibrated. As in so many analytical models, the assumptions required to operate it made the model incapable of duplicating field observations.

Two of the misconceptions associated with the queueing model were that breakdown would occur when the capacity of the PCO was exceeded. The model assumed that specific approach volumes would exist hour after hour and that the queue buildup would rapidly grown out of control, with queues building much faster than they could be dissipated. Phenomenal queue-length buildups of many miles were predicted at the point of breakdown.

Such, however, was not the case. Based on observed headways, travel speeds, and the control section length, the DMJM model shows that the point at which the approach volume will begin to exceed the service rate occurs at about 600 vehicles per hour (vph). This is equivalent to 2.3 queue passages/hr. However, "breakdown" (in the sense used by traffic engineers) will not occur. Even when approach volumes exceed the service rate of the system, an average of 600 vph or more will continue to flow through the canyon.

With approach volumes higher than 600 vph, the normal reaction (and the often-expressed belief) is to "cut the queues" in order to expedite vehicles through the control section. However, the analysis revealed that the key constraint to service rate is travel time. Consequently, the appropriate response to excessive queue buildup is to reduce the time lost to travel. The only practical way to do this is to reduce the number of queues per hour or, in other words, to extend the length of queues guided through the control section. For example, if only 2.0 queues are operated per hour under approach-volume conditions of 650 vph, the service rate increases to 626 vph. Theoretically, this means that 24 vehicles would be left waiting as opposed to the 50 vehicles that would have been left waiting with 2.3-queue passages/hr. It should be noted, however, that the vehicles left waiting would have experienced only minimal delay to that point, because they would have been among the last vehicles to arrive in the waiting queue.

There are two practical procedures for regulating the number of queue passages per hour. The operation can accommodate all queued vehicles until approach volumes reach 600 vph; consequently, the procedures need only be used when approach volumes exceed that level. Because the volumes entering both ends of the canyon will not be monitored, the procedures are based on physical queue relationships with approach volumes. When approach volumes reach 600 vph, the DMJM model predicts that 259 vehicles will be in a queue and passage time plus pilot-car turnaround time will equal 18 min. Either of these two factors can therefore be used to monitor the buildup of approach volumes during the day. A distance equal to 259 queued vehicles (7,770 ft) can be marked on the roadway and monitored by the operator of Pilot Car A as it completes a passage. Similarly, a controller can time the turnaround and discharge times to determine when 18 min has elapsed.

When either of the two monitoring methods indicates that 600-vph approach volumes are being experienced, the Glenwood Canyon TC will know that a queue buildup that cannot be completely dissipated with each passage is being experienced. At that time, the number of vehicles in each queue should be increased gradually, thereby reducing the number of queues per hour, and the operator of Pilot Car A should begin reporting estimates of the number of vehicles left waiting at the beginning of each passage. Depending on the intensity of arrival rates, time of day, season of the year, and response to the reduction in queues per hour, the TC may choose to continue the PCO. On the other hand, circumstances will occasionally dictate that the PCO be placed on standby and the roadway be opened to two-way traffic until such time as arrival rates taper off to manageable levels.

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An Evaluation of Portable Traffic Signals at Work Zones

GERALD L. ULLMAN AND STEVEN Z. LEVINE

Portable traffic signal systems are now being marketed by several manufacturers. These systems have the potential for replacing flaggers in many work zones that require alternating one-way traffic control. However, because these systems are relatively new, information is needed about their effect on traffic operations and safety at work-zone locations. The Texas Transportation Institute recently conducted studies of a fixed-time portable signal system at three work-zone lane closures on two-lane, two-way highways. At each site, data were collected on traffic volumes, driver noncompliance with the signals, and vehicle stopped delay. The studies showed that a substantial savings in flagger labor costs could be achieved by using a portable fixed-time signal system with only a minimal increase in motorist delay costs. Conservative estimates of the savings at the study sites ranged from $9 to $14 per hour. The studies also suggested that the potential for vehicle accidents within the work zone may be higher with portable traffic signals because of occasional driver noncompliance with these signals. The trade-off between this possible increase in vehicular accidents and the reduction in flagger accidents could not be estimated from this research.

As a general rule, work-zone lane closures on two-lane, two-way highways require some method of coordinating opposing traffic movements in the remaining open lane *(1)*. Most often this coordination is provided by flaggers stationed at each end of the lane closure. Unfortunately, flagging is a costly method of traffic control, requiring two or more persons continuously for the duration of the closure. In addition, flaggers must work close to moving traffic, which leaves very little room for error by either flagger or driver. Because flagging is such a labor-intensive and hazardous activity, it would be desirable to use other methods of traffic control whenever possible.

Traffic signal systems similar to those installed at intersections have been used in work zones in limited cases as an alternative to the use of flaggers. However, the cost of a traditional traffic signal installation ranges from $25,000 for a fixed-time system to $50,000 for a traffic-activated system. Consequently, traffic signals have only been feasible for long-term stationary work operations. As an example, the Texas State Department of Highways and Public Transportation has generally limited the use of traffic signals to lane closures on restricted-width bridges where construction will take 3 months or longer to complete.

Recently, however, several manufacturers have developed and are now marketing portable traffic signal systems. These systems are free-standing, self-contained, and easily transportable. They are generally simple to set up and program, and are designed to be adaptable to a variety of situations.

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Portable traffic signal systems have the potential for replacing flaggers in many work-zone operations requiring control of alternating one-way traffic. However, because these systems are relatively new, experience with them in actual work-zone application has been limited. Information about the effect of portable signal systems on work-zone safety and traffic operations is needed. The Texas Transportation Institute, as part of a study to improve flagger safety sponsored by the Texas State Department of Highways and Public Transportation, recently completed limited field studies of a portable fixed-time traffic signal system at several work-zone lane closures on two-lane, two-way highways. This paper presents the results of these studies.

STUDY PROCEDURE

Site Description

Portable fixed-time traffic signals were tested at three work-zone locations on two-lane, two-way rural highways (without paved shoulders) in Texas. Maintenance work on the roadway surface at each location required that one travel lane be closed. In each case, portable signals were used instead of flaggers to alternate opposing traffic through the one-lane section. The sites chosen for study represented a range of traffic volumes and work-zone lengths, as shown in Table 1. Also shown in Table 1 are the signal timing settings used at each site. Repairs at study Sites 1 and 2 were 1-day work activities, whereas repairs at Site 3 involved two 1-day lane closures. At Site 3, flaggers were used for traffic control on the first day, and signal control was used on the second.

Sites 1 and 2 had sight distances in excess of 1,000 ft to the work zone on both approaches, whereas severe horizontal and vertical geometry at Site 3 limited sight distance to about 500 ft

TABLE 1 SUMMARY OF TRAFFIC VOLUMES, WORK-ZONE LENGTHS, AND SIGNAL TIMING SETTINGS

Site	Traffic Volumes, 1985 AADT	Work-Zone Length (ft)	Signal Timing Settings (sec) Cycle Length	Green Phase	All-Red Clearance
1	600	600	78	10	26
2	2,400	2,600	246	30	90
3	10,000	1,100	140	30	37

NOTE: AADT = annual average daily traffic.

in either direction. At none of the sites was there visibility from one end of the lane closure to the other. The speed limit at each site was posted at 55 mph, with actual travel speeds very close to this value.

The traffic control plan for the sites was similar to that used for flagger-controlled minor work-zone operations *(1)*, except that an orange-and-black symbolic Signal Ahead sign (W3-3) replaced the Flagger Ahead sign in advance of the closure, as shown in Figure 1.

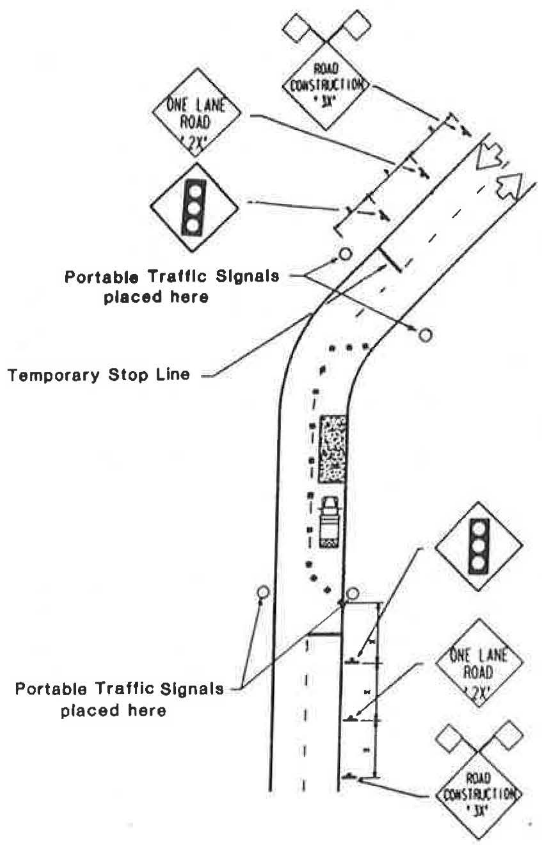

FIGURE 1 Traffic control plan.

Data Collection and Analysis

A variety of data was collected during the setup and operation of the portable signals, including traffic volume, driver compliance with the signals, and vehicle stopped delay. Delay and compliance data were collected for about 4 hr each day during the time that work was actually being performed in the closed lane.

Stopped-delay data were also collected for flagger control on the first day of the lane closure at Site 3. These data were not available from Sites 1 and 2, which were only one-day operations. However, data collection personnel at Site 1 (average daily traffic of 600) noted that all vehicles approaching the work zone during the time of the portable-signal study were isolated arrivals. It was assumed that flaggers would have allowed these vehicles to pass through the work zone without stopping, because they were the only vehicles present at that particular time. Consequently, averaged stopped delay per vehicle would have been negligible had flaggers been the method of traffic control. Unfortunately, a similar estimation was not possible at Site 2, because of the greater traffic volumes and longer work zone. Nevertheless, it was possible to compare vehicle stopped delay for flagger-controlled and signal-controlled operation at Sites 1 and 3.

STUDY RESULTS

Motorist Delay

One of the advantages to using flaggers is that they are responsive to random vehicle arrivals and gaps in the traffic stream, and can assign traffic movements through the work zone so as to minimize vehicle stops and delays. Fixed-time signals do not react to isolated random vehicle arrivals. Rather, motorist delay under signal control is a function of the timing parameters (cycle length, green phase time, etc.). Consequently, motorist delay should increase at a work zone when fixed-time portable signals are used in place of flaggers. At Site 1, which had low traffic demand, this was found to be the case. Table 2 shows that average stopped delay per vehicle was higher at Site 1 when traffic signals were used.

However, flaggers were not found to have as distinct an advantage over fixed-time signals when traffic demands were greater. As Table 2 shows, average stopped delay at Site 3 was nearly identical for both flagger and signal control. This site was a longer work zone than Site 1 and had dramatically higher traffic demand. Flaggers at Site 3 could not allow vehicles to pass through the work zone as they arrived (as could have been done at Site 1), but instead had to methodically assign traffic movement to one direction and then to the other. In effect, flaggers duplicated the operation of the fixed-time signals. Consequently, average stopped delay per vehicle was very similar for the two types of traffic control. These results indicate that at higher traffic volumes, fixed-time signals at a work-zone lane closure can provide a level of service to drivers comparable with that provided by flaggers. However, when volumes are low, signals may provide a poorer level of service than that attainable with flagger control.

TABLE 2 COMPARISON OF STOPPED DELAY: FLAGGER CONTROL VERSUS FIXED-TIME SIGNAL CONTROL

Site	Hourly Volume	Average Stopped Delay (sec/vehicle) Flagger	Signal	Increase	Added Stopped Delay (vehicle hr/hr)
1	50[a]	0[b]	24	24	0.3
3	750[c]	36	38	2	0.4

NOTE: Site 2 was not used in the comparison of stopped delays because such data were not available (and could not be reasonably estimated) for flagger control.
[a]Approach volume-to-capacity ratio (v/c) = 0.13.
[b]Estimated from observed traffic arrivals. No vehicles would have been forced to stop at this location had flaggers been used.
[c]v/c = 0.9.

Although the quality of service provided to drivers is an important factor to be considered, it is probably more important to examine the impacts of signal control from an economic standpoint. Portable signal systems are designed to be simple and easy to operate, so they require little additional setup time over that necessary to close the travel lane to traffic. Consequently, the primary operating cost associated with using portable signals is the amount of additional delay that it causes drivers approaching the work zone. Additional motorist delay per hour generated by the portable traffic signals above that incurred (or that would have been incurred) under flagger control is shown in the last column of Table 2. The values for both sites are nearly identical, and amount to less than 0.5 vehicle-hr of additional stopped delay per hour. The large increase in average delay at Site 1 affected only a small number of motorists, whereas the large number of drivers at Site 3 were affected by only a small increase in delay.

The low cost of additional motorist delay at the two study sites was more than offset by the savings in flagger labor costs. As Table 3 shows, fixed-time portable traffic signals provided significant cost savings over the use of flaggers. Computed savings at Sites 1 and 3 amounted to $9 and $14 per hour, respectively.

TABLE 3 SUMMARY OF PORTABLE SIGNAL COSTS AND BENEFITS

Site	Cost of Additional Motorist Delay ($/hr)[a]	Savings in Labor Costs ($/hr)[b]	Savings Achieved by Portable Signals ($/hr)
1	3.12	12.00	8.88
3	4.16	18.00	13.84

[a]Based on recent estimates of value of travel time = $10.40/vehicle-hr *(2)*.
[b]Based on typical wages and benefits of approximately $6/hr for Maintenance Technician I working for the Texas State Department of Highways and Public Transportation.

The portable signals examined in this study were reported to cost approximately $8,000 per pair. Using the previous conservative estimates of flagger labor cost savings, the signals would pay for themselves after 1,600 hr of service. Although these comparisons do not include any signal maintenance costs, the system still appears to have been a cost-effective alternative to flagger control at the sites studied.

Driver Noncompliance with Traffic Signals

One of the major concerns surrounding the use of portable signals in work zones is with whether drivers will obey them. Failure of a driver to obey the signal could lead to a serious head-on collision with an oncoming vehicle within the work zone.

In the following results of the noncompliance data collected at each site, column 1 gives the total number of motorists observed approaching and passing through the work zone, and column 2 gives the number of those vehicles that entered the work zone while facing a red indication. Columns 1 and 2 were then used to generate column 3, the rate of observed noncompliance per 1,000 vehicles.

	Vehicles Approaching Work Zone		
Site	*Total No.*	*No. Running Red*	*No. Running Red/1,000*
1	43	0	0
2	400	2	5
3	500	2	4

Although the rates indicate that noncompliance was not a major problem, the results show that a few vehicles were observed to enter the work zones on the red. These vehicles were stopped by research or work personnel, or both, before they had traveled very far into the site, so no accidents or major conflicts occurred. However, the potential for mishap was obviously present in these instances.

Although not shown, two different types of violations occurred at Sites 2 and 3. The first involved vehicles that initially came to a stop, but then entered the work zone while the light was still red. It appeared that the drivers of the vehicles saw the signals, but then chose to proceed through the work zone on the red even though they could not see completely through the work zone. (As stated previously, at none of the sites was there visibility from one end of the work zone to the other.) This type of noncompliance indicates that some drivers may question the validity of portable signals. It may be possible to improve signal validity by putting out a temporary stop line 50 to 60 ft in advance of the signal, as shown in Figure 1. The stop line identifies where drivers should stop and reinforces the need to stop. Also, a supplemental temporary Stop Here on Red sign (R10-6) *(1)* may be erected next to the bar to further enforce the need for stopping and add validity to the presence of the signals.

The other type of violation occurring at Sites 2 and 3 involved vehicles that ran the red light and entered the work zone without stopping, which suggests that they never saw the signals. Unfortunately, it may be quite difficult to reduce or eliminate these types of incidents. It was suggested that the manufacturer of the portable signals increase the wattage of the lamp heads in order to make them more visible in daylight. Other attention-getting devices may be available to increase the conspicuity and attention-getting capability of the signals. However, identification and experimentation with these types of devices was beyond the scope of this study.

SUMMARY

The results have been presented of field studies examining the use of fixed-time portable traffic signals instead of flaggers at work zones requiring alternating one-way traffic control. On the basis of these limited studies, fixed-time signals appear to be a suitable alternative to the use of flaggers for alternating one-way traffic through a work zone. Significant savings in flagger labor costs can be realized with what appears to be a minimum of additional delay costs to motorists. However, the trade-offs between the potentials for reduced flagger accidents and increased vehicle accidents in work zones cannot be accurately estimated at this time. Some supplemental signs and devices have been suggested to reduce the occurrence of motorist noncompliance with the signals, but the devices have not been tested under field conditions.

As the use of portable signals increases and drivers become more accustomed to their presence in work zones, it would be expected that motorist compliance with them would improve. The limited studies documented here can only serve as a starting point to determining the effects of portable signals at work-zone lane closures. Continued research and experience with portable signals will be needed before the full benefits and costs associated with their use are known.

ACKNOWLEDGMENT

This research was conducted by the Texas Transportation Institute and sponsored by the Texas State Department of Highways and Public Transportation in cooperation with FHWA.

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Supplemental Devices to Enhance Flagger Safety

SCOTT C. BOOKER, GERALD L. ULLMAN, AND STEVEN Z. LEVINE

Improper flagging techniques and driver misunderstanding of flagger messages can compromise the effectiveness and safety of a flagger. Supplemental devices may be necessary to complement the standard traffic control and flagging techniques outlined in the *Manual on Uniform Traffic Control Devices* (MUTCD) to ensure that drivers understand what actions are expected of them at work zones controlled by flaggers. The Texas Transportation Institute recently evaluated a reusable, temporary stop bar and a freestanding, oversized Stop/Slow sign paddle at lane closures on two-lane, two-way highways where flaggers were used to alternate one-way traffic. Operational data on distances from the flagger at which vehicles stopped, speeds through the work zone, and approach speeds were analyzed. The data showed that the temporary stop bar and oversized paddle were useful in helping drivers decide when and where to stop in front of the flagger. However, the stop bar and sign paddle had no significant effect on reducing approach speeds or speeds through the work zone. The flaggers who actually used the supplemental devices commented that the oversized Stop/Slow paddle helped drivers respond to their commands better and that the temporary stop bar helped identify a point at which drivers were to stop.

There is growing concern about the effectiveness and safety of flaggers in work zones. Improper flagging techniques or driver misunderstanding of messages may result in inaccurate driver expectancy. This leads to inappropriate driver response, with consequences as serious as collisions with other vehicles or with flaggers.

Standard requirements and procedures for flagging are presented in the *Manual on Uniform Traffic Control Devices* (MUTCD) *(1)*. However, it appears that even though flaggers perform a critical role in work-zone traffic control, flagging duties are often assigned to the newest members of the work crew, who may have had little or no training in proper flagging techniques. This may cause inconsistent messages to be sent to drivers, compromising flagger performance and safety. A need therefore arises to complement standard MUTCD traffic control and flagging techniques with supplemental devices to improve driver understanding of actions expected of them at the work zone. Two such devices, a reusable temporary stop bar and an oversized Stop/Slow paddle mounted on a freestanding base, were evaluated as part of a study to improve flagger safety sponsored by the Texas State Department of Highways and Public Transportation. This paper presents the results and conclusions from this research effort.

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DESCRIPTION AND PURPOSE OF DEVICES STUDIED

Temporary Stop Bar

The temporary stop bar used in this study consisted of six interlocking sections of white rubber, each approximately 6 in. wide, 40 in. long, and 0.4 in. thick. The sections were placed three long by two wide, making the stop bar a total of 12 in. wide and 10 ft long.

The stop bar, or stop line, is most often found at Stop-sign or traffic-signal-controlled intersections. Stop bars have also been used at some major work zones involving lane closures on two-lane, two-way highways where it is necessary to alternate one-way traffic for an extended period of time. These stop bars are normally painted on the pavement and are therefore not commonly used at work operations lasting only a few days or less. The rubber stop bar, however, can be easily placed, picked up, and reused again and again.

The purpose of the stop bar is to identify the point at which vehicles should stop if instructed to do so by the flagger. The stop bar may also help communicate the flagger's message to stop to an approaching motorist.

Oversized Sign Paddle

The sign paddle used in this study consisted of a 30 × 30-in. standard Stop sign (R1-1) and a 36 × 36-in. black-on-orange Slow sign mounted back to back on a freestanding wooden frame. The top portion of the wooden frame was manually rotated by the flagger to allow either sign to face oncoming traffic. Figure 1 shows the oversized sign paddle. The signs were mounted at a height of 6 ft from the bottom of the signs, approximately the same height as normal Stop or warning signs.

The evaluation of the oversized Stop/Slow paddle is of special significance because of the latest revision to Section 6F-2 of the MUTCD. The March 1986 revision states that the sign paddle should be the primary hand-signaling device and that flag use should be limited to emergency situations and spot locations that can best be controlled by a single flagger *(1)*.

Previous research on driver understanding of work-zone flagger signals and signaling devices has indicated that Stop/Slow paddles are an effective method of transmitting messages to a driver *(2, 3)*. Nevertheless, many workers complain that

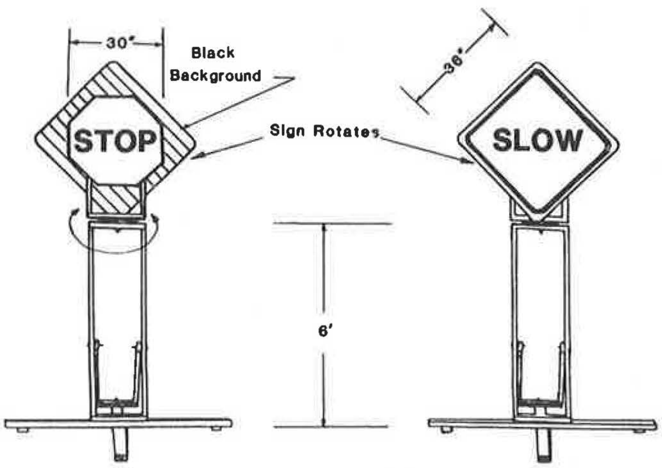

FIGURE 1 Freestanding oversized Stop/Slow paddle.

the typical hand-held sign paddle is too heavy and difficult to use in strong winds. Also, the paddle does not appear to have the attention-getting value of the more commonly used flag *(3)*.

This situation is remedied by using the oversized Stop/Slow paddle because the flagger stands next to the freestanding sign paddle, combining the high comprehension of a sign paddle with the high visibility of a flagger. The flagger does not hold the paddle, but merely changes the sign when necessary.

The oversized Stop/Slow paddle has the obvious advantage of being easier to identify from a greater distance than the typical 18 × 18-in. hand-held paddle. The oversized paddle also provides an additional Slow message to vehicles as they are leaving the restricted one-lane section.

STUDY PROCEDURE

Site Description

The reusable temporary stop bar and oversized sign paddle were evaluated at a work-zone location on a two-lane, two-way rural highway near Port Arthur, Texas. At this location, a lane was closed and flaggers were used to alternate one-way traffic through the work zone. The site was a straight and level section of highway and there was virtually no development in the general area. The average annual daily traffic (AADT) at this site was approximately 7,000 vehicles per day. At the work zone, the eastbound lane was closed over a 3/4-mi section to allow a shoulder to be added. Flaggers with two-way radios were used at each end of the work zone to alternate traffic through the restricted section.

The following advance signing was used at the approaches to the work zone: *(a)* Road Construction Ahead (with a 40-mph advisory speed plate), *(b)* Be Prepared to Stop, *(c)* One Lane Traffic Ahead (with 1,000-ft supplemental plate), and *(d)* Flagman Ahead. The signs were spaced at approximately 500-ft intervals.

Data Collection and Analysis

Three different treatments were examined during this field study in both the open and closed lanes.

1. *Existing*: Consisted of the standard MUTCD setup with flaggers using only flags and hand signals to communicate with approaching vehicles.
2. *Temporary stop bar*: Same as the existing setup with addition of the temporary stop bar across the lane of traffic being stopped by the flagger. The flagger was allowed to stand anywhere behind the stop bar.
3. *Oversized Stop/Slow paddle*: Same as the existing setup with addition of the oversized Stop/Slow paddle just off the roadway adjacent to the flagger.

Three types of data were collected during the field study for each of the three treatments.

1. *Vehicle stopping points at work-zone approaches*: Distances between the flagger and the stopping point of the first vehicle (measured to the front of the vehicle) as well as distances between the stop bar and the first vehicle when the stop bar was in use were measured to the nearest foot.
2. *Vehicle through speeds at work-zone approaches*: Vehicles approaching the work zone that were instructed by the flagger to proceed through the work zone without stopping were timed with a stopwatch over a 200-ft section located just before the position of the flagger. The times were recorded and later converted to speed in miles per hour.
3. *Vehicle approach speeds to the work zone*: A car-following technique using a vehicle equipped with a time-speed-distance measuring instrument was used to record travel speeds of approaching vehicles. The approach speeds were recorded at 500-ft intervals from approximately 3,000 ft in advance of the work zone to the point at which the vehicle came to a stop.

Data were collected over a 2-day period. Each treatment was studied for approximately 2 hr in the open and closed lanes each day. Table 1 shows the order in which the treatments were studied. This order allowed each treatment to be studied over a different time period than that on the first day.

TABLE 1 TREATMENT ORDER

Time Period	Open Lane	Closed Lane
Day 1		
8:00 a.m.–10:00 a.m.	Existing	Stop bar
11:00 a.m.–1:00 p.m.	Sign paddle	Existing
2:00 p.m.–4:00 p.m.	Stop bar	Sign paddle
Day 2		
8:00 a.m.–10:00 a.m.	Stop bar	Sign paddle
11:00 a.m.–1:00 p.m.	Existing	Stop bar
2:00 p.m.–4:00 p.m.	Sign paddle	Existing

RESULTS

Stopping-Point Data

Stopping-point data collected on the first vehicle directed to stop by the flagger are summarized in Table 2. The data suggest that the temporary stop bar and the oversized Stop/Slow sign paddle were useful in helping drivers decide when and where to stop in front of the flagger. The variability of the distance between the flagger and the first stopped vehicle was greatly reduced when the stop bar and sign paddle were used.

As can be seen in Table 2, the standard deviations of stopping distances from the flagger were reduced when either the stop bar or the sign paddle was used, as compared with the existing conditions with no supplemental devices. Less variability was evident in the closed lane, most likely because of additional visual information behind the flagger (e.g., cone taper, work area) that helped drivers decide where to stop. In the open lane, this additional visual information was not present, so the variability in how far away drivers stopped from the flagger was greater. It appears that the supplemental devices were especially useful in the open lane. When the standard deviations of stopping distances in the open lane were compared for the existing condition and for use of the stop bar and the sign paddle, it was found that use of these devices reduced the standard deviations by two-thirds.

TABLE 2 DISTANCE BETWEEN FLAGGER AND FIRST STOPPED VEHICLE

	Closed Lane			Open Lane		
Treatment	*N*	Avg Distance (ft)	Standard Deviation	*N*	Avg Distance (ft)	Standard Deviation
Existing	44	57	32	54	67	99
Stop bar	46	47	21	45	43	38
Sign paddle	51	50	23	45	38	32

NOTE: *N* = sample size; 1 ft = 0.305 m.

The temporary stop bar was very effective in identifying a point behind which the drivers were to stop. Only 5 of 91 vehicles (5.5 percent) encroached on the stop bar, and no vehicles stopped beyond it. Thus, the flaggers were able to regulate the distance between themselves and the first stopped vehicle. Flaggers generally stood 20 to 30 ft behind the stop bar.

Vehicle Speeds Through the Work Zone

Speed data collected on approaching vehicles that were directed by the flagger to proceed through the work zone are summarized in Table 3. As can be seen, neither the average nor the standard deviation of the through speeds was significantly different among any of the three treatments.

TABLE 3 APPROACH SPEEDS OF VEHICLES DIRECTED BY FLAGGER TO PROCEED THROUGH WORK ZONE

	Open Lane		Closed Lane	
Treatment	Avg Speed (mph)	Standard Deviation	Avg Speed (mph)	Standard Deviation
Existing	51.0	9.1	45.2	7.3
Stop bar	49.3	7.8	46.2	8.9
Sign paddle	48.1	8.5	45.9	7.2

NOTE: 1 mph = 1.61 km/hr.

The stop bar, whose purpose is to identify a stopping point, was not expected to have an effect on through speeds. It was expected, however, that the oversized Slow sign might reduce through speeds. As seen in Table 3, this was not found to be the case. Apparently drivers proceeded through the work zone at what they believed to be a comfortable and reasonable speed. The slightly lower through speeds in the closed lane can be explained by the lane-changing maneuver required at the beginning of the lane closure.

It should be noted that flaggers made no attempt to slow traffic by using hand or flag signals during any of the treatments. Also, the geometrics of the site and location of the work crew relative to the through lane allowed for relatively high speeds.

Vehicle Speeds Approaching the Work Zone

Speed profile data collected on vehicles approaching the work zone showed no substantial difference among the three treatments in either the open or the closed lane. Again, drivers approached the work zone at whatever speed they believed to be comfortable, regardless of the treatment in place.

Flagger Comments

The flaggers using the supplemental devices during the field study commented that the oversized sign paddle helped drivers respond better to the Stop and Proceed commands. Many of the flaggers would point to the sign paddle as vehicles approached rather than use hand or flag signals, which have been misunderstood by drivers.

SUMMARY AND RECOMMENDATIONS

Results have been presented of field studies evaluating the use of a temporary stop bar and a freestanding oversized Stop/Slow paddle as supplemental devices to enhance flagger safety. The purpose of these supplemental devices is to improve driver understanding of actions expected of them at work zones controlled by flaggers, such as a lane closure on a two-way, two-lane highway.

On the basis of these limited studies, the temporary stop bar and oversized sign paddle appear to be effective devices in helping drivers understand when and where to stop in front of the flagger if instructed to do so. The stop bar and sign paddle, however, appeared to have little effect on speeds of vehicles instructed to proceed through the work zone or on speeds of vehicles approaching the work zone.

It should be noted that the sign paddle constructed and tested in these studies does not conform to the standards presented in Section 6F of the MUTCD. Specifically, the shape of the paddle should be an octagon, not a diamond, because the message to stop is more critical than the message to travel at a slower speed. In future implementations of such a paddle, a standard-shaped sign should be used.

The stop bar and sign paddle were evaluated independently. It is recommended, however, that they be used together by placing the stop bar approximately 30 ft in advance of the flagger and sign paddle. In addition, a more portable design for the sign paddle should be developed. It is possible that a small trailer could be modified to hold such a paddle that could be towed from site to site.

ACKNOWLEDGMENT

This research was conducted by the Texas Transportation Institute and sponsored by the Texas State Department of Highways and Public Transportation in cooperation with FHWA.

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Optimization of Equipment Use in Routine Highway Maintenance

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An optimization procedure was developed for assigning equipment to routine highway maintenance activities so as to minimize total fuel consumption. The procedure is based on a linear programming technique and determines the optimal assignment of equipment in number of equipment days for which a particular equipment type is to be assigned to a specific maintenance activity. The program is capable of handling a large number of activity-equipment combinations and performs optimization of fuel use provided that some of the equipment types considered are interchangeable. An application of the procedure to an equipment assignment problem is presented using the actual equipment use data from a typical subdistrict in Indiana. The technique was found to be efficient and provided feasible results for establishment of equipment assignment guidelines for fuel conservation.

Highway maintenance consists of a variety of activities that require many different types of equipment. These activities are both labor and fuel intensive. Fuel consumed by maintenance equipment may account for as much as one-third of the total material cost and about one-tenth of the total actual maintenance cost *(1)*. A previous study concerning fuel use in routine highway maintenance found that the same task was performed by interchanging different types of equipment that had substantially different fuel consumption rates *(1)*. Consequently equipment management tools that can enable a better control of fuel consumption are important elements of maintenance management. Optimization techniques can be applied to the problem of assigning different types of equipment to various maintenance activities so as to minimize total fuel consumption.

Mathematical modeling techniques have been successfully applied to the problems related to pavement management *(2–4)*. However, the application of mathematical optimization techniques to routine highway maintenance has long been considered infeasible because of the wide variation in the characteristics of routine maintenance activities and because of many uncertain elements such as the weather and the difficulty in accurately assessing maintenance needs.

Simulation is another operations research technique that can be applied to routine maintenance activities. A project-level simulation model of roadside mowing was developed in the early 1970s *(5)*. Later a highway maintenance simulation model was developed for the Louisiana Department of Highways *(6)*. Other than these two simulation models, however, there have been no serious efforts in this area. One reason is that simulation models often require a great many assumptions, such as a probability distribution of activity occurrences, which may inversely affect the validity of the models.

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Because the specific objective of the current study was to maximize energy conservation, an approach focusing on the equipment assignment component of the overall maintenance scheduling process was needed. A linear programming technique was applied to develop a mathematical model for determining the optimal equipment assignment to minimize total fuel consumption. A sample application is discussed to demonstrate the feasibility of incorporating this equipment assignment technique into the current activity-scheduling process.

OPTIMIZATION METHODOLOGY

The concept of the optimization model developed in this study is based on the interchangeability of equipment types for particular tasks within each activity. Equipment that would use less fuel should be assigned as much as possible to minimize total fuel consumption. The fuel survey data collected in a previous study *(1)* and field observations conducted in this study showed that different equipment types are used to perform the same tasks. For example, pickup crew cabs and dump trucks are used interchangeably in rest area maintenance. Similarly, for hauling purposes, pickup trucks, pickup crew cabs, dump trucks, and do-all trucks have also been used interchangeably. However, the fuel use rates of this equipment vary considerably. Furthermore, the same equipment type has different fuel use rates when used in different activities. It is possible, therefore, to optimize the equipment assignment so as to minimize total fuel consumption in the performance of various activities.

A trend analysis conducted on fuel use during the study indicated that pickup trucks, pickup crew cabs, dump trucks, and do-all trucks used about 70 percent of the total fuel consumed for all routine maintenance activities excluding snow and ice removal. Therefore, consideration of only these equipment types can save a substantial amount of fuel.

The optimization model approaches the problem of fuel savings on an aggregate basis. The decision variable used in the model is the number of equipment days of a particular type to be used for an activity. This optimal value can then be taken as the target value of equipment days to be assigned to the activities. The variable of equipment days was used as an aggregate measure because there are daily fluctuations in equipment scheduling due to such factors as the level of accomplishment, equipment availability, labor availability, and weather conditions. Specific scheduling can best be dealt with by experienced schedulers. Scheduling equipment units while making efforts to conform to targeted values is typical of the activity-scheduling procedure currently used by subdistricts of the Indiana Department of Highways for preparing the biweekly activity plan *(7)*.

Model Development

The optimization model developed in this study has two types of constraints: *(a)* planned level of accomplishment of activities included in the model and *(b)* equipment availability. Both constraints are expressed in equipment days. Figure 1 is a flowchart showing the process of model development. A data base containing equipment use, fuel use, productivity, and equipment breakdown data is frequently used during model development.

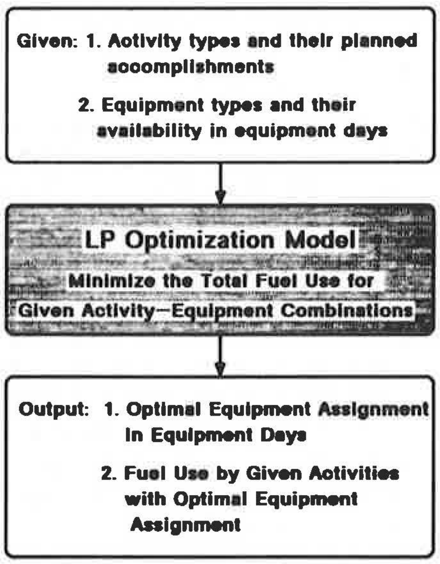

FIGURE 1 Maintenance equipment assignment technique.

First, the planned level of accomplishment of all maintenance activities is set and activities that are considered in the model are selected from the activity list. A set of equipment types of interest is then selected. The availability of selected equipment types is expressed in equipment days. Total available equipment days of a particular equipment type is computed by simply multiplying the number of units of the equipment type by the number of working days available during the analysis period. From the total available equipment days, the number of equipment days lost because of mechanical breakdowns and the number of equipment days necessary to perform other activities that are not considered in the model must be subtracted. The remaining equipment days for each selected equipment type, then, forms the equipment availability constraint.

After the equipment-activity combinations have been identified, interchangeable equipment types are grouped within each activity. Groups consist of only equipment types that are interchangeable for a specific task. If only a particular equipment type can be used to perform a task, constraints are appropriately formulated to indicate this requirement. The equipment-use factor of each equipment type within an interchangeable-equipment group is provided as input and the resulting sum of equipment-use rates is considered as a combined-equipment-use factor. The equipment-use factor is defined as the average number of equipment units of a particular type used to complete a scheduled amount of activity within one working day. The combined-equipment-use factor reflects the actual need for equipment for an activity. For example, if a pickup truck and a pickup crew cab are used interchangeably in shallow patching, and if the pickup truck's use factor is 0.5 and that of the pickup crew cab is 0.7, the combined-use factor of this interchangeable-equipment group will be 1.2. This means that for every 100 working days of shallow patching, 120 units of either pickup trucks or pickup crew cabs, or a combination of these two types, will be needed. Combined-equipment-use factors are used to compute conversion factors called K-values, which translate the level of accomplishment for an activity into the number of equipment days necessary to complete the activity by a particular type of equipment within an analysis period. The resulting equipment days, then, forms the equipment requirement constraint.

After these constraints have been determined, the objective function can be formulated. Each coefficient of the decision variable in the model is computed by multiplying a combined-use factor, the fuel-use rate of a type of equipment used for an activity, and a conversion factor K-value.

Model Formulation

The formulation of the maintenance equipment assignment technique using linear programming is discussed below. The objective function is to minimize the total number of gallons of fuel consumed in performing all scheduled maintenance activities considered.

Minimize

$$\sum_i \sum_j R_{i,j} \times U_{i,j(l)} \times K_{i,j(l)} \times Y_{i,j}$$

Subject to the following constraints:

1. Demand constraints: The demand for all scheduled activities must be met.

$$\sum_j Y_{i,j} \geq D_{i(l)} \qquad \text{for all } i$$

2. Capacity constraints: The total number of equipment days assigned to any equipment type must not exceed the number of equipment days available.

$$\sum_i Y_{i,j} \leq C_j \qquad \text{for all } j$$

3. Nonnegativity constraints: All variables must be greater than or equal to zero.

$$Y_{i,j} \geq 0 \qquad \text{for all } i, j$$

where

$Y_{i,j}$ = number of equipment days of equipment type j assigned to activity i,
$R_{i,j}$ = fuel consumed by one unit of equipment type j in accomplishing one production unit of activity i,
$U_{i,j(l)}$ = combined-use factor of equipment type j in interchangeable-equipment group l when used in activity i,
N_i = scheduled level of accomplishment of activity i,
$D_{i(l)}$ = number of equipment days required to perform the scheduled level of accomplishment (N_i) of activity i by equipment type j that belongs to an interchangeable-equipment group l,
C_j = number of available equipment days of equipment type j, and
$K_{i,j(l)}$ = units of accomplishment of activity i by equipment type j of equipment group l.

$D_{i,(l)}$ is computed as follows:

$$D_{i,(l)} = \frac{N_i}{K_{i,j(l)}}$$

It should be noted that the interchangeable equipment types must have the same K-value.

Estimation of K-Values

The K-value can be interpreted as the capacity of one equipment unit of a particular equipment type to perform a particular task in one work day, called a crew day. This value is stated in terms of the production unit of the activity in which the equipment is used. Thus, K-value is expressed in units of level accomplishment per equipment type per crew day.

For example, a K-value of 1.1 for dump trucks when used in crack sealing indicates that 1.1 lane-mi of sealing can be accomplished on the average by one dump truck per crew day. The use of K-values allows the consolidation of different units of measurement into one common unit for the decision variables employed—equipment days. K-values are used to translate the information on scheduled production units for different activities into the equipment days necessary to complete the scheduled levels. The resulting equipment days are then used as work demand constraints in the optimization model. K-values are also used to transform the optimal solutions, given in equipment days, back into the original production units of each activity so that fuel consumption can be computed by using available fuel-use rates, given in gallons per production unit. K-values are computed by the following formula:

$$K_{ij(l)} = \frac{P_i}{\sum_{j \in l} F_{ij}}$$

where

$K_{ij(l)}$ = K-value for equipment type j in an interchangeable-equipment group l for activity i,
P_i = production per crew day for activity i,
F_{ij} = use factor of equipment type j when used in activity i,
$\sum_{j \in l} F_{ij}$ = combined-use factor for equipment type j in an interchangeable-equipment group l when used in activity i.

The combined-use factor indicates how many equipment units would be required to accomplish a certain level per crew day if only one type of equipment is used.

Model Output

The decision variables are given in units of equipment days. For example, $Y_{207,1}$ is the number of equipment days allowed for equipment type 1, a pickup truck, to be used for activity 207, crack sealing. The model tries to minimize the total amount of fuel consumed by the activity-equipment combinations considered. Therefore, the optimization model may indicate that some activities should receive more or fewer equipment days for certain equipment types than what is normally used for those activities. As long as the equipment types can be interchanged, such recommendations should be followed because the overall fuel use will eventually be minimized by letting other activities use less fuel-consuming types of equipment. If the results appear to be grossly misrepresented or not realistic, equipment grouping needs to be reconsidered and constraints need to be adjusted to reflect any corresponding changes.

In actual scheduling, once an equipment unit has been assigned to an activity, it is not available for other activities for the entire day. The average number of equipment units to be assigned to perform one activity during one crew day can be computed by dividing the values for decision variables by crew days scheduled. Therefore, if one decision variable has 200 equipment days for a particular type of equipment and 100 crew days have been scheduled, the new use factor will be 2.0.

APPLICATION OF THE MODEL

A sample problem applied to the subdistrict level was used to compare the fuel use expected by the current equipment assignment practice observed in the field survey with the optimal equipment assignment determined by the model. The problem was developed by using the routine maintenance accomplishment data *(8)*, equipment use data *(1)*, and equipment availability data compiled during the study.

Description of Sample Subdistrict

The Fowler subdistrict chosen for the analysis is a typical subdistrict in Indiana, where most of the highways are non-Interstate routes. This sample subdistrict was one of the six subdistricts in which a field survey on equipment and fuel use was conducted earlier *(1)*.

Description of Maintenance Demand

Table 1 gives the 1984 maintenance level of accomplishment of the subdistrict for the 12 major fuel-consuming activities. It provides an overall view of the maintenance needs for this subdistrict, including the work done on both Interstate and other state highways. In this subdistrict, activities on the Interstate require less fuel. On the other hand, most of the activities on other state highways consume a considerable amount of fuel. Therefore, for modeling purposes the sample problem considered only the 12 activities on other state highways.

Equipment Availability

Table 2 shows how equipment availability constraints were derived. In this sample problem, five types of hauling equipment were considered. First, four major equipment types were selected: pickup truck, pickup crew cab, dump truck, and do-all truck. Utility trucks were then added because pickup trucks and pickup crew cabs can often do the same work as utility trucks when used for sign maintenance. During FY 1984, the sample subdistrict had 11 pickup trucks, 6 pickup crew cabs, 1 utility truck, 20 dump trucks, and 7 do-all trucks. To compute the number of available equipment days of each equipment type, 250 working days or crew days per year was used. The value for annual available equipment days was adjusted for possible mechanical breakdowns. The statewide average breakdown rates were used here because the existing equipment management system does not provide equipment breakdown rates for each equipment type by subdistrict.

From the adjusted equipment days were subtracted the equipment days used for activities not included in the optimization model. It was also necessary to subtract equipment days used for supervision of field activities by the superintendent and three unit foremen, because this activity (activity 112) is not recorded on crew-day cards. It was assumed that one pickup is used for each of the supervisory positions on each working day. The remaining equipment days then becomes the constraint to the optimization model.

Computation of K*-Values*

The computation of K-values is a key element of the maintenance equipment assignment technique. In a previous report *(1)* equipment-use factors were computed for all equipment-activity combinations. The use factor indicates how often a particular type of equipment is used. For example, a use factor of 1.10 indicates that 110 units of this equipment type are used in 100 crew days of this activity, or 110 equipment days are assigned for 100 crew days of this activity. This means that more than one unit is used on some of the crew days.

A comparison of computed use factors, field survey data (crew-day cards), and the field operations handbook *(7)* shows which equipment types can be interchanged. For example, for Activity 207, crack sealing, the equipment-use factors for

TABLE 1 ACTUAL LEVEL OF ACCOMPLISHMENT FOR 12 MAJOR ACTIVITIES AND ESTIMATED FUEL CONSUMPTION, FY 1984, FOWLER SUBDISTRICT

				INT		OSH		ALL	
Activity Code	Activity Name	Unit of Measurement	Fuel Use * (gal/unit)	Actual Accomp. ** (units)	Estimated Fuel Use (gallons)	Actual Accomp.** (units)	Estimated Fuel Use (gallons)	Actual Accomp. ** (units)	Estimated Fuel Use (gallons)
201	Shallow patching	Tons of mix	8.78	113	990	814	7,150	928	8,150
205	Seal coating	Lane miles	85.14	-	-	95	8,090	95	8,090
207	Sealing cracks	Lane miles	23.27	-	-	186	4,330	186	4,330
210	Spot repair of unpaved shoulders	Tons of aggregate	2.15	36	80	655	1,410	691	1,490
212	Clipping unpaved shoulders	Shoulder miles	52.86	-	-	75	3,960	75	3,960
221	Machine mowing	Swath miles	1.35	-	-	2,177	2,940	2,177	2,940
231	Clean & reshape drainage structures	Linear feet	0.22	140	30	41,426	9,110	41,566	9,140
235	Cleaning minor drainage structures	# of structures	3.81	32	120	361	1,380	393	1,500
251	Subdistrict sign maintenance	Man-hours	1.02	638	650	2,306	2,350	2,944	3,000
283	Buildings and ground maintenance	Man-hours	1.52	-	-	4,170	6,340	4,170	6,340
284	Material handling and storage	Man-hours	3.52	-	-	2,153	7,580	2,153	7,580
289	Other support activities	Man-hours	2.69	-	-	3,742	10,070	3,742	10,070

* Source: Reference 1.
** Source: Reference 8.

TABLE 2 ESTIMATED AVAILABLE EQUIPMENT DAYS OF FIVE EQUIPMENT TYPES FOR 12 ACTIVITIES INCLUDED IN MODEL, FY 1981, FOWLER SUBDISTRICT

Equipment No. & Name	1 Pickup truck	2 Pickup crew cab	8 Utility truck	9 Dump truck	10 Do-all truck
* Equipment availability					
No. of equipment	11	6	1	20	7
No. of total equipment days available (a)	2,750	1,500	250	5,000	1,750
Breakdown rate (b)	12%	4%	2%	18%	12%
Remaining equipment days available	2,420	1,440	245	4,100	1,540
* Equipment days used for activities other than 12 activities included in the model					
Interstate (INT)	76	637	37	1,021	10
Other State Highways (OSH)	404	224	69	2,014	57
INT + OSH	480	861	106	3,035	67
Supervision (c)	1,000	-	-	-	-
Total excluded	1,480	861	106	3,035	67
* Equipment days available for 12 activities included in the model	940	579	139	1,165	1,473

a) 250 working days/year
b) Statewide average equipment breakdown rates were used
c) 1-superintendent and 3-unit foremen are assumed to use 1 pickup truck each to supervise field maintenance activities

dump trucks (No. 9) and do-all trucks (No. 10) are 1.77 and 0.57, respectively, as shown in Table 3. Dump trucks are used in crack sealing to spread cover aggregate (usually sand) over the bituminous material applied to cracks. Do-all trucks can substitute for dump trucks in this work. Because these two types are used for the same purpose, they form an interchangeable group for this particular activity (207), and the use factor of this group is the summation of the use factors of dump trucks and do-all trucks. For the sample analysis, the combined-use factor then becomes 2.34. This value is reasonable, because the

TABLE 3 INDIVIDUAL EQUIPMENT-USE FACTORS AND COMBINED-USE FACTORS

Activity Code	Usage Factors * #1	#2	#8	#9	#10	Combined Usage Factors for Interchangeable Equipment Types #1+#2	#9+#10	#1+#2+ #9+#10	#1+#2+ #8	#9 only
201	0.10	1.10	-	0.91	0.12	1.20	1.03	-	-	-
205	1.00	1.00	-	9.00	-	2.00	-	-	-	9.00
207	0.53	1.13	-	1.77	0.57	1.66	2.34	-	-	-
210	0.75	0.36	-	0.50	1.33	1.11	1.83	-	-	-
212	0.85	0.60	-	3.35	-	1.45	-	-	-	3.35
221	0.12	0.81	-	0.07	0.01	-	-	1.01	-	-
231	0.51	0.86	-	2.56	-	1.37	-	-	-	2.56
235	0.74	0.35	-	0.17	0.04	-	-	1.30	-	-
251	0.18	0.03	0.79	-	-	-	-	-	1.00	-
283	0.37	0.37	-	1.05	-	0.74	-	-	-	1.05
284	0.09	0.02	-	1.23	0.14	0.11 (Omitted)	1.37	-	-	-
289	0.19	0.14	-	0.70	0.14	0.33	0.84	-	-	-

Equipment Types: #1 - Pickup truck; #2 - Pickup crew cab; #8 - Utility truck; #9 - Dump truck; #10 - Do-all truck

* Source: Reference 1.

handbook for foremen *(7)* estimates that two dump trucks are necessary for each crack-sealing operation.

This basic idea of a trade-off between equipment types was used to estimate other combined-use factors. Table 3 gives the 12 activities and equipment-use factors for the five types of major hauling equipment. Basically, pickup trucks could be interchanged with pickup crew cabs, and dump trucks with do-all trucks. Where equipment types are not interchangeable, constraints were constructed accordingly. For sign maintenance, pickup trucks, pickup crew cabs, and utility trucks can be interchanged.

After the combined-use factors for the equipment types needed for different activities were determined, K-values were computed. The annual average level of accomplishment per crew day for the 12 activities in the Fowler subdistrict during FY 1984 are given in Table 4. The K-value is obtained by dividing the average level of accomplishment per day by the combined-use factor as shown in Table 4. The K-value is therefore measured in the accomplished production units per equipment unit per crew day. Figure 2 shows which equipment types were considered interchangeable for various activities.

Estimated Fuel Consumption

The objective function of the optimization model is to minimize total fuel consumption by equipment types to accomplish the needed maintenance work. The model is run for unconstrained and constrained cases in terms of equipment availability. In the unconstrained case, optimal equipment assignment was derived without considering the equipment availability at the subdistrict level, whereas in the constrained

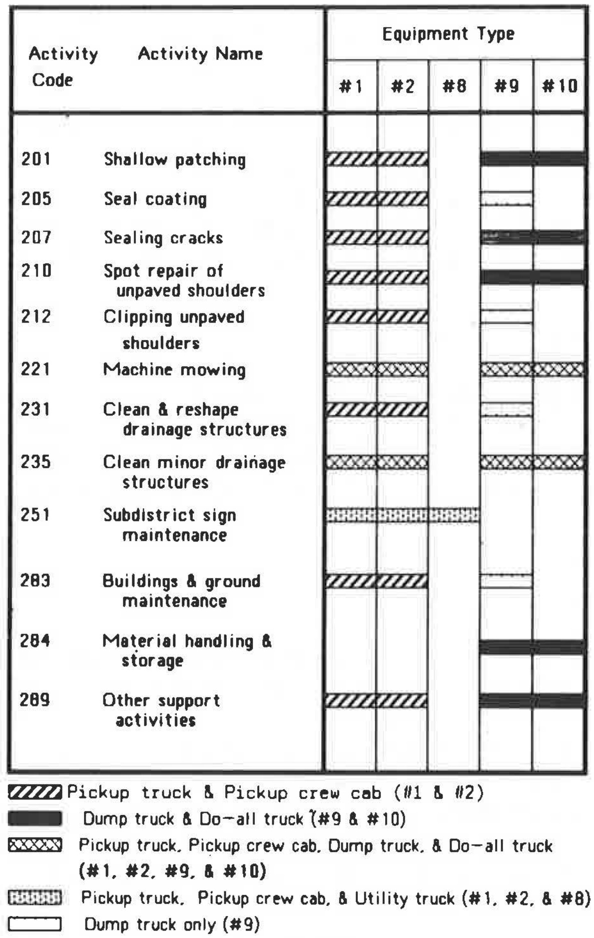

FIGURE 2 Interchangeable equipment types for example subdistrict.

TABLE 4 ESTIMATED CAPACITY OF EQUIPMENT TYPES: K-VALUES

Act. Code	Accomp. per Day*	Unit of Measure	Combined Usage Factors (no. of equipment/crewday): 1 Pickup truck	2 Pickup crew cab	8 Utility truck	9 Dump truck	10 Do-all truck	K-Values (production/equipment/crewday): 1 Pickup truck	2 Pickup crew cab	8 Utility truck	9 Dump truck	10 Do-all truck
201	3.79	tons of aggregate	1.20	1.20	-	1.03	1.03	3.16	3.16	-	3.68	3.68
205	8.64	lane miles	2.00	2.00	-	9.00	-	4.32	4.32	-	0.96	-
207	2.51	lane miles	1.66	1.66	-	2.34	2.34	1.51	1.51	-	1.07	1.07
210	26.20	tons of aggregate	1.11	1.11	-	1.83	1.83	23.60	23.60	-	14.32	14.32
212	3.13	shoulder miles	1.45	1.45	-	3.35	-	2.16	2.16	-	0.93	-
221	22.21	swath miles	1.01	1.01	-	1.01	1.01	21.99	21.99	-	21.99	21.99
231	881.40	linear feet	1.37	1.37	-	2.56	-	643.36	643.36	-	344.3	-
235	20.06	structures	1.30	1.30	-	1.30	1.30	15.43	15.43	-	15.43	15.43
251	15.07	man-hours	1.00	1.00	1.00	-	-	15.07	15.07	15.07	-	-
283	32.00	man-hours	0.74	0.74	-	1.05	-	43.24	43.24	-	30.48	-
284	16.19	man-hours	-	-	-	1.37	1.37	-	-	-	11.81	11.81
289	12.23	man-hours	0.33	0.33	-	0.84	0.84	37.06	37.06	-	14.56	14.56

* Estimated from crewday cards and IDOH's accomplishment records (MM-113): Reference 8.

case, the actual equipment availability was considered. The fuel consumption calculated under both cases was compared with actual fuel consumption, as estimated. Table 5 gives fuel consumption rates of equipment types for different activities included as input to the optimization model. The values of estimated fuel consumed by various equipment types under current assignment practice were computed by using these rates. Table 6 shows the fuel consumption for the activities included in the model for the sample subdistrict in FY 1984.

Summary of Results

The Linear, Interactive and Discrete Optimization (LINDO) computer program developed at the University of Chicago *(9)* was used to solve the problem. Results of the optimization efforts are summarized in Tables 7 through 9 and discussed below.

Constrained Problem

Table 7 shows a comparison of optimal equipment assignment resulting from the model and the estimated equipment use derived from the field survey data *(1)*. For the constrained case the disposable equipment days given in Table 2 formed the equipment availability constraints. It can be seen that there is a difference between the estimated field equipment use and optimal equipment use. For example, in the case of crack sealing, the optimal assignment was to use only pickup trucks and dump trucks instead of pickup trucks, pickup crew cabs, dump trucks, and do-all trucks as in the estimated field assignment.

The estimated fuel consumption by the equipment-activity combinations included in the model under the field assignment practice was 44,442 gal (Table 6), whereas the fuel consumption for the optimal equipment assignment was 40,612 gal (Table 8), resulting in an 8.6 percent reduction from the estimated field equipment use. This reduction is substantial because the fuel consumed by the activities considered in the model accounts for only about 60 percent of the total fuel consumed in routine maintenance at the state level. Therefore, if other activities were included in the model, the estimation of the amount of fuel saved would increase even if the percentage of reduction remained the same. A simple multiplication of the reduction of this example by the number of subdistricts (37 subdistricts in Indiana) can mean a savings of approximately 141,710 gal of fuel every year. This could amount to about $106,283 in cost savings every year when fuel cost is $0.75/gal. Table 8 also shows (in parentheses) which activities would use less or more fuel in the optimal case than was estimated for the field assignment.

Table 9 shows the available equipment days and the consumed equipment days for each type of equipment for both the estimated field equipment assignment and the optimal equipment assignment. It is evident that the model can determine the critical equipment types as well as the redundant equipment types. This information can help determine which equipment types need to be added or decreased in the current fleet. For example, the most critical equipment type for this subdistrict is

TABLE 5 FUEL CONSUMPTION RATES OF FIVE EQUIPMENT TYPES FOR DIFFERENT ACTIVITIES INCLUDED IN OPTIMIZATION MODEL

Activity Code	Activity Name	Unit of Measurement	#1 Pickup truck	#2 Pickup crew cab	#8 Utility truck	#9 Dump truck	#10 Do-all truck
201	Shallow patching	Tons of mix	3.66/ 7.35	2.69/ 6.67	-	4.78/ 3.17	3.71/ 3.08
205	Seal coating	Lane miles	1.10/ 9.00	2.42/ 4.40	-	8.03/ 4.14	-
207	Sealing cracks	Lane miles	2.89/ 4.33	3.07/ 5.75	-	6.15/ 2.17	6.55/ 2.36
210	Spot repair of unpaved shoulders	Tons of aggregate	0.21/ 8.24	0.54/ 5.27	-	0.93/ 2.74	0.76/ 6.20
212	Clipping unpaved shoulders	Shoulder miles	4.32/ 7.31	4.11/ 8.05	-	10.25/ 2.95	-
221	Machine mowing	Swath miles	0.36/ 7.10	0.48/ 7.92	-	1.60/ 4.30	0.80/ 2.88
231	Clean & reshape drainage structures	Linear feet	0.01/ 6.68	0.02/ 6.82	-	0.05/ 2.84	-
235	Cleaning minor drainage structures	# of structures	1.28/ 7.88	0.92/ 7.50	-	7.20/ 3.39	1.92/ 6.83
251	Subdistrict sign maintenance	Man-hours	1.04/10.69	0.69/ 9.03	1.03/ 7.62	-	-
283	Buildings and ground maintenance	Man-hours	0.27/10.45	0.16/ 7.45	-	0.43/ 3.35	-
284	Material handling and storage	Man-hours	-	-	-	1.35/ 3.84	1.54/ 3.80
289	Other support activities	Man-hours	0.68/11.53	0.62/ 8.69	-	1.37/ 4.68	2.00/ 3.52

Note: gallons per production unit/miles per gallon.
Source: Reference 1.

TABLE 6 FUEL CONSUMED BY FIVE MAJOR TYPES OF HAULING EQUIPMENT FOR 12 MAJOR ACTIVITIES, FOWLER SUBDISTRICT

Activity Types	Fuel Use by Equipment Type per Activity in Percentage *						Total Fuel Used by All Equipment Types **	Fuel Used by the Five Equipment Types
	#1	#2	#8	#9	#10	Total	OSH	OSH
	%	%	%	%	%	%	(gallons)	(gallons)
201	4.17	33.70	-	49.54	5.07	92.5	7,150	6,614
205	1.29	2.84	-	84.88	-	89.0	8,090	7,200
207	6.58	14.91	-	46.78	16.04	84.3	4,330	3,650
210	7.33	9.04	-	21.63	47.01	85.0	1,410	1,199
212	6.95	4.67	-	64.96	-	76.6	3,960	3,033
221	3.20	28.80	-	8.30	0.59	40.9	2,940	1,202
231	2.32	7.82	-	58.18	-	68.3	9,110	6,225
235	24.86	8.45	-	32.13	2.02	67.5	1,380	932
251	18.35	2.03	79.77	-	-	100.0	2,350	2,350
283	6.57	3.89	-	29.70	-	40.2	6,340	2,549
284	-	-	-	47.17	6.13	53.3	7,580	4,040
289	4.80	3.23	-	35.65	10.41	54.1	10,070	5,448
							Total	44,442

* Estimated using data found in Reference 1.
** From Table 1.

the pickup crew cab. The other four types considered in the model are in sufficient supply for this subdistrict to carry out regular maintenance activities. The equipment days available for do-all trucks greatly exceeds the actual demand. The reason for this abundance is, however, that most do-all trucks are kept for snow and ice removal in winter, and the model did not include this emergency activity.

Unconstrained Problem

In order to see how much fuel could be saved if all necessary equipment were available, an unconstrained case was analyzed. Table 7 shows the equipment assignment obtained by the unconstrained version of the optimization model. The unconstrained equipment assignment is somewhat different from both the field assignment and constrained assignment. The fuel

TABLE 7 EQUIPMENT DAYS FOR ESTIMATED FIELD ACTUAL EQUIPMENT ASSIGNMENT VERSUS OPTIMAL EQUIPMENT ASSIGNMENT

	Estimated Field Assignment *					Optimal - Constrained					Optimal - Unconstrained				
	Equipment Types					Equipment Types					Equipment Types				
Activity	#1	#2	#8	#9	#10	#1	#2	#8	#9	#10	#1	#2	#8	#9	#10
201	22	237	-	196	26	0	258	-	0	221	0	258	-	0	221
205	11	11	-	99	-	22	0	-	99	-	22	0	-	99	-
207	39	84	-	131	42	123	0	-	174	0	123	0	-	174	0
210	19	9	-	13	33	28	0	-	0	46	28	0	-	0	46
212	20	14	-	80	-	35	0	-	81	-	0	35	-	81	-
221	12	79	-	7	1	99	0	-	0	0	99	0	-	0	0
231	24	40	-	120	-	64	0	-	120	-	64	0	-	120	-
235	13	6	-	3	1	0	23	-	0	0	0	23	-	0	0
251	28	5	121	-	-	0	154	0	-	-	0	154	0	-	-
283	48	48	-	137	-	0	96	-	137	-	0	96	-	137	-
284	12	3	-	164	19	-	-	-	182	0	-	-	-	182	0
289	58	43	-	214	43	53	48	-	257	0	0	101	-	257	0
Total	306	579	121	1,165	165	424	579	0	1,050	267	336	667	0	1,050	266

Equipment types: #1 - Pickup truck; #2 - Pickup crew cab; #8 - Utility truck; #9 - Dump truck; #10 - Do-all truck

* Estimated using data found in Reference 1 and 8.

TABLE 8 FUEL CONSUMED BY EACH ACTIVITY UNDER THREE EQUIPMENT ASSIGNMENT SCENARIOS

Activity Number	Estimated Field Assignment	Optimal Assignment for Constrained Case	Optimal Assignment for Unconstrained Case
	gallons	gallons	gallons
201	6,614	5,738 (-876)	5,738 (-876)
205	7,200	7,078 (-122)	7,078 (-122)
207	3,650	3,568 (-82)	3,568 (-82)
210	1,199	1,063 (-136)	1,063 (-136)
212	3,033	3,043 (+10)	3,020 (-13)
221	1,020	792 (-410)	792 (-410)
231	6,225	5,827 (-398)	5,827 (-398)
235	932	432 (-500)	432 (-500)
251	2,350	1,602 (-748)	1,602 (-748)
283	2,549	2,376 (-173)	2,376 (-173)
284	4,040	3,981 (-59)	3,981 (-59)
289	5,448	5,112 (-336)	5,073 (-375)
Total	44,442	40,612 (-3,830)	40,550 (-3,892)

TABLE 9 EQUIPMENT DAYS USED BY EACH EQUIPMENT TYPE UNDER THREE EQUIPMENT ASSIGNMENT SCENARIOS

Equip. No.	Equipment Type	Available Equipment Days	Equipment Days Used: Estimated Field Assignment	Optimal Assignment: Constrained	Optimal Assignment: Unconstrained
1	Pickup truck	940	306	424	336
2	Pickup crew cab	579	579	579	667
3	Utility truck	139	121	0	0
9	Dump truck	1,165	1,165	1,050	1,050
10	Do-all truck	1,473	165	267	267

consumption for the unconstrained optimal assignment was 40,550 gal, as shown in Table 8. There could be as much as an 8.8 percent reduction from the estimated current fuel consumption. However, because there was only one critical equipment type—the pickup crew cab—the difference of total fuel consumption between the constrained and unconstrained assignments was only about 0.2 percent for this subdistrict.

Sensitivity Analysis

A sensitivity analysis is recommended when any equipment type is found to be critical for equipment assignment. The critical equipment type can be identified by examining the results of the constrained and unconstrained versions of the optimization program. The objective of the sensitivity analysis is to determine explicitly the impact of each type of equipment on overall fuel consumption. In the sample problem, only the pickup crew cab was found to be critical. Adding an extra pickup crew cab to the current fleet of the subdistrict would help conserve fuel; however, the marginal fuel savings is only 0.2 percent. In other subdistricts the marginal fuel savings may be substantial if one or two equipment types were critical. In such situations, it may be beneficial to borrow the necessary units from other subdistricts as needed.

Importance of the Input Data

The validity of the results of the optimization technique developed in this study is largely dependent on the accuracy of the input data. Three types of information are critical: equipment-use factors, fuel consumption rates, and interchangeability of equipment types.

Currently, use factors obtained from the field survey *(1)* are the averages for six subdistricts selected for the survey. Therefore, they may not necessarily reflect exactly the equipment-use pattern of a particular subdistrict. Also, there is a problem of the time lapse between the period (FY 1982) when the field data were taken for computing equipment-use factors and the study period (FY 1984).

Fuel consumption rates are probably the most important input data affecting the accuracy of the results. Fuel consumption rates of all equipment types are given in gallons per production unit. These rates are greatly affected by the condition of job sites even within each activity. Hauling distance and the manner in which equipment units are used can also substantially affect the fuel requirement for one unit of production. Fuel consumption rates now available are also the average values for six subdistricts used for the field survey *(1)*. In order to increase the accuracy of the results for a particular subdistrict, it is recommended that each subdistrict monitor fuel consumption rates for its own fleet.

Interchangeability of equipment can be found by observing crew-day cards and by field observation. In the example, it was assumed that the interchangeability observed in the period during which the field survey was done would remain the same for the study period. However, equipment interchangeability may alter over the years. Such alterations need to be taken into account before the optimization program is run.

These problems of use factors, fuel consumption rates, and interchangeability of equipment types, however, can be resolved by regularly updating the equipment-use and fuel consumption data. Any changes in equipment interchangeability can be evaluated by examining updated equipment-use factors. The only data not currently recorded on crew-day cards are those for fuel consumption. If the fuel consumption data are kept current, IDOH would be in a better position to keep a close control of its fuel conservation programs.

CONCLUSIONS

The example discussed in this paper demonstrated the usefulness and efficiency of the maintenance equipment assignment technique developed in this study. The technique allocates equipment to various maintenance activities within the given constraints of resources and maintenance requirements.

Because this technique treats the equipment assignment problem macroscopically, it will not be affected by fluctuations in equipment use due to various conditions pertinent to equipment scheduling, such as weather and equipment breakdowns. The technique is capable of dealing with a large number of activities and a variety of equipment types regardless of the existence of interchangeability of equipment types. Fuel reduction will not, of course, be attained unless interchangeable equipment types or units exist, because it is basically the result of trading off one type of equipment for another so as to minimize fuel consumption. The potential use of such an optimization technique in highway maintenance equipment management is considered to be feasible.

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Traffic Paint Performance in Accelerated-Wear Tests

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Accelerated-wear tests of traffic paints on portland cement concrete and asphalt-concrete pavements are described. Installation and performance of several paints, including chlorinated rubber and chlorinated rubber-alkyd, alkyd, acrylic and alkyd-acrylic, epoxy, and water-based paints, are discussed. Durability and appearance ratings provided reliable indications of paint performance, but reflectivity ratings were extremely variable. Chlorinated rubber paint provided the best service life, but also had the longest drying time, averaging more than 3 min.

In 1981 the New York State Department of Transportation initiated a study to compare the durability of candidate pavement-marking materials—both paints and more durable materials—through accelerated-wear tests. In this paper the performance of 125 sets of traffic paint stripes installed between 1981 and 1983 is described. The performance of the more durable markings evaluated in this project will be reported separately. The purpose of this evaluation was to identify traffic paints that offer improved durability compared with that of New York State standard traffic paints. The general goal was to select for in-field evaluation paints that could provide year-round delineation on at least part of the state highway system.

INVESTIGATION

Test Sites and Test Section Layout

Two test sites were used in this study—the Washington Avenue Extension in the city of Albany and Wolf Road in the town of Colonie. The former is a four-lane divided portland cement concrete pavement (PCCP) with a 10-ft shoulder on the right and a raised curbed median. Lane widths are 12 ft, and the 1984 two-way annual average daily traffic (AADT) was 17,400 vehicles. This highway has partial access control, with signalized intersections and no midblock access. The test site was located in a long tangent section of the eastbound driving lane.

Wolf Road is a four-lane highway with asphalt-concrete pavement (ACP), a 16-ft flush median, and a curb adjacent to the driving lane. Lane widths are 15 ft for the driving lane and 12 ft for the passing lane. This highway has unlimited access, with numerous commercial driveways and intersections. The 1984 two-way AADT was 24,500 vehicles. Test stripes were installed in several tangent sections of the southbound driving lane, again located to eliminate the effects of turning and slowing traffic. Both pavements were constructed in 1970 and were in good condition at the time of this test.

Seven lines were installed for each set of test stripes—six 10-ft long longitudinal and one transverse stripe across the lane at the upstream end of the longitudinal lines (Figure 1). Two lines of each set were located in the apparent wheelpath; the other four were spaced across the lane. This layout was thought to offer several advantages over a test layout consisting of transverse stripes:

1. The longitudinal orientation of the test stripes was similar to that for normal pavement markings, so that wear patterns would more directly reflect those of in-service markings. This is especially critical because in winter months, snowplow use may cause abnormal wear on the leading edges of transverse stripes.
2. The 10-ft test stripes provide a much larger sample on which to base durability observations. Wheelpath wear zones on transverse stripes are limited to a few inches of the line.
3. The different locations of the longitudinal lines within the lane provide multiple exposure levels within each set of test stripes. This was considered desirable to compare the effects of abnormally high wear in the wheelpath during the winter months with those of more typical wear outside the wheelpath.

For most paints, both white and yellow were used on both PCCP and ACP. In some cases, duplicate test stripes were installed because the first set was not considered satisfactory. In addition, several sets of the standard state traffic paints were installed as controls each year by the various participants in the program.

FIGURE 1 Typical completed stripe sets.

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Installation Procedures

Most test stripes were installed during July and August 1981, 1982, and 1983 by several paint and paint component manufacturers and by state personnel. Most stripes were installed with portable walk-behind stripers, but a few sets were installed with a state truck-mounted striper. Adequate work areas were available alongside each test area on which practice lines could be laid on tar paper or similar material to obtain the desired adjustments in wet-film thickness, bead-application rates, material temperature, and line appearance. Once the desired line quality had been achieved, the seven test lines were placed on the pavement.

Installation of all test lines was monitored by research personnel to obtain information on handling characteristics of the various materials and to ensure uniformity among the test stripes to the greatest extent possible. Information obtained during installation included application rate, material temperature and climatic condition, material drying time, and initial reflectivity.

Evaluation Procedures

In periodic surveys, stripes were rated for durability, appearance, and reflectivity. During good weather, evaluations were conducted monthly, but during the winter the interval varied, depending on snow, ice, and dirt accumulation on the pavement and on air temperature. The following procedures were used to evaluate stripe condition:

1. Durability was evaluated with ASTM D 821-47 (Evaluating Degree of Abrasion, Erosion, or a Combination of Both, in Road Service Tests of Traffic Paints) and D 913-51 (Evaluating Degree of Chipping of Traffic Paint). A single rating on a scale of 0 to 10 (10 is perfect and 0 is complete line loss) was assigned to each of the six longitudinal stripes. The lower of the abrasion or chipping ratings was used to indicate condition, and the controlling wear mode was noted. Typical ratings are shown in Figures 2–5.
2. ASTM D 713-69 (Conducting Road Service Tests on Traffic Paint) was used to rate appearance. A separate rating was assigned to each longitudinal line.

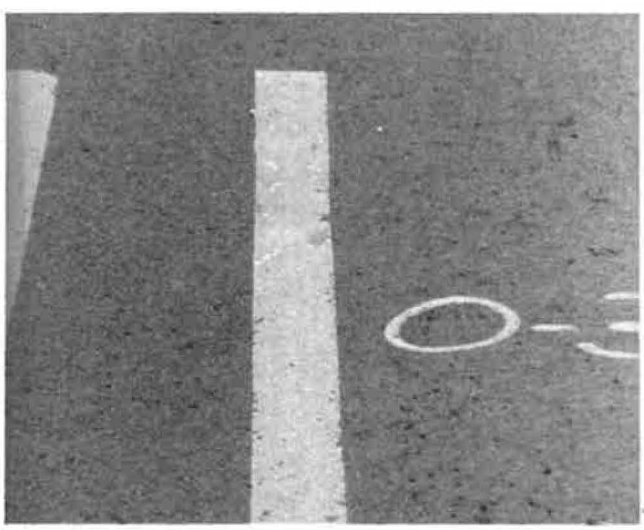

FIGURE 2 Paint stripe rated 9.

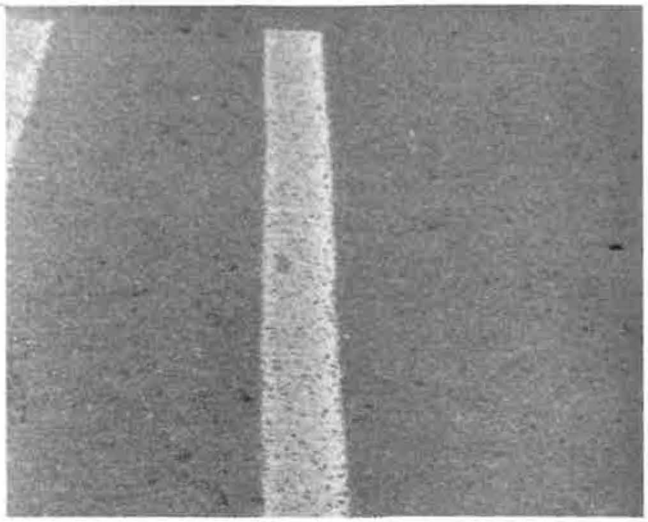

FIGURE 3 Paint stripe rated 6.

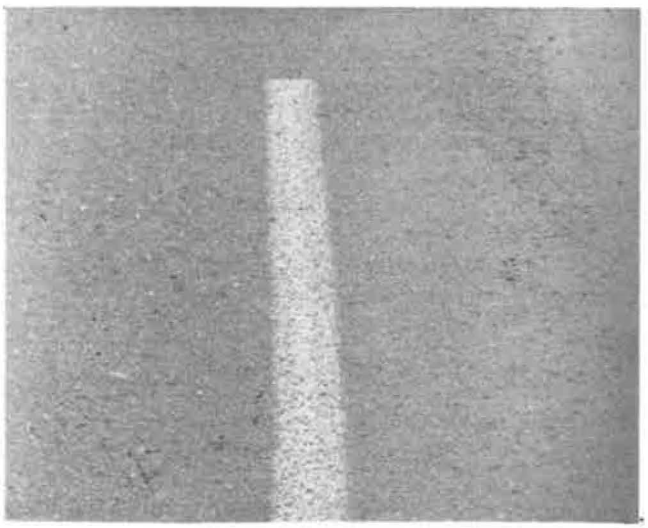

FIGURE 4 Paint stripe rated 4.

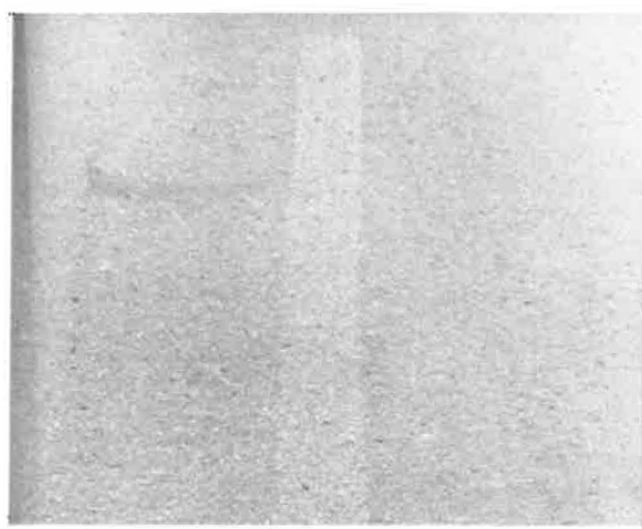

FIGURE 5 Paint stripe rated 1.

3. A reflectometer patterned after a device developed by the Michigan Department of Transportation and described in detail in an earlier research report *(1)* measured reflectivity. Five reflectivity measurements were made along the length of each longitudinal line, and six measurements were made on each transverse line where it intersected the longitudinal lines. An average brightness value was then computed for each line.

4. On the basis of results of the periodic surveys, service life was determined for each of the six longitudinal stripes in terms of each of the three evaluation criteria—durability, appearance, and reflectivity. For durability and appearance, the failure level was set at a rating of 5. For reflectivity, the failure level was 140 for white and 110 for yellow. To determine the exact length of service life in days, a straight-line interpolation was performed between the two surveys on either side of the failure point.

Materials Evaluated

A total of 125 sets of test stripes were installed; 29 formulas from 7 resin types were used. The control plants were New York State standard modified-alkyd paints with nominal drying times of 20 or 60 sec when applied at 140°F. Table 1 gives a description of the 29 paint formulas. Selection of traffic paints for this evaluation was based on recommendations of the suppliers and manufacturers participating. A total of 17 firms were solicited for participation. The criterion used to select materials for inclusion was either that a paint be commercially available (i.e., operational) at the time of installation or that the manufacturer consider the product to offer improved performance compared with paints then commercially available and that it become operational in the immediate future.

RESULTS

One of the earliest decisions necessary in analysis of the study results was the grouping of the six longitudinal stripes into wear-severity levels. Examination of the raw survey data revealed that the PCCP site fell into three levels—Stripes 2 and 5 experienced the most rapid wear, which was termed the "wheelpath" severity level; Stripes 3 and 6 experienced an intermediate wear rate; and Stripes 1 and 4 experienced the "nonwheelpath" wear rate. On the ACP site, the wheelpath was less clearly defined, and Stripes 2, 3, 5, and 6 all experienced essentially equal wear rates, termed the "wheelpath" rate. Stripes 1 and 4 wore at a slower rate, termed the "nonwheelpath" rate. Table 2 summarizes the effect of lane position on service life for each of the three evaluation criteria. A paired *t*-test was used to compare differences among lane positions (wear severity levels), and all the differences among severity levels in Table 2 were found to be significant at the 95 percent

TABLE 2 EFFECT OF LANE POSITION OF STRIPE ON SERVICE LIFE

	PCCP*			ACP*	
Evaluation Criteria	WP	INT	NWP	WP	NWP
Durability					
Average Life, days	129	146	264	155	205
Std Deviation, days	29	33	150	60	132
Sample Size	60	60	60	65	65
Appearance					
Average Life, days	126	139	226	148	179
Std Deviation, days	27	30	127	65	108
Sample Size	60	60	60	65	65
Reflectivity					
Average Life, days	124	129	158	96	102
Std Deviation, days	34	36	57	44	51
Sample Size	60	60	60	65	65

*WP = wheelpath (Stripes 2 and 3 in Fig. 1), INT = intermediate (Stripes 3 and 6), NWP = non-wheelpath (Stripes 1 and 4).

NOTE: All differences among wheelpath means are statistically significant at 95-percent confidence when tested using paired comparison.

TABLE 1 DESCRIPTION OF PAINTS TESTED

Formula	Resin Type	Mfr	Appl	Derivation	Solvent
1	Acrylic	3	3	Experimental	Toluene
2	Acrylic	3	3	Experimental	Toluene
3	Alkyd	3	2,3	NY 20-Second	Toluene
4	Alkyd	8	2	Ind. Standard	Toluene
5	Alkyd	8	2	Md. Standard	Toluene
6	Alkyd	3	3	Experimental	Toluene
7	Alkyd	8	8	Ky. Standard	Toluene
8	Alkyd	3	9,2	NY 60-Second	Toluene
9	Alkyd	3	1	NY Cold-Applied	Toluene
10	Alkyd	8	2,3	NY 60-Second	Toluene
11	Alkyd-Acrylic	5	2	Calif. Standard	Toluene
12	Chlorinated Rubber-Alkyd	8	8	Penn. Standard	MEK
13	Chlorinated Rubber-Alkyd	2	2	NJ Modified	Toluene
14	Epoxy	9	9	Commercial	MEK
15	Epoxy	7	1	Commercial	MEK
16	Chlorinated Rubber	4	2	Texas Standard	MEK
17	Chlorinated Rubber	4	2	Ill. Standard	MEK
18	Chlorinated Rubber	4	2	NJ Standard	MEK
19	Chlorinated Rubber	3	3	Experimental	MEK
20	Chlorinated Rubber	2	2	Wyo. Standard	MEK
21	Chlorinated Rubber	2	2	NJ Modified	MEK
22	Chlorinated Rubber	2	2	NJ Modified	MEK
23	Chlorinated Rubber	3	3	Experimental	MEK
24	Chlorinated Rubber	2	2	NJ High-Viscosity	MEK
25	Chlorinated Rubber	2	2	Ill. Modified	MEK
26	Water-Based	3	3	Experimental	Water
27	Water-Based	3	3	Experimental	Water
28	Water-Based	3	3	Experimental	Water
29	Water-Based	3	3	Experimental	Water

confidence level. Service life in terms of reflectivity varied only slightly between the wheelpath and nonwheelpath positions of the stripes. The differences in appearance were somewhat more pronounced, and in durability, the nonwheelpath stripes lasted much longer than those in the wheelpath. It is also apparent that differences in service lives were greater on PCCP than on ACP.

Service lives for all 125 sets of stripes are summarized in Figure 6 for each of the three evaluation criteria and wear severity levels. For the wheelpath and intermediate severity levels, most paints tested provided service lives between 90 and 180 days (3 to 6 months) regardless of the evaluation criterion used, and only a small number of paints survived beyond 6 months. For the nonwheelpath severity level, average service lives were somewhat higher, and the service lives of several paints were considerably longer than 6 months. However, these extended service lives were experienced primarily in durability and appearance, whereas in reflectivity, service lives for the nonwheelpath severity level were only slightly longer than those for the wheelpath and intermediate levels.

Figure 7 demonstrates typical differences between service lives observed for wheelpath and nonwheelpath severity levels. The durability ratings for three typical paints are shown over the entire evaluation period; ratings for wheelpath and nonwheelpath positions shown separately. Two important concepts are demonstrated in this figure. First, wear rates accelerated dramatically at the beginning of winter for all three paints at both wheelpath and nonwheelpath severity levels. Second, wheelpath stripes were more affected by the onset of winter weather than were nonwheelpath stripes.

Although substantial differences in service life were observed in these wear tests, the differences observed were highly dependent on the evaluation criteria used to measure service life and severity of wear. It is hoped that much of the difference in service life relates to the material formulas tested, but a number of other parameters could also affect service life. These must be examined to assess the observed service life differences. The effects of these parameters, as well as the differences among paint formulas, are discussed in the following sections.

Winter Severity and Repeatability of Service-Life Estimates

A total of 29 paints of different formulas were installed during the 3 years of this evaluation, but only 7 were installed in more than one year, and the other 22 were installed in the same year. Any effects of differences in severity of weather during winter would be reflected in observed performance differences among paints installed in different years. Table 3 summarizes weather severity over the three winter evaluation periods. Total snowfall accumulation each winter is presented as well as the number of storms with measurable accumulation. The application of salt and abrasives to the pavement during winter maintenance activities affects pavement marking wear. Thus, several small storms may result in more severe wear than one large storm, because more abrasives are applied over a longer period. Likewise, timing of the storms may also affect service life, because storms occurring early in the winter result in rapid

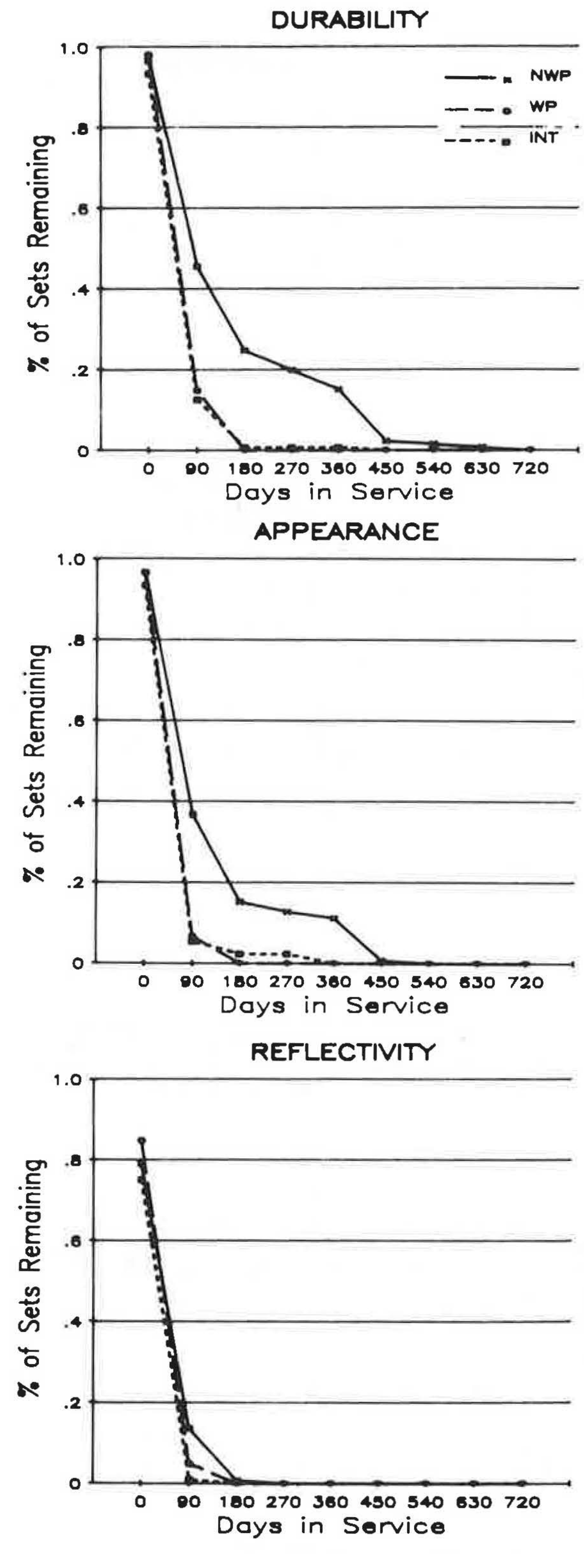

FIGURE 6 Service lives provided at various wear severity levels.

wear earlier in the life of the marking. Thus Table 3 presents storm data for November and December as well as for the entire season.

Examination of Table 3 reveals that weather severity varied greatly among the three winters. The first winter was the most severe, with more frequent storms, higher total accumulation of

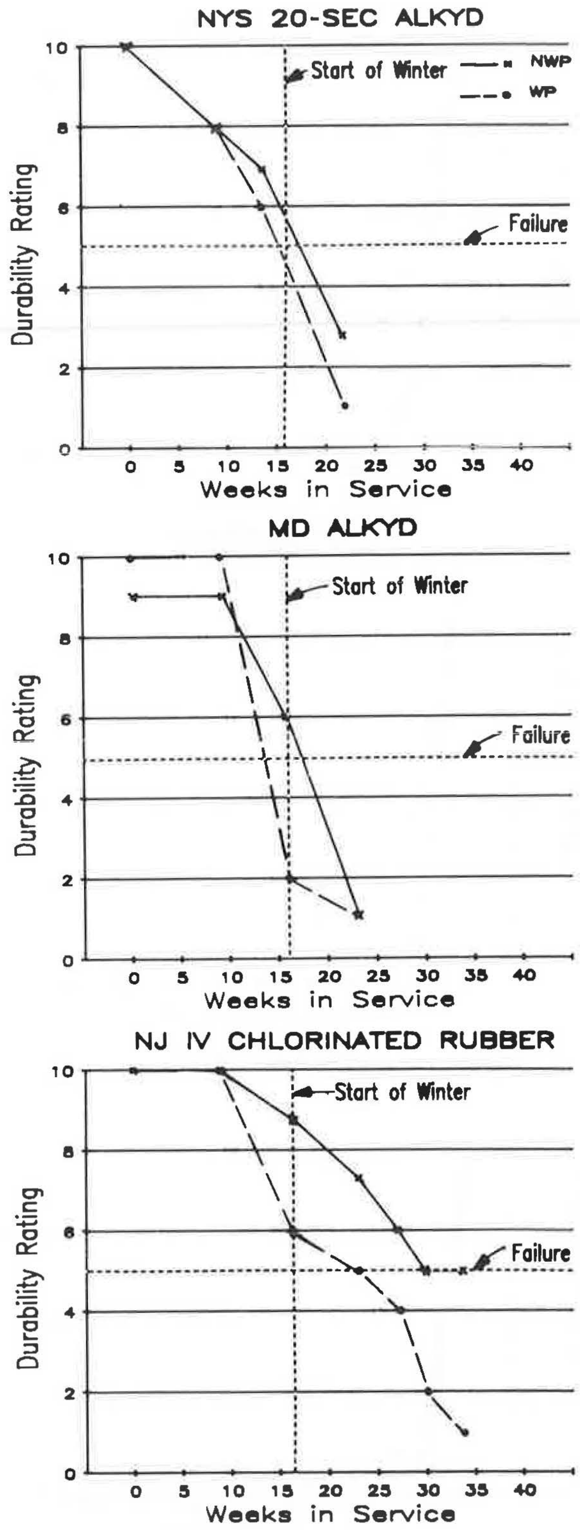

FIGURE 7 Condition of typical stripe sets.

snow, and more storms during the early part of the season. The second winter (1982–1983) appears the least severe. Although total accumulation of snow was greater than in 1983–1984, most of that accumulation resulted from a few major storms occurring late in the season. November and December 1982 were relatively mild, with few storms and little accumulation.

On the basis Table 3, it would be expected that the longest service lives would result for materials installed in 1982 and the shortest for those installed in 1981. The data in Table 4, which gives average service lives of materials installed in each of the three years, can be seen to support this trend in terms of material durability and appearance. Most differences between the years are statistically significant. The trend for reflectivity is less pronounced and relates to differences in weather severity only in the nonwheelpath positions.

TABLE 3 SUMMARY OF SEASONAL SNOWFALL

	Snow Accumulation, in.		Total Storms		Total Storms >6 in.	
Season	Nov. -Dec.	Entire Season	Nov. -Dec.	Entire Season	Nov. -Dec.	Entire Season
1981–82	32.5	96.9	16	44	1	5
1982–83	6.1	75.0	6	24	-	5
1983–84	13.4	65.2	11	38	-	2

TABLE 4 SERVICE LIVES OVER 3 YEARS

	Service Life, days								
	1981			1982			1983		
Evaluation Criteria	$\bar{x}$	σ	n	$\bar{x}$	σ	n	$\bar{x}$	σ	n
Durability									
Wheelpath	128	24	57	163✓	73	44	141✓	20	24
Intermediate	135	26	28	159✓	41	23	143	21	9
Non-Wheelpath	159	65	57	328✓	174	44	235✓*	117	24
Appearance									
Wheelpath	126	23	57	153✓	79	44	136	20	24
Intermediate	134	20	28	146	40	23	140	24	9
Non-Wheelpath	144	31	57	260✓	155	44	231✓	115	24
Reflectivity									
Wheelpath	105	38	57	105	45	44	127✓*	39	24
Intermediate	129	31	28	130	45	23	125	31	9
Non-Wheelpath	111	43	57	139✓	77	44	153✓	52	24

✓ = Significant difference compared to 1981 (95%).
* = Signifieant difference, 1982-83 (95%).

Table 4 thus shows an apparent trend relating observed service lives to winter weather severity. However, different material formulas were used in each of the three years, and the observed differences may thus be related to material properties as well as to weather severity. Consequently, it is necessary to examine observed differences in performance for materials installed in more than one year or for multiple installations within the same year. Comparison of those results would provide a measure of repeatability of the evaluation process. Seven of the 29 formulas were installed in two different years; a total of 20 stripe sets were replicated. Examination of service lives for those 20 pairs reveals considerable variability between years. The variability between repeated stripe sets is summarized in Table 5, which provides the average range (difference in service life between repeated samples) and the relative range (average range divided by average service life for repeated samples) in service life between years and within years. Depending on evaluation criterion and severity level, average range in service life between years varied from as little as 31 to as much as 117 days, or about 1 to 4 months. Of more interest is the relative range. These values ranged from 0.21 to 0.53. In other words, the average difference in service life between years ranged from about one-fifth to over one-half of the mean of the two years.

Within-year repeatability was much better than that between years. Based on 12 duplicate sets of stripes placed in the same

TABLE 5 BETWEEN-YEAR AND WITHIN-YEAR SERVICE-LIFE VARIABILITY FOR REPLICATE SAMPLES

	Between Years (n = 20)		Within Years (n = 12)	
Evaluation Criteria	Average Range*	Relative Range*	Average Range*	Relative Range*
Durability				
Wheelpath	50	0.34	16	0.12
Intermediate	34	0.21	--	--
Non-Wheelpath	117	0.46	42	0.23
Appearance				
Wheelpath	47	0.38	12	0.09
Intermediate	31	0.22	--	--
Non-Wheelpath	74	0.37	37	0.19
Reflectivity				
Wheelpath	36	0.51	32	0.24
Intermediate	42	0.37	--	--
Non-Wheelpath	53	0.53	34	0.28

*Average range = difference in service life between repeat samples; relative range = average range divided by average service life for repeat samples.

year, the range in service life averaged 12 to 42 days for the various severity levels and evaluation criteria. The relative ranges were also lower, averaging from about one-tenth to one-quarter of the mean values for the duplicate sets.

The data in Table 5 thus show that estimates of service life from accelerated-wear tests are subject to considerable annual variation. Repeated samples tested within the same year typically resulted in differences of 2 to 6 weeks in service life, and repeated samples between years resulted in average differences of up to 4 months. Considering the wide range observed between repeated samples, the results of these tests cannot be used to identify differences of less than several months between paints installed in different years. For paints installed in the same year, differences of less than several weeks are probably not reliable.

Further examination of the data used to compile Table 5 reveals that for 14 of the 20 repeated stripe sets, installation included 1982, which had the mildest winter. For these 14 pairs of stripe sets, those installed in 1982 showed markedly improved service lives compared with those installed in 1981 or 1983. For four sets there was less improvement in service life for those installed in either 1981 or 1983, and for one set there was little difference in service life between the two years. Although this sample is small, it provides a strong indication that the milder winter of 1982–1983 substantially affected service life.

Paint Color and Pavement Type

Because most paint formulas were applied in both colors and on both pavement types, paired comparisons were used to examine differences in service lives related to paint color and pavement type. In durability and appearance, yellow performed better than white; service life ranged from a few days in the wheelpath and intermediate positions to nearly 2 months for the nonwheelpath position. In reflectivity, white performed better than yellow, but the differences represent only a few days of service life. In the wheelpath, stripes on ACP provided nearly a month's longer service than those on PCCP in durability and appearance. However, outside the wheelpath, stripes on PCCP lasted nearly 2 months longer than those on ACP. In reflectivity, stripes on PCCP lasted longer than those on ACP for both wheelpath and nonwheelpath positions.

Effects of Installation Parameters

Dry-film thicknesses of plate samples obtained during installation, with and without beads, were measured as well as initial reflectivity on beaded plate samples. Wet-film thickness was adjusted by the installers to 15 mils, which was verified by measurements with a wet-film-thickness gauge. Dry-film thicknesses corresponding to 15 mils wet are dependent on solvent content of the paint as well as on actual applied wet-film thickness. For 15 mils wet, typical dry-film thickness is expected to range from about 8 to 12 mils. Most plate samples had dry-film thicknesses within that range. For 20 samples of the 125 sets placed, thickness was between 6 and 8 mils, for 15 it was between 12 and 15 mils, for 3 it exceeded 15 mils. In view of the variety of materials installed, considerable variation in dry-film thickness was to be expected. In addition, normal variation encountered during application would be expected to result in some differences along the length of a line. Thus, the dry-film thicknesses observed, although exceeding the theoretical range by a few mils, indicate that most test materials were installed close to the desired 15-mil wet-film thickness.

Beaded thickness is more difficult to assess, because it depends on paint and bead application rates, solvent content, bead gradation, embedment depths, and other factors. Thickness of the beaded plate samples showed a wide range, but was generally within what was expected.

Reflectivity of the sample plates as measured with the retroreflectometer was also examined. A wide range of brightness values was observed, ranging from poor in a few cases to excellent in a few others. Service lives of pavement markings obviously depend at least partially on initial thickness and brightness. A simple regression analysis was used to determine these relations for the test stripes, and it was found that there was very little correlation between service life and initial thickness and brightness values. Initial thickness and brightness were mostly within the expected ranges. In addition, a number of other parameters—weather, paint formula and color, pavement type, and others—also exhibited varying degrees of influence on service life. Thus this lack of correlation between service life and initial brightness and thickness is not surprising.

Drying times measured for the test stripes ranged from less than 1 min to longer than 6 min. Those of a minute or less are desirable from the standpoint of traffic control during placement. However, few paints could achieve such short times. The two New York State alkyds—20- and 60-sec—had drying times of 1 min or less for 12 of the 20 sets placed; three more sets had times between 1 and 2 min. Several other paints were also characterized by 1- to 3-min drying times. Drying times are summarized by paint type in Table 6.

Paint Formulas

Table 6 lists average service lives of each paint formula, presented separately for each of the 3 years. The paints are listed in descending order of service life measured in the nonwheelpath position, because this parameter was earlier shown to provide the clearest indication of difference between paints.

TABLE 6 SUMMARY OF SERVICE LIFE

					Days of Service						
					Durability		Appearance		Reflectivity		
Formula	Resin Type	Derivation	Ranked by Durability	Ranked by Reflectivity	WP	NWP	WP	NWP	WP	NWP	n
1981 TEST STRIPES											
12	Chlorinated Rubber-Alkyd	Penn. Standard	1	7	133	278	127	161	113	122	3
18	Chlorinated Rubber	NJ Standard	2	5	179	232	171	189	93	128	4
16	Chlorinated Rubber	Texas Standard	3	1	154	200	158	181	124	139	4
17	Chlorinated Rubber	Ill. Standard	4	9	150	184	143	170	111	118	4
5	Alkyd	Md. Standard	5	13	138	185	130	159	75	82	2
19	Chlorinated Rubber	Experimental	6	2	125	154	124	144	122	132	4
1	Acrylic	Experimental	7	4	130	152	124	144	129	128	4
7	Alkyd-Acrylic	Ky. Standard	8	10	110	152	109	132	108	108	4
14	Epoxy	Commercial	9	14	129	151	128	138	70	82	2
11	Alkyd	Calif. Standard	10	15	129	148	124	140	36	36	4
6	Alkyd	Experimental	11	3	120	135	115	128	130	128	4
26	Waterbase	Experimental	12	6	112	133	95	123	115	123	4
4	Alkyd	Ind. Standard	13	11	114	126	128	141	94	91	2
8	Alkyd	NY 60-Sec	14	12	101	118	109	117	78	85	4
3	Alkyd	NY 20-Sec	15	8	109	113	117	122	120	120	3
1982 TEST STRIPES											
21	Chlorinated Rubber	NJ Modified	1	2	258	549	233	488	133	194	4
23	Chlorinated Rubber	Experimental	2	1	194	495	159	337	151	198	2
22	Chlorinated Rubber	NJ Modified	3	4	218	458	283	443	130	188	4
20	Chlorinated Rubber	Wyo. Standard	4	10	208	428	188	275	92	126	4
13	Chlorinated Rubber-Alkyd	NJ Modified	5	5	203	418	185	350	118	179	4
25	Chlorinated Rubber	Ill. Modified	6	11	175	366	189	331	86	110	4
2	Acrylic	Experimental	7	7	178	338	148	211	143	182	2
14	Epoxy	Commercial	8	15	69	266	58	122	26	40	2
18	Chlorinated Rubber	NJ Standard	9	14	74	238	67	132	64	82	2
28	Waterbase	Experimental	10	3	150	238	140	194	138	192	2
15	Epoxy	Commercial	11	16	68	213	68	122	36	61	2
29	Waterbase	Experimental	12	6	156	207	128	164	138	168	2
27	Waterbase	Experimental	13	8	129	177	115	162	122	145	3
9	Alkyd	NY Cold Applied	14	12	57	161	49	144	29	87	1
28	Waterbase	Experimental	15	9	110	148	108	136	126	138	2
10	Alkyd	NY 60-Sec	16	13	122	148	117	131	85	84	4
1983 TEST STRIPES											
24	Chlorinated Rubber	NJ High Viscosity	1	1	160	372	157	361	152	214	4
13	Chlorinated Rubber-Alkyd	NJ Modified	2	3	144	211	138	203	142	163	7
5	Alkyd	Md. Standard	3	4	144	185	140	183	94	107	3
20	Chlorinated Rubber	Wyo. Standard	4	2	144	184	135	255	147	173	6
8	Alkyd	NY 60-Sec	5	5	111	137	109	135	72	80	4

Note: WP = wheelpath, NWP = non-wheelpath, n = number of stripe sets.

This table shows that several chlorinated rubber paints and a chlorinated rubber-alkyd were the best performers, with average service lives considerably above those of the department's standard paints. Performance of each paint type can be summarized as follows:

1. Chlorinated rubber and chlorinated rubber-alkyd: These paints were consistently the best performers, with average durabilities considerably better than those of the department's alkyd paints and other paint types. All the various state standard chlorinated rubbers and chlorinated rubber-alkyds performed well, as did several variations of the New Jersey IV formula. In all these formulas, methyl ethyl ketone (MEK) was used as the solvent. In one—the NJ Modified (NJ IV with Cellolyn 604), a chlorinated rubber-alkyd (formula 13)—toluene was substituted. Although formula 13 did not perform quite as well as the others in this group did, it performed better than most paints from the other groups and much better than the New York State alkyds. With the exception of formula 13 most of these paints also had slow drying times.

2. Alkyds: The New York State alkyd paints were consistently the poorest performers. Of the four other alkyds, all performed better than the New York State paints, but none lasted more than a few weeks longer than the New York State paints. None of the alkyds had service lives that approached those of most of the chlorinated-rubber and chlorinated-rubber-alkyd paints.

3. Acrylic and alkyd-acrylic: An acrylic paint installed in 1982 performed nearly as well as the chlorinated-rubber paints, but the other two in this group were only slightly better than the New York State alkyds.

4. Epoxy: Two epoxy paints were installed. Both performed somewhat better than the New York State paints, but neither was outstanding.

5. Water based: Four water-based paints were installed. Their performance ranged from a little better than to about the same as that of the New York State alkyds.

Although nonwheelpath durability provided the best distinction among paints, appearance and reflectivity were also important. Paints that ranked well in durability also did generally well in appearance and to a lesser extent in reflectivity. The relationship among the three criteria is explored further in Table 7, which presents a correlation matrix for the three criteria and durability levels. Correlation coefficients between durability and appearance were high for all three positions—

TABLE 7 MATRIX OF CORRELATION COEFFICIENTS RELATING SERVICE LIFE TO VARIOUS DURABILITY LEVELS AND EVALUATION CRITERIA

	Durability		
Evaluation Criteria	Wheelpath	Intermediate	Non-Wheelpath
Durability			
Wheelpath	1.00	0.94	0.55
Intermediate	0.94	1.00	0.63
Non-Wheelpath	0.55	0.63	1.00
Appearance			
Wheelpath	0.92	--	--
Intermediate	--	0.91	--
Non-Wheelpath	--	--	0.87
Reflectivity			
Wheelpath	0.44	--	--
Intermediate	--	0.37	--
Non-Wheelpath	--	--	0.57

Note: Correlation coefficients based on linear regression of service lives for 125 stripe sets.

wheelpath, intermediate and nonwheelpath—about 0.9. Although the correlation with reflectivity was not high, most paints that rated well on durability also generally tended to rate well in reflectivity, and those lower in durability generally rated low in reflectivity. A notable exception are the water-based paints, which generally rated somewhat better in terms of reflectivity than durability, and the epoxies, which had reflectivity ratings lower than durability ratings.

Examination of performance data for individual sets of stripes revealed that there was considerable performance variability between stripe sets, even for the best paints. Although some paint groups were clearly superior to others, performance variations among formulas within paint groups, combined with the effects of differences in installation, climate, and traffic, resulted in wide variations in performance within paint groups.

Failure Modes

When the durability ratings were determined, separate values were assigned for abrasion and chipping. When a stripe set reached failure, the controlling failure mode was noted. Overall, slightly more than half the sets failed by abrasion, about one-fourth through chipping, and the remaining sets failed in both modes simultaneously. It is desirable for traffic paints to fail by abrasion (i.e., to wear out) rather than through chipping, which represents a premature separation from the pavement substrate. Thus it is encouraging that only about one-fourth of the paints tested failed through chipping. The acrylic, alkyd-acrylic, and epoxy paints generally had the lowest rate of chipping failure, whereas the alkyds failed predominately by abrasion. About half the chlorinated rubbers and chlorinated rubber-alkyds experienced abrasion failure, but the other half failed through chipping or in both modes simultaneously. Most water-based paints failed through chipping.

DISCUSSION AND RESULTS

Results of these accelerated-wear tests demonstrated that there are considerable differences in the service lives of various traffic paints. In general, similar estimates of service life were obtained for durability and appearance, but for reflectivity service lives were much shorter.

Variability in service life was quite large between duplicate stripe sets installed in the same year or in more than 1 year. Within-year differences were generally no more than a few weeks for duplicate sets of paint stripes, but, between years, differences between duplicate sets averaged a few months. Thus, the results of these accelerated-wear tests should not be used to evaluate small differences in performance between paints, especially if those paints were installed in different years.

In spite of the sizable variability in performance experienced between duplicate stripe sets and the relatively small differences in performance experienced in the wheelpath stripes, some large differences in performance were found among paints used in the nonwheelpath stripes. The range in performance among paints was much larger than the differences between repeated tests with the same paint; thus the range appears to be a valid measure of performance. It also appears that differences in winter weather severity among years affected the wear rates observed. However, the relative ranking of the various paints and paint groups was very similar in each of the three annual evaluation periods, even though the service lives actually observed varied from year to year.

Performance was also closely related to paint group. All the best-performing paints were chlorinated rubbers or chlorinated rubber-alkyds, and the poorest were alkyds and water-based paints. However, most paint groups exhibited a range in performance, so identification of a paint group does not necessarily indicate the performance capability of that particular paint.

Finally, the best-performing paints provided satisfactory durability and appearance for a year or more in nonwheelpath positions and acceptable reflectivity for as long as 7 months. Considering the high traffic volumes on the test sites and the location of the test stripes, which were closer to the wheelpath than the normal location of longitudinal paint lines, these tests indicate that some traffic paints can provide year-round delineation on a sizable portion of the state highway system. On the basis of the results and their discussion in this paper, the following findings can be stated:

1. Service lives of the standard New York State alkyd traffic paints were the lowest of all paints tested.
2. The best-performing paints were several formulas of chlorinated rubber and chlorinated rubber-alkyd. Service lives of the best paints were more than three times as long as those of the state standard traffic paints.
3. Some formulas of other paint types—including alkyds, acrylics, epoxies, and water-based paints—provided improved service lives over those of the state standard paints. However, these improvements were generally of 50 percent or less.
4. Duplicate stripe sets installed in the same year generally varied in service life by several weeks, and those installed in more than one year varied by a few months. Thus, small differences in service life observed in these accelerated-wear tests are not reliable, especially if the paints were not installed in the same year.
5. The very rapid wear experienced by wheelpath stripes after the onset of winter tends to mask differences among paints. Thus, nonwheelpath stripes provided the clearest measure of performance differences among paints.
6. Durability and appearance ratings provided good measures of differences among paints, but reflectivity measurements were less reliable.

7. Nearly all the best-performing chlorinated-rubber and chlorinated-rubber-alkyd paints contained MEK as a solvent, but one chlorinated rubber-alkyd that contained toluene also performed well.

8. Several paints provided drying times in the range of a minute or less, but these were generally the poorest performers. Most paints providing good performance had drying times of more than 2 min, but the toluene-based chlorinated rubber-alkyd had a drying time generally of less than 2 min.

9. A number of traffic paints appear capable of providing year-round delineation on a substantial portion of the New York State highway system with only one application per year.

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Measures of Snowplowable Raised Pavement Marker Reflector Wear

SANAT N. BHAVSAR

Measures of amount of wear sustained by snowplowable raised reflective pavement markers are recommended to encourage the use of objective measures and provide a basis for standardization of wear measures. Such an evaluation was carried out on NJ-29 and NJ-31 in 1984–1985 and on US-1 in 1974–1975 after two successive winters of use. The effect and extent of various types of physical wear were checked. The scope of this effort allowed determination of which measures were useful in classifying average functional reflective surface area and average visibility distance from year to year, marker to marker, and route to route, so that a statistical analysis of differentiation between the items of comparison could be performed at a high level of significance. There is an increasing need to establish a scientific relationship between the day and night measures, which could be generated by future research work.

Night driving is not only more hazardous than daytime driving, but the percentage of fatalities is increasing. The primary factor is thought to be inadequate visibility *(1)*. There is a need to have and keep adequate night visibility and provide proper delineation during all seasons and types of weather.

Stimsonite Model 96 snowplowable raised reflective pavement markers are becoming widely used for dry and wet night delineation. However, no specific, uniform, and systematic procedure is available for a periodic survey and evaluation of the functionality of these markers. A first step is taken toward providing uniform measures of wear. The purpose of this paper is to encourage the use of suggested measures of wear and to provide a beginning for the standardization of such measures. Measures of wear have been inadequate in the past when information on wear was compared among states and agencies and are needed to satisfy the following objectives: *(a)* to check the durability of new products for delineation and compare them with an existing product being used, *(b)* to evaluate modifications in the existing product, and *(c)* to establish new replacement criteria because of changes or exceptions in conditions causing wear.

Measures of wear and their documentation are described. The importance of each measure and which wear measures have been found useful to satisfy these objectives are discussed. A procedure is given to estimate the condition and visibility of the markers. A technique has been described to estimate night visibility of the markers. It is beyond the scope of this effort to come up with a much-desired link between day and night measures of wear, which should be established through future research work.

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DAYTIME MEASURES

Each marker casting and a reflector insert were closely examined for the following types of wear or condition:

1. Cracking: The acrylic reflector was checked for any cracks, either external on the acrylic shell or internal in the hard core.
2. Breaking: A reflector was noted as broken if any part of the sides or the top was observed to be broken.
3. Delamination: The acrylic surface was inspected for any delamination between the core and the shell of the reflector.

All of the foregoing measures are nominal in nature, allowing their documentation as cracked, broken, or delaminated. Figure 1 shows a perfect reflector, and Figure 2 shows a cracked reflector with top delamination. Delamination of a part of the top as well as the side and cracks are shown in Figure 3; and in Figure 4 a part of the top and side is shown with a crack through the core.

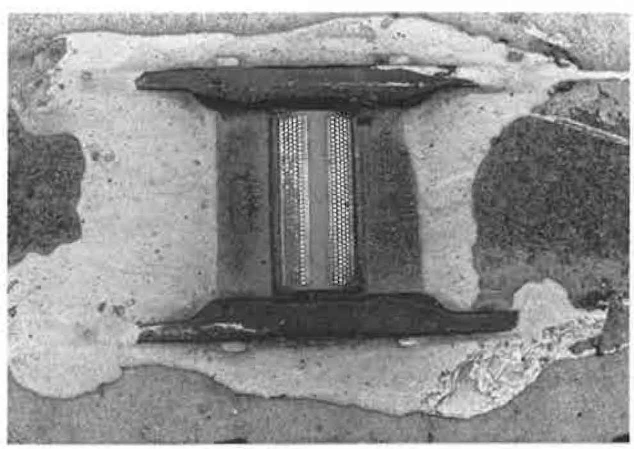

FIGURE 1 Perfect reflector.

The following measures are more quantitative in nature:

1. Percent reflective surface: The retroreflective surface of the reflector was divided into north and south faces for evaluation purposes. NJ-29 and NJ-31 and US-1 run in a north-south direction. Each face was given a "percent functioning" surface rating in 5-percent increments between zero and 100 percent, which provides a measure of the proportion of the total reflector face remaining reflective after cracking, breaking, and delamination are accounted for.

FIGURE 2 Cracked reflector with top delamination.

FIGURE 3 Cracked reflector with top and side delamination.

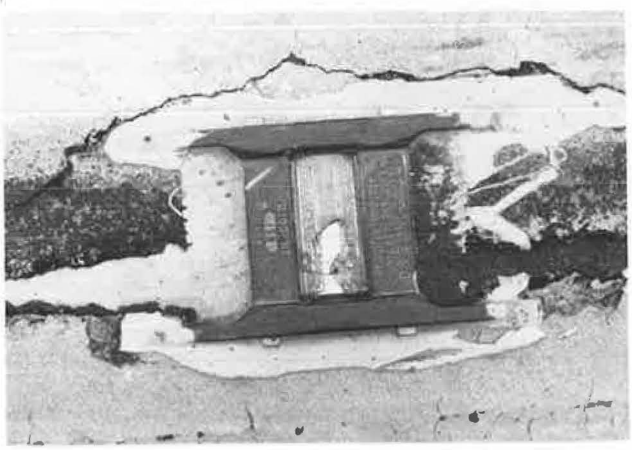

FIGURE 4 Broken reflector.

2. Percent epoxy: This is the measure of the amount of the reflective surface accidentally covered by the epoxy use for installation of the casting. It was noted in 5-percent increments what percentage of the total reflector face was covered with epoxy.

3. Percent paint: Some markers were painted over by mistake when the pavement was restriped. The percentage of the paint-covered surface, which was not available for reflectorization, was estimated.

4. Percent top: The top of the reflector, which is nonreflective, was observed for cracks, delamination, and any part that was broken. Percent of the top broken, in increments of 5 percent, was determined approximately.

5. Missing reflector or casting: A missing reflector insert or a missing casting was documented.

Method of Observation

Observations were made on foot in the daylight; all markers were inspected closely, and any reflector surface covered with mud or dirt was cleaned with a brush for a better view of the wear. Necessary safety precautions were taken while inspection of the markers was in progress.

Data Collection and Treatment

All measures were recorded on standard preformatted forms. Each marker was given a specific number, which could easily be traced for subsequent comparison or in case any information was missing. The data collected were analyzed by generating a mainframe data base using a RAMIS II system. Those markers covered with epoxy, painted over, and missing castings were excluded from the analysis because reflector wear was obscured from view.

DIFFERENT USES OF DAY MEASURES

Stimsonite Model 96 snowplowable raised reflective pavement markers, both regular profile and low profile, were installed on NJ-29 in September 1983. One hundred eighty regular-profile and 215 low-profile markers were placed at intervals of 80 ft on the tangent section and 40 ft on curves greater than 3 degrees. The objectives of this installation were *(a)* to observe the different types of wear after each winter, *(b)* to determine which measures of wear were statistically sensitive in a comparison, and *(c)* to see whether there is a distinction between regular- and low-profile markers for reflector insert durability. The markers were surveyed each year for two winters. The snowfall for 1983–1984 was 26.5 in. and for 1984–1985 was 25 in.

The only controlled variable for analysis was a casting type distinguished by a regular and a low profile. The uncontrolled variables included traffic wear, volume of traffic, type of vehicle, amount of snowfall, snowplow wheel and steel-blade passes, and weather conditions; however, these conditions were quantified and documented whenever possible.

In Table 1 physical wear is classified as percent cracked (C), broken (B), or delaminated (D) when these are not mutually exclusive. In the last column the percentage of the reflective surface that shows any or all of these forms of wear is given. Low-profile markers show less physical wear, and the percentage of broken and delaminated reflective surface was significantly different between regular- and low-profile markers at least at the 95 percent confidence level.

A cracked, broken, or delaminated reflector is an imperfect reflector, but these measures of wear are mainly an indication of the cause of damage.

It was observed that at a point on the 6-mi stretch of NJ-29 where markers were installed, almost all trucks carrying rocks

TABLE 1 PHYSICAL WEAR OF REFLECTOR SURFACES, NJ-29

	Percentage of Wear			
Profile	Cracked	Broken	Delaminated	C, B, or D
Regular	59.4	76.9[a]	72.9[b]	92.2
Low	63.3	70.1[a]	52.0[b]	87.1

[a]Significant at the 95 percent confidence limit.
[b]Significant at the 95, 99, and 99.5 percent confidence limits.

from a quarry were going south, dividing the low-profile section of markers. The phenomenon of heavy trucks going south was considered an important variable affecting the statistical analysis of differentiation between regular- and low-profile markers. The wear on reflectors when the influence of heavy trucks was eliminated, or when only the markers north of the quarry were analyzed, is shown in Table 2. A "good" reflective surface was characterized as one in which 50 percent or more of the reflective surface was functioning. This is an arbitrary measure used by several states to check the usability of the marker and is also incorporated into criteria for replacement, discussed later. Average percent functioning surface indicates the amount of intact reflective area remaining.

Low-profile markers were significantly differentiated from regular-profile markers in having more functioning reflective surface and top durability.

Top damage is the beginning of damage to the marker and can serve as the precursor of reflective surface damage.

TABLE 2 REFLECTIVE SURFACE WEAR, NJ-29

Profile	"Good Surface" (%)	Avg Percentage Functioning Surface	Avg Percentage Top Intact
Regular	55.3[a]	55[b]	47[a]
Low	77.9[a]	69[b]	70[a]

NOTE: Results are for markers north of quarry (see text).
[a]Significant at the 95, 99, and 99.9 percent confidence limits.
[b]Significant at the 95 percent confidence limit.

REFLECTOR WEAR AMONG DIFFERENT ROUTES

In September 1984, 270 regular-profile markers were installed on NJ-31 and were surveyed after the first winter to estimate the annual wear. The method of observation was similar to that adopted for NJ-29 except that every fourth marker was inspected for wear. A 1976 report by M. V. Jagannath and A. W. Roberts on evaluation of snowplowable raised pavement markers in New Jersey *(2)* contained the rating of reflector loss and damage to Stimsonite Model 99 markers on US-1 during the winters of 1973–1974 and 1974–1975. The objective of this comparison was to see the effect of traffic and snowplowing on marker wear.

The average percentage of functioning reflective surface remaining is compared for NJ-29, NJ-31, and US-1 in Table 3. It was noted that the wear on reflective surfaces was higher on NJ-31 after the first winter and on NJ-29 after the second winter than on US-1 since installation. It should be noted that traffic volume and characteristics were different on all three routes and the castings on US-1 were slightly different from those used on NJ-29 and NJ-31.

NIGHT MEASURES

Day measures of wear provide physical type and extent, whereas night measures are estimates of what a motorist sees. It is not advisable to make observations during the day on some highways because of personal safety, but it can be more convenient to do so.

An estimate was made of the dry-night visibility of markers on NJ-29 in May 1985 after 2 years of wear. The number of markers visible approximately every 0.4 mi was noted from a moving vehicle, and slides were taken using ASA 400 film in a camera with an *F*/1.2 lens at 1/60 sec. Because the distance between the markers at all points was known, the average visibility of both regular-profile and low-profile markers was calculated to be 260 ft. The availability of data for night measures was limited because of heavy-truck traffic, so the establishment of statistical significance at the 95 percent level of confidence was not possible. It is suggested that at least 30 measures of visibility for each type of marker would be needed in both directions for a proper statistical analysis. It was not possible to relate the night visibility to daytime wear measurement because of the scope of the effort, but this should be done in a separate research project.

DISCUSSION

Daytime Measures of Wear

The daytime measurement of available functional reflective surface could be carried out in two ways. One of the best methods is to register the functional area in increments of 5 percent, as described earlier. In some states the criterion for a

TABLE 3 AVERAGE PERCENTAGE FUNCTIONING REFLECTIVE SURFACE

		After First Winter		After Second Winter		
Test Site	Type of Road	Remaining Reflective Surface (%)	Snowfall (in.)	Remaining Reflective Surface (%)	Snowfall (in.)	Annual Avg Daily Traffic
NJ-31	Two lanes with shoulders	73	25	NA	NA	13,280[a]
NJ-29	Two lanes without shoulders	86	26.5	54	25	8,390[a]
US-1	Six lanes, divided, with shoulders	82	20.2	59	16.4	60,000[b]

[a]In 1983. [b]In 1976.

"good" reflector is that it have 50 percent or more functioning reflective area. Hence, the reflective surface area available could be classified either "50 percent or more" or "less than 50 percent." The advantages of this method are that it is probably faster, it makes calculating the "adequately" functioning reflectors easier, and it helps in quick maintenance decision making. However, an estimate of average functioning reflective surface for the installation cannot be obtained with this simple method.

The measures of physical damage to the reflector, such as cracking, breaking, and delamination, give an estimate of the extent of overall damage to the reflector. These measures should not be used as criteria for replacement of the reflectors. However, they help in understanding the severity of each type of damage and the cause of damage and in determining how many reflectors are simply "damaged" or "not damaged."

Nighttime Measures of Wear

It is not always possible to collect data on daytime measures of wear on heavily traveled, four-lane highways and freeways. A feasible solution would be to resort to the night measures, such as visibility range, and how many of them are perceivable. A night measure of the visibility of the markers under clean and dry conditions could be substituted as a check on reflector wear level. A measure of wet-night visibility would be the ultimate for a replacement criterion because provision of wet-night visibility is the primary purpose of using the markers.

It is advisable to photograph the markers at night because estimating visibility of the markers from a moving vehicle could cause error. A fast film—ASA 400 or higher—may be used in a 35-mm camera fitted with an $F/1.2$ lens at a speed of 1/60 sec; high beams are used, which simulates low beams in a photograph. Slides taken from a moving car approximately reproduce the scene viewed from a stopped car. The slides could then be viewed by one or two persons to determine the visibility of the markers and their contribution toward providing adequate nighttime delineation.

Both day and night measures of wear are useful in comparing types of markers and in selecting durable markers. Wear measures from year to year could provide a rate of wear on a route, which in turn could be used to plan the maintenance of the markers. The measures of wear are, in general, applicable to any kind of road.

Formation of Replacement Criteria

A criterion for replacement of the reflectors can be formulated based on either day or night wear measures, or both. For example, it would be wrong to state the replacement policy using day measures as follows: "When 25 percent of the markers have less than 50 percent reflective surface remaining, replacement of reflectors should be planned for the whole installation." This criterion allows an average functioning reflective area to be as low as 37.5 percent or as high as 87.5 percent, which forms outer limits of tolerance. It could allow an installation having much more than 50 percent average functioning reflective surface area to be replaced or one with much less than 50 percent average functioning reflective surface area to go unreplaced.

When both day and night measures are used, the replacement policy could be worded as follows: "Installations in service for 3 years or longer should be evaluated, and if it is determined that the average of the functioning reflective surface area in an installation is less than 50 percent, or the average visibility of the reflectors at night in an installation is less than 240 ft using low beams, then all the reflectors in an installation should be replaced." As compared with the previous wording, this statement allows only 50 percent as a lower limit for average functioning reflective area. The measurement of reflective area should be registered in small increments, such as 5 percent, to encourage more accurate data collection.

It should be noted that making observations from a moving vehicle during the day and counting imperfect markers would provide a grossly inaccurate measure of wear. It was calculated that for NJ-29 in the second year after installation, the amount of perfect (devoid of any damage) regular markers was only 7.3 percent, whereas the amount of average functioning reflective surface was 55 percent (Table 2). This is evidence that the amount of physical damage should not be used as a replacement criterion.

It is not always possible to measure wear accurately because of safety considerations during observation. For example, standing or stopping in the middle of the road can be hazardous under certain conditions. But experience and evaluation could lead from an approximate measure, such as daytime wear, to a substitute measure that would be easier to use in planning maintenance schedules. For reasons of safety and for uniformity in data collection, training of personnel is necessary before they go out into the field.

FINDINGS AND RECOMMENDATIONS

Daytime measures of physical wear of reflectors provide an estimate of the extent of such marker wear. The measure of percentage of functioning reflective surface area allows calculation of either the average functioning reflective area for the installation or of the number of markers that have less than 50 percent of the reflective area remaining. A measure of visibility of markers at night would provide an indication of what the driver sees at an installation. Criteria for replacement of reflectors for regular maintenance can be formulated by using both day and night measures.

Low-profile markers are more durable and have superior wear resistance against cracking, breaking, and delaminating. Regular-profile markers suffered more wear compared with low-profile markers after the same time since installation and under similar operating conditions.

Low-profile markers have significantly more functioning reflective area after 2 years of wear compared with reflectors placed in regular castings.

The type of traffic, such as heavy trucks, has a significant effect on reflector wear. A research study is needed for better prediction of the effects of variables such as weather, volume of traffic, types of vehicles, snowplow wheels, road geometry, and amount of snowfall. This would help to determine and evaluate the wear on the reflectors due to each variable separately.

A separate research project should be carried out to develop a predictable relationship between the physical wear and damage and the appearance of markers evaluated during daylight and the visibility of the markers at night.

After the recommended studies have been completed and an adequate reflector visibility standard has been determined, a satisfactory maintenance schedule can be planned.

FUTURE RESEARCH NEEDS

The measures of wear used for NJ-29 and NJ-31 are reliable for keeping track of reflector damage. The observation or inspection is carried out during daylight and covers almost every aspect of the reflector. However, there is a need to define the relationship between a daylight measure and night visibility so that one variable can be predicted as a function of the other. An adequate night visibility standard for the markers should be determined in a separate research project. This information can then be used to frame the maintenance cycle for the replacement of the reflectors so that adequate night visibility is provided continuously. It can also help in budgeting and planning by predicting the service life of the reflectors fairly accurately; thus, proper allocation of funds and manpower would be made for regular maintenance.

The effects of uncontrolled variables such as temperature, use of abrasives and chemicals, amount of snowfall, volume of traffic, type of vehicle, and characteristics of snowplow wheels and blades, which might be related to reflector deterioration, could not be estimated separately by the process of wear measurement described earlier. Research in wear measurement is necessary to determine the individual contributions of these variables to physical wear and damage. Methods or techniques to make the reflectors less prone to damage or to allow less damage to occur could then be addressed in further research.

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The content of this paper reflect the views of the author, who is responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the New Jersey Department of Transportation or FHWA. This paper does not constitute a standard, specification, or regulation.

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Hazardous Wastes Within the Transportation Planning Context

THOMAS L. WECK

In the 1980s hazardous wastes are everyone's concern. For the transportation planner, hazardous wastes have become a significant factor in the location and expansion of roadways and other transportation facilities. In order to examine the issue of potential hazardous waste problems, a preliminary screening study should be undertaken at the initial planning or location study phase. The goal of such a study is to identify the potential for hazardous waste problems with a view to their avoidance, which is the optimal solution from a transportation planning viewpoint. Although the data review and surface field investigation are an important part of a preliminary screening study, they generally fail to address the historic profile of land use adequately. In order to determine the potential of hazardous waste contamination from historic land uses, an important supplemental step in the preliminary screening process is to carry out a computerized aerial photographic (CAP) analysis, which is a powerful tool for looking into the past and has proved to be a very accurate predictor of hazardous waste contamination. When the cleanup of a hazardous waste site becomes necessary, there are two basic components to the design: a remedial investigation and a feasibility study. There are four special features unique to cleanup activities at hazardous waste sites. These include the need for a quality assurance–quality control (QA/QC) program, a health-and-safety plan, an emergency and contingency plan, and on ongoing monitoring program. The extensive requirements of hazardous waste site cleanups only reinforce the need for identification early in the planning phases of a transportation project so that, wherever possible, hazardous waste contamination problems can be avoided.

In the 1980s hazardous wastes are everyone's concern. For the transportation planner, hazardous wastes have become a significant factor in the location and expansion of roadways and other transportation facilities. If hazardous waste problems are not taken into account, substantial extra costs and time delays for transportation projects can result. There have already been, unfortunately, cases in which hazardous waste contamination discovered for the first time during the construction phase of a project has resulted in tens of millions of dollars of extra costs for cleanup and years of delay over the originally scheduled completion date for the project.

Clearly it is advantageous to address hazardous waste problems earlier rather than later in the transportation planning process. The earlier the issue is addressed, the greater the flexibility of response in the development of a solution, and the greater the flexibility, the less the resulting extra costs and time delays. This is shown graphically in Figure 1. In the planning or location phase of a project, when flexibility of response is greatest, it may be possible in many instances to avoid a potential or known hazardous waste site altogether. Avoidance is the solution of choice whenever feasible. If a hazardous waste problem is left unaddressed until the design phase, the flexibility of response may have been reduced to the point at which avoidance is no longer cost-effective or possible. In this case, minimization of impact through a minor shifting of alignment or an engineering design modification may be the optimal solution. If a hazardous waste problem is not addressed until the construction phase, flexibility of response is generally low. Often the only feasible solution is a full-scale cleanup. The extra costs and time delays of this least desirable solution will in all likelihood be dramatically greater than what would have been available at earlier stages in the transportation planning process.

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Two aspects of hazardous wastes are examined: the most effective way of addressing hazardous waste problems in the location study and planning phase of a project (the time at which they ideally should be addressed) and, for those cases in which site cleanup becomes necessary, the basic steps involved in the design of a cleanup and the special factors that must be taken into account during cleanup activities.

PRELIMINARY SCREENING STUDY

The goal of a preliminary screening study is to identify the potential for hazardous waste problems with a view to their avoidance, which is the optimal solution from a transportation planning viewpoint. A preliminary screening study should be undertaken when the initial planning and location study phase begins. A preliminary screening study comprises six basic steps.

Step 1. Initial Classification of Risk by Land Use Category

The first step in a preliminary screening study is to classify land use within the project area into three groups: high, medium, and low risk. High-risk land use categories include all known hazardous waste sites, all landfills (which are automatically suspect), and industrial sites under Standard Industrial Classification (SIC) codes that have historically been associated with hazardous and toxic waste contamination. These would include the industries for paper products, oil refining, chemicals, metal fabricating, electrical machinery, and plastics, to name a few. The medium-risk group would include *(a)* hazardous waste sites that have been subject to cleanup but at which there has been no final determination of completeness of the cleanup and

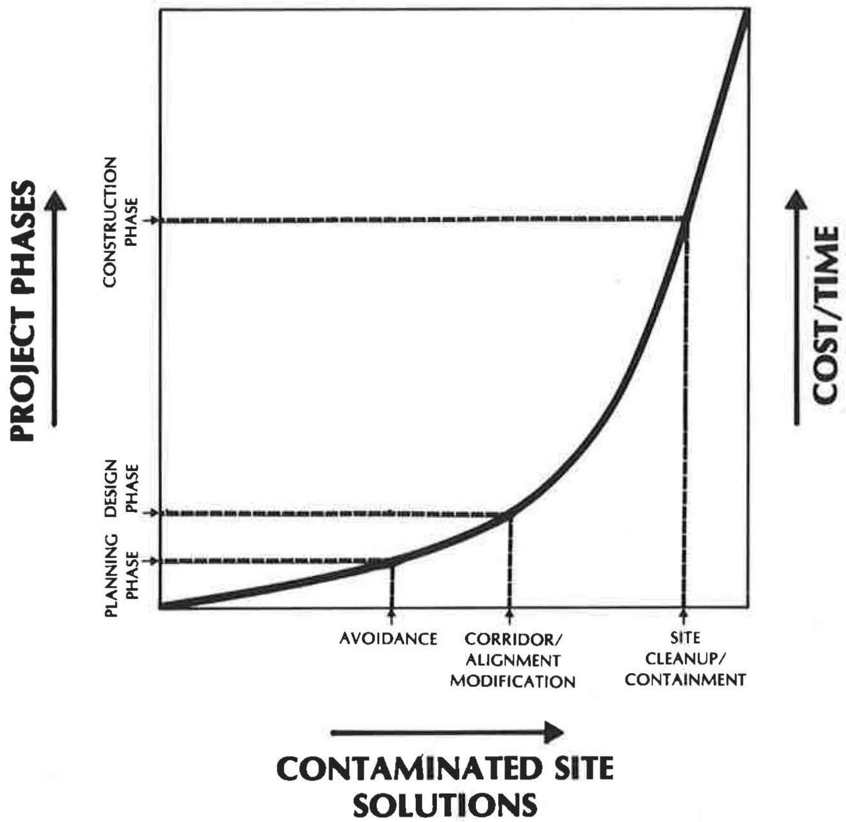

FIGURE 1 Hazardous waste site cleanup.

(b) industrial sites under SIC codes that historically have shown themselves to be possible candidates for hazardous or toxic waste contamination. These would include such industries as automobile assembly, textiles, and wearing apparel. The low-risk group would include all other land use categories. This classification should then be refined according to the following steps.

Step 2. Review of Available Data

The second step in the preliminary screening study is to make a detailed review of all data available at federal, state, and local levels that may provide information as to potential or actual sources of toxic and hazardous waste contamination for the land use within the project area. At the federal level, Environmental Protection Agency (EPA) files on Superfund sites and facilities under the Resource Conservation and Recovery Act of 1976 (RCRA) should be consulted. At the state level, the equivalent of a division of waste management within the state's department of environmental protection would be the best source. At the local level, regional authorities, counties, and municipalities should be canvassed regarding pertinent information they may have on file.

Step 3. Preliminary Field Investigations

The third step in the preliminary screening study is to make a visual surface examination within the project area in an effort to identify any apparent or possible problem areas with regard to hazardous waste contamination. It is during this preliminary field investigation that illegal dumping activities may be discovered. For example, it is not altogether improbable that a stack of metal drums, for example, may be found partially buried in a remote wooded area within a project area.

Step 4. Computerized Aerial Photographic (CAP) Analysis

Although the data review and surface field investigation are important refinements to the initial classification of risk by land use category, they alone are insufficient for a comprehensive screening because they generally fail to address the historic profile of land use adequately. What may appear on the surface to be only a vacant lot or grassy field may very well be the site of hazardous waste contamination that occurred decades earlier. To assume that what appears to be benign on the surface is in fact benign is to invite an unpleasant surprise later, when flexibility of response may be severely curtailed.

In order to address the issue of historic land use and the potential for hazardous waste contamination from such use, a fourth step in the preliminary screening process is to carry out a CAP analysis. This computerized analytic procedure is highly cost-effective and has proved to be an accurate predictor of the location of hazardous waste contamination. Because of its high utility and widespread applicability to transportation planning, it is useful to outline the steps of a CAP analysis in some detail. The basic steps are as follows.

Collect Aerial Photos

The first step in the CAP analysis is the collection of standard 9 × 9-in. aerial photographs for as many different years as possible for the entire project area in question. These aerial photographs, which have a standard scale of 1 in. = 2,000 ft or 1 in. = 1,000 ft, are available from a variety of sources, including the U.S. Geological Survey, the U.S. Army Corps of Engineers, state departments of environmental protection, county planning boards, and local aerial photography firms, to name the more common sources. In previous applications of CAP analysis it has generally been found possible to obtain 9 × 9-in. aerial photographs dating back as far as 50 to 60 years and at intervals of one every 10 years or less up to the present time. In other words, it has generally been possible to obtain an excellent profile of land use over time, usually going back as far as the 1920s, that includes a time series of 6 to 10 aerial photographs for the entire project area.

Identify Suspect Uses

Once the aerial photographs have been collected, a trained aerial photographic interpreter examines them to identify areas of suspect use. In this regard it should be noted that stereoscopic pairs of aerial photographs are significantly easier for photointerpretation than single aerial photographs. The principal tool used for aerial photointerpretation is a stereoscope, which enables the aerial photointerpreter to view the photographed surface in three dimensions and to magnify areas of interest. In addition, using an attachment called a stereometer, the aerial photointerpreter can measure heights of objects in the photographs.

Through stereoscopic photograph interpretation, features can be recognized as having positive relief (located above ground level), negative relief (below ground level), or zero relief (at ground level). Assuming that stereoscopic pairs are available, which is generally the case, a trained aerial photointerpreter can readily identify sources of potential hazardous waste contamination, including landfills, lagoons, dump storage areas, tank storage areas, and even spills, whether accidental or intentional. The following are some of the major characteristics of these sources of contamination.

Industrial Activity Buildings and other industrial structures identified exhibit positive relief. Ground outlines of former building sites (zero relief) and excavations (negative relief) can be distinguished. Other signs of industrial activity are parking lots, smokestacks, incinerators, site roads, and trucks and other vehicles.

Drum Storage Drums and barrels are identified on the basis of positive relief, shape, and grouping. Ground stains are usually present when drum storage is identified.

Tank Storage Tank storage facilities are usually associated with a large industrial operation (refinery, utility, chemical company). They exhibit positive relief.

Liquid Storage Liquid storage facilities are also usually associated with a large industrial operation (refinery, etc.). They are a much greater potential source of contamination than tank storage facilities and are distinguished by the presence of liquid (which appears flat and is usually black), negative relief, and surrounding dikes (positive relief).

Standing Liquids Standing liquids are usually associated with industrial or landfill operations. However, the accumulation is more likely to be unplanned. When it appears to be planned, it is usually confined to a ditch and a surrounding dike is not usually present. It is distinguished by the presence of liquid and negative relief.

Lagoon Lagoons are characterized by the same features as those for liquid storage, except that the purpose is for liquid disposal or runoff rather than industrial use.

Sludge Sludge is usually associated with large industrial operations and is characterized by a lighter color than liquids. Sludge has a negative relief and is typically found in the presence of surrounding dikes (positive relief).

Fill Fill is usually associated with grading operations. It is distinguished from undisturbed ground by its lighter color at inception (lack of vegetation) and positive relief. It is distinguished from landfill operations by its uniformity of color (generally light), smooth texture, flat surface, and lack of obvious waste.

Landfill A landfill is usually a sanitary landfill where municipal solid wastes and construction debris are permanently deposited. Characteristic features are positive relief, variable light and dark coloration, irregular texture, presence of waste piles, road network, trucks, incinerators, and leachate (lighter color) at extremities of the landfill. There may also be liquid storage, lagoons, and drum storage.

Waste Disposal Waste disposal is usually associated with an industrial facility. It can be recognized by variable light and dark coloration, irregular texture, and positive relief. It may be permanent disposal or temporary storage of waste material.

Digitize and Normalize Input

Following the identification of possible sources of contamination on the 9 × 9-in. stereo pairs, the scales of the aerial photographs are enlarged to permit easy digitization, the process of translating paper drawings of photographs into computer images. Each photograph is enlarged to a scale of 1 in. = 200 ft to facilitate positive identification of minute features and to reduce the margin of error in the subsequent analytic process.

Digitization is then accomplished through the use of an electronic drafting board, called a digitizing tablet, with a defined coordinate system. The tablet is sensitive to the movement of a pointing device along its surface. The two most common pointing devices are the cursor and the light pen. Points, lines, or polygons from the photographs are translated into computer images by moving the pointing device over the digitizing tablet and pressing predefined buttons to define starting and ending points of the line constituting various shapes.

By so digitizing cultural, industrial, and environmental features, the resulting information can be readily readjusted for scale and displayed in a variety of useful formats for analytic purposes. The scales are also normalized during the digitization process for the sake of comparability in subsequent analysis.

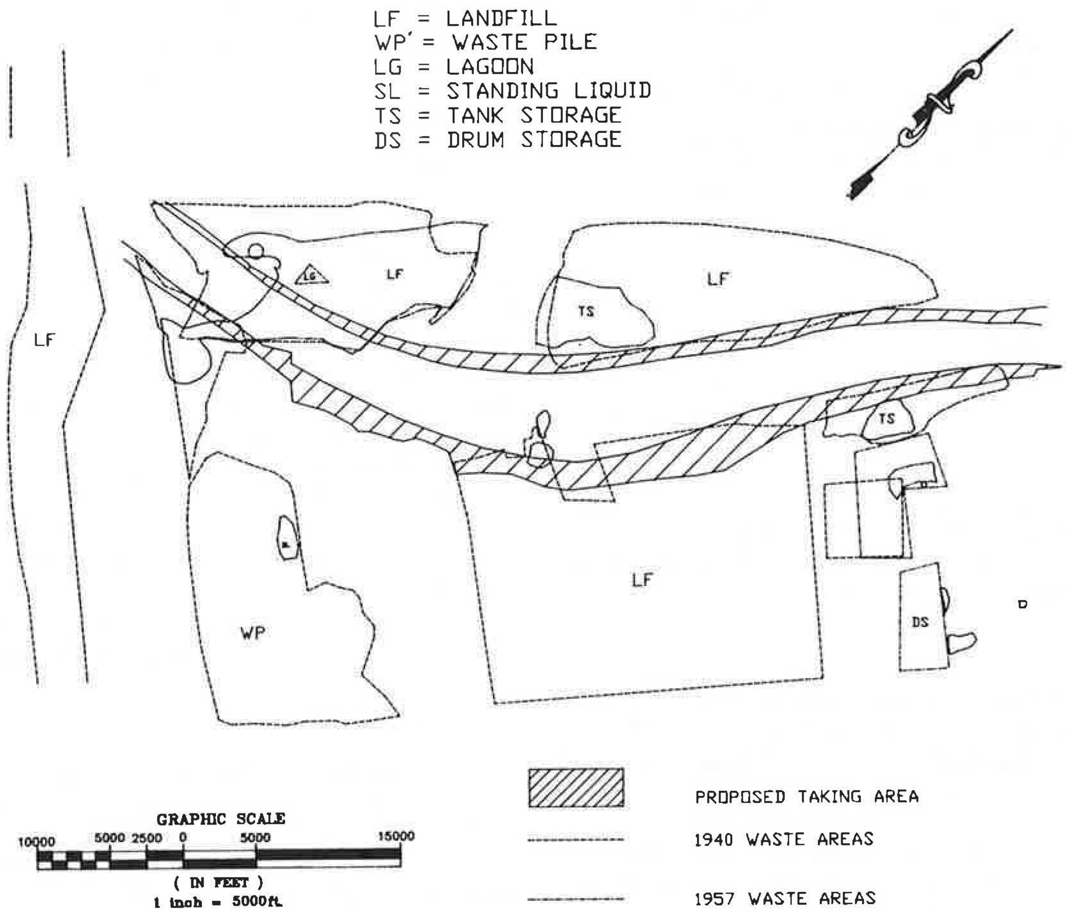

FIGURE 2 **Hazardous waste screening studies.**

Generate Overlays

Once the digitized and normalized photographic information has been input into the computer, overlays are generated that identify known waste areas and industry site locations, transportation features, topographic features, and any type of information labeling desired. For ease of use, the information for different years is generally produced in different colors on the computer screen. The overlays can be mixed and matched in any combination of multiple sets and the overlay scales can be enlarged or compressed to provide more detail or to generalize features, depending on what is most useful. Figure 2 gives an example of a typical overlay that can be generated by the CAP analysis.

Flag Problem Areas

From the computer-generated overlays, potential problem areas can be flagged without difficulty and preliminary evaluations made regarding the ease of changing the corridor location or specific alignment of a proposed transportation facility in order to avoid such problem areas.

Step 5. Reclassification of Risk

Based on the foregoing three refinement activities, a final reclassification of risk by land use category is prepared.

Step 6. Preliminary Testing

On the basis of the final reclassification of risk by land use category, all high-risk classifications and some or all of the medium-risk classifications should be subjected to subsurface testing for the standard range of hazardous wastes. The current EPA regulations require that groundwater and soil samples be tested for 129 priority pollutants plus the next 40 highest unknown peaks. The preliminary subsurface testing is carried out in an effort to verify the presence of contamination and, where it is present, to serve as a starting point for the subsequent determination of a contamination plume profile designating the spatial dimension of the contamination. Moreover, when there appear to be cost-benefit trade-offs requiring a decision between shifting a proposed project within a transportation corridor or from a specific alignment to avoid a hazardous waste problem area or holding to the originally proposed corridor or alignment with the possible requirement that a hazardous waste cleanup may be necessary, preliminary testing is of vital importance to the decision process.

It should be noted that, to date, when field verifications of preliminary testing have been carried out, the CAP analysis has demonstrated itself to be an accurate predictor of the existence of historic hazardous waste problems. It is this type of accuracy that makes CAP analysis a powerful technique for quickly examining the extent to which past industrial or other activities may have resulted in hazardous waste contamination problems.

This six-step preliminary screening study should delineate where the hazardous waste problem areas may exist so that, when it is feasible, they can be avoided. When because of engineering or other environmental constraints, one or more potentially contaminated areas cannot be avoided, steps can be taken early in the transportation planning process to determine the type and extent of hazardous waste contamination that must be dealt with.

SITE CLEANUP

Basic Steps in Design

When the cleanup of a hazardous waste site becomes necessary in conjunction with a transportation project, either because it has been determined through a preliminary screening study that such cleanup cannot be avoided or because, in the absence of adequate preliminary screening, a hazardous waste site has been encountered for the first time during construction, there are two basic components to the cleanup design: a remedial investigation and a feasibility study.

Remedial Investigation

The first step in a remedial investigation is to posit a series of engineering operations typically known as unit operation scenarios (UOSs) and to evaluate them for appropriateness. UOSs encompass controls of surface water, groundwater, gas migration, and waste.

Common UOSs under each of the four basic controls that may be suitable and appropriate to the specifics of a particular hazardous waste site are as follows:

- Surface water controls
  - –Regrading and diversion structure
  - –Surface sealing
  - –Revegetation
  - –Cutoff trench
  - –Basin ponds
  - –Containment berm
- Groundwater controls
  - –Bentonite slurry trench
  - –Grout curtain
  - –Sheet piling cutoff wall
  - –Grout bottom sealing
  - –Underdrain
  - –Well point system
  - –Deep well system
  - –Well injection system
- Gas migration controls
  - –Gas vent trench
  - –Gas extraction well
- Waste controls
  - –Treament of contaminated water
  - –Chemical fixation
  - –Chemical injection
  - –Excavation and reburial
  - –Leachate recirculation

It is possible that during this evaluation further testing may be required. For example, a gravel vent trench for gas migration control is generally only feasible to a depth of 20 to 30 ft. Beyond this depth a gas extraction well may be necessary for gas migration control. Further field testing may be necessary to determine the depth of gas production in the hazardous waste site.

Feasibility Study

In a feasibility study the UOSs are integrated into one or more conceptual designs, which are evaluated with respect to cost-effectiveness. A final design is then prepared. For example, if a site cleanup involves drummed wastes, the final design may specify overpacking of some of the drums for further processing later and the bulking of the other drums for landfilling. The shelf life of the overpacked drums would have to be determined and compatibility requirements for the bulked drums specified.

In the preparation of the final design, it again may be necessary to carry out further subsurface testing. For example, if waste containment is the preferred alternative and a bentonite slurry trench is proposed, further testing may be necessary regarding soil porosity, permeability, and cation exchange to ensure that the properties of the bentonite remain unchanged over time when exposed to the specific leachate at the site.

Special Features

There are four special features unique to hazardous waste site cleanup activities. These include the need for a quality assurance–quality control (QA/QC) program, a health-and-safety plan, an emergency and contingency plan, and an ongoing monitoring program.

Quality Assurance–Quality Control (QA/QC) Program

The goal of a QA/QC program is to verify the accuracy and precision of the findings and completeness of the chain-of-custody documentation. In a hazardous waste site cleanup activity, the verified accuracy and precision are a necessary part of the state or federal review agency's requirements in order to certify the completeness and adequacy of the cleanup.

Moreover, in any hazardous waste site cleanup activity, the agency or agents responsible for the cleanup (or both) are always only one step away from being drawn into litigation. Allegations that a site cleanup itself may have caused the inadvertent spread of contaminants, resulting in harm to third parties, are always a danger. (One of the most common areas of concern is contamination of groundwater sources heretofore free from the contaminates present at the hazardous waste site in question.) It is imperative to designate a properly trained QA/QC officer with proper authority within his agency's or firm's organizational structure to specify the QA/QC program and to monitor its implementation throughout the cleanup.

The QA/QC program must function during all phases of the site cleanup as well as during testing and design for all sampling procedures. There must be an accurate and complete documentation of all activities associated with sample acquisition in the field and sample analysis at the laboratory and transfer of custody of the samples in the field as well as at the laboratory. There must be training of all staff involved in the cleanup with regard to standard clearly specified procedures detailed in the QA/QC program. There must be provision for systemwide audits as well as random audits to check on the proper implementation of the QA/QC program. In addition, corrective procedures must be in place, both in terms of organizational responses and technical capability, to correct any deficiencies as soon as they are manifested.

Health and Safety Plan

The goal of the health and safety plan is to safeguard the well-being of all those engaged in the site cleanup activity as well as those populations adjacent to the site. At the outset, a health and safety officer must be designated to specify and monitor the health and safety plan for the cleanup. There is a series of steps that must be carried out in the development and application of the plan.

First, the health and safety officer must make a site evaluation for the cleanup in order to determine the major health and safety issues. Second, proper engineering safeguards must be installed, such as fencing, signing, and other controls, to ensure that only authorized personnel have access to contaminated or controlled areas on the site. In controlling the site the health and safety officer must delineate the four basic zones: exclusion, contamination reduction, support, and buffer.

The exclusion zone is the area in which the contamination has been located. This zone is off limits to all personnel except those who have been properly trained and who are wearing proper types of protective clothing. The contamination reduction zone is the ring around the exclusion zone in which the goal is to capture all of the contamination that may be coming out of the exclusion zone on equipment or clothing or through any other medium so that there is no spread of contamination beyond the immediate site. Cleanup equipment, health and safety equipment, and so on, are stored in the support zone. Finally, the buffer zone is designed to give an extra measure of protection to populations adjacent to the site.

For all personnel working on the site, there should be a medical surveillance program to determine antecedent medical conditions to use as a medical benchmark against which to measure exposure to any toxic or hazardous substances that have affected or may later affect their health and well-being. In this regard there should also be an ongoing site-monitoring program, particularly for explosive or toxic gases that may be released during site cleanup. In addition, the health and safety officer must specify the levels of personal protection that are appropriate to the site cleanup. These range from Level A, the so-called "moon suit," through Levels B, C, and D. Level-A protection provides complete insulation against respiratory as well as percutaneous hazards. The advantage of this level of protection is its completeness. The disadvantages are the expense of providing for equipment and the dramatic decrease in efficiency of workers enclosed in such protective gear. The efficiency rate for workers in Level-A protective clothing may decrease by a factor of 4 or 5 over that which would be achieved without any level of protection.

Emergency and Contingency Plan

The emergency and contingency plan should contain four basic procedures: evacuation, contact, containment, and remedial action. The evacuation procedures specify how the site is to be evacuated in the event of an emergency such as an accidental release of a toxic gas or liquid. The contact procedures specify what outside agencies are to be contacted, in what order, and for what type of emergency. Agencies typically contacted in such emergencies would include fire department, police department, ambulance, Federal Emergency Management Agency (FEMA), health officers, and the poison control center. The containment procedures specify what measures should be put in place immediately after the emergency has occurred in an effort to contain the further spread of the accidentally released toxic materials. Finally the remedial action procedures should specify the types of corrective measures to be put into place to eliminate the emergency situation so that cleanup activity can recommence.

Ongoing Monitoring Program

In most hazardous waste site cleanups, there is a requirement for postcleanup monitoring with regard to leachate and gas control. The purpose of these monitoring programs is to satisfy the appropriate review and regulatory agencies that the site cleanup is in fact adequate and complete and that the site has been stabilized. Stabilization of a hazardous waste site occurs when the reduction in the volume and characteristics of leachate or gas generated (or both) within the site reaches levels that will not endanger the environment adjacent to the site if and when the leachate or gas migrates across the site boundaries without further treatment or attenuation.

CONCLUSION

The extensive requirements of hazardous waste site cleanups reinforce the need for identification early in the planning phases of a transportation project so that, wherever possible, hazardous waste contamination problems can be avoided. The mission of departments of transportation is to provide for the safe and efficient movement of people and goods. It is the mission of other departments to deal with the problem of cleaning up the hazardous and toxic waste sites found throughout the country. The goal of a waste-screening study should be to keep these two missions separate.

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