TRANSPORTATION RESEARCH RECORD 693

Safety in Construction and Maintenance Work Zones and Transportation of Hazardous Materials

TRANSPORTATION RESEARCH BOARD

COMMISSION ON SOCIOTECHNICAL SYSTEMS
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1978

Transportation Research Record 693
Price $3.00

mode
1 highway transportation

subject areas
21 facilities design
40 maintenance
51 transportation safety
70 transportation law

Transportation Research Board publications are available by ordering directly from the board. They may also be obtained on a regular basis through organizational or individual supporting membership in the board; members or library subscribers are eligible for substantial discounts. For further information, write to the Transportation Research Board, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, DC 20418

Notice
The papers in this Record have been reviewed by and accepted for publication by knowledgeable persons other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The views expressed in these papers are those of the authors and do not necessarily reflect those of the sponsoring committee, the Transportation Research Board, the National Academy of Sciences or the sponsors of TRB activities.

To eliminate a backlog of publications and to make possible earlier, more timely publication of reports given at its meetings, the Transportation Research Board has, for a trial period, adopted less stringent editorial standards for certain classes of published material. The new standards apply only to papers and reports that are clearly attributed to specific authors and that have been accepted for publication after committee review for technical content. Within broad limits, the syntax and style of the published version of these reports are those of the author(s).

The papers in this Record were treated according to the new standards.

Library of Congress Cataloging in Publication Data
National Research Council. Transportation Research Board.
Safety in construction and maintenance work zones and transportation of hazardous materials.

(Transportation research record; 693)
Reports prepared for the 57th annual meeting of the Transportation Research Board.
1. Road construction–Safety measures–Addresses, essays, lectures. 2. Roads–Maintenance and repair–Safety measures–Addresses, essays, lectures. 3. Hazardous substances–Transportation–Safety measures–Addresses, essays, lectures.
I. Title. II. Series.
TE7.H5 no. 693 [TE153] 380.5'08s [625.7'042]
ISBN 0-309-02839-6 79-17957

Sponsorship of the Papers in This Transportation Research Record

Sponsorship is indicated by a footnote at the end of each report. The organizational units and officers and members are as of December 31, 1977.

Contents

Work Zone Safety

H. L. Anderson, Federal Highway Administration

In 1976 the Federal Highway Administration initiated a program to improve safety in construction and maintenance zones. The program pressed for improvements in the Manual on Uniform Traffic Control Devices relating to traffic control at work sites, initiated a number of training programs on work site safety, allocated $2.5 million for research in innovative safety practices in work areas, and measured progress through an extensive national review of safety practices at work sites. As a result, safety at work sites has improved, but there are still major problem areas. As an example, accident data are still not used to identify safety problems at work sites, and construction materials and equipment are often stored hazardously close to the roadway. If considerably more progress is not made in improvement of work site safety, the Federal Highway Administration will be forced to consider more stringent requirements for work site activities, including traffic-control plans developed as a prerequisite for project approval. In addition, we must provide additional guidance on driver needs in work sites based on human factors research.

Early in 1976 the Federal Highway Administration (FHWA) initiated a program that emphasizes improved safety in construction and maintenance zones. Safety is a serious problem in construction and maintenance zones and we are using our resources in a concentrated effort to reduce the number of casualties at these sites. FHWA has stressed five areas for improvement:

1. Pressed for improvements in the Manual on Uniform Traffic Control Devices (MUTCD) related to work site control;
2. Launched at least three different training courses on the subject;
3. Initiated over $2.5 million in research to develop new and innovative safety practices in work areas;
4. Conducted two extensive national reviews of safety practices at actual work sites; and
5. Issued an advance notice of proposed rule making, which requires specific plans and responsibilities relating to work site safety.

As a result of these activities, work sites are now safer for the motoring public than they were a few years ago, but progress has been disappointingly slow and the work site safety problem still persists. We still have the problem of getting the word to highway construction and maintenance personnel. This may be caused by a long-established attitude toward risk management. Risk management is a very popular concept in highway safety today. Its basic premise is that any field of human endeavor involves a safety risk. Generally, these risks are much higher in the construction industry than in many others. Often the hazards related to construction are expressed as, "You can expect to lose a certain number of lives for every so many floors you construct in a new building." In the construction industry the primary objective is to get the job done at a minimum of risk, but getting the job done is first and foremost.

The construction industry has made great strides in enhancing the safety of the worker. As an example, the worker is required to wear steel-toed shoes, insulated gloves, and hard hats, and safety inspectors are present to see that the worker is protected. This is a good, solid philosophy for safety at isolated work sites. Unfortunately, transferring this philosophy to highway construction sites does not provide adequate attention to the motorists. At the highway construction sites we must consider the safety of the public that passes through the area as well as the worker, which has not always been the case in the past.

At most highway construction sites, management knows the exact number of kilograms of asphalt used, the cubic meters of excavation, and the exact details of on-the-job injuries. But, very seldom does the management keep any records of traffic accidents that occurred at the job site, except when construction personnel are involved. Admittedly, protection of the public is far more difficult than protection of the worker alone. The local constructor has far less control over the public than over the workers. The public cannot be required to wear hard hats or steel-toes shoes although they pass through hard-hat areas; they cannot be docked their pay for unsafe acts or provided with special training. Often the act of protecting the worker by barrier systems or lane closures increases the hazard to the motorist. The reverse conditions and effects also exist.

The point is that the concept of accepting a certain amount of risk to get the job done is no longer valid at construction sites when the public is involved. The public will not, and should not, accept the same risks as a construction worker; it is the responsibility and moral obligation of the work site management to provide the public with the highest degree of safety that is feasible. We know that there are at least 500 traffic fatalities a year at work sites.

An example of the safety problem at construction sites recently occurred in one of the southeastern states where there were five fatalities during reconstruction of an elevated section of an Interstate. The most recent fatality occurred on November 8, 1977, when a truck jackknifed in a temporary transition lane at the construction site. This caused a chain reaction collision and a fire, which killed one person and injured two others.

The initial accident, caused by a jackknifed truck, occurred on a temporary median crossover at one end of the construction area. This resulted in a lockup of traffic in the construction zone, which was partially obscured from approaching traffic by the crest of a hill. The results, a catastrophic rear-end collision, involved nine vehicles. More warning in advance of this construction site would have been desirable.

The signs at the project met the minimum requirements of MUTCD but could have been improved. Transition areas are historically accident-prone locations at best, but designation of a transition area on the far side of a crest vertical is asking for problems. Any disruption in the transition area, such as the jackknifed truck, will quickly result in a backup of traffic into the restricted sight distance condition that exists at the crest vertical. Additional attention to the design of the detour might have prevented this accident.

One of the results of our past research efforts was a seven-state study of construction zone accidents conducted by Midwest Research Institute. The research effort looked at 79 construction sites where, during the construction period, there was an increase of over 613 accidents at these sites (total accidents before construction, 8172; total accidents during construction, 8785; percent increase in accidents, 7.5). Table 1, derived from the project final report, compares the accident rates by states. In two states the accident rate during

Table 1. State rankings by increase in accident rate.

State	Number of Projects	Accident Rate Before Construction[a]	Change During Construction (%)
1	9	142	-9
2	15	75	-3
3	16	167	+8
4	10	174	+10
5	10	117	+28
6	5	130	+38
7	10	165	+163

Note: 1 km = 0.6 mile.
[a]Number of accidents per 100 000 000 vehicle-km.

Table 2. Change in mean accident rate by type of construction.

Construction	Number of Projects	Mean Accident Rate Before Construction[a]	Change in Accident Rate During Construction (%)
Bridge work	5	55	+50
Reconstruction of existing roadway	2	173	+33
Upgrading to Interstate standards	9	104	+16
Median barrier work	15	117	+9
Resurfacing, patching	26	92	+8
Pavement widening	12	359	+3
New alignment	5	132	+0.4

Note: 1 km = 0.6 mile.
[a]Number of accidents per 100 000 000 vehicle-km.

construction actually decreased; however, in two other states the rates increased by 38 and 163 percent respectively. This shows that increases in accidents are not inevitable. Good practices reduce accident rates and poor practices increase accident rates.

Table 2 (also derived from the project final report) compares the changes in mean accident rates by types of construction activities. The two types of construction activities that have the greatest increase in accident rates were bridge work and pavement reconstruction. These types of work will constitute the vast majority of construction activities occurring over the next 10 years. Consider that in 1970 only $560 million in federal funds were obligated for reconstruction projects. In fiscal year 1977, almost $2.3 billion in federal funds were obligated for upgrade of existing roads. That represents an increase of over 400 percent in reconstruction activities in the last 7 years. During fiscal year 1977, about 21 100 km (13 100 miles) of existing federal-aid highways were the site of construction zones during the year. This figure is expected to increase substantially in the future as we continue to increase the upgrading of our existing road system.

In the fall of 1977, FHWA again conducted a safety review of construction sites. This review indicated that the safety at these sites had been enhanced over the previous review conducted a year earlier, but there were still some major safety problems and the variation between states and regions was significant. There were four major areas where deficiencies exist that need vast improvement. The first area of deficiency was that management is still not collecting or using accident data at construction sites. Therefore, management still does not know how to overcome their specific safety problems nor even what their safety problems are.

The second major area was that of guardrail and barrier rail transitions. The use of barrier and guardrail to protect the work area has improved, but there are still too many blunt-end and transition hazards. A third area relates to a lack of understanding or concern by construction personnel for the motoring public. As an example, construction equipment and vehicles were located hazardously close to the traveled way. The last area involved the problem of pavement dropoffs. In many cases, major dropoffs were not effectively shielded from the motorists. In other cases, unnecessary dropoffs were allowed to exist. The problem of removing unneeded and confusing pavement marking is still with us but is far less prevalent than in the past.

One effective method of removing pavement markings is the excess oxygen burner method. FHWA is presently developing an implementation package for this method, which will be distributed to the states in the near future. This device and other stripe-removal equipment will be included in a national demonstration project. The excess oxygen method consists of mixing high-pressure propane gas and high-pressure air or oxygen. This produces a 1371°C (2500°F) gas, which quickly burns off and removes old markings. The Office of Development and Texas have been evaluating this method and several modifications. From the Texas experience, the methods appear quite successful. The cost of the burning method is estimated at $0.33/m ($0.10/ft) compared to an estimated $1.05/m ($0.32/ft) for sandblasting. The burning units are commercially available from a few equipment manufacturers in the United States.

Another effective method is a combination of water and sandblasting. During the review 2 years ago, acceptable methods of pavement removal were almost impossible to find.

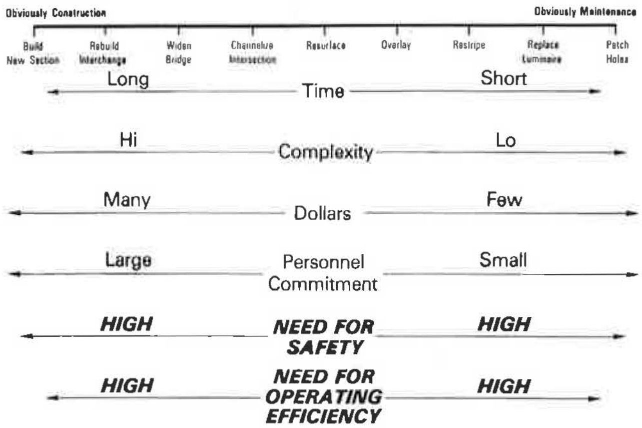
The 9-state survey also found a number of other problems prevalent throughout the states. These include the use of damaged and dirty warning signs, inadequate taper lengths, and other conditions that could be vastly improved through minor modification or with a better understanding of safe traffic operations. In the last survey FHWA also found that only 7 states currently are attempting to use accident data to improve work site safety. In 39 states traffic control at construction sites is considered either incidental to other construction costs or covered by lump-sum bid prices. What does FHWA plan to do to accelerate safe practices at work sites? If considerably more progress or improvement is not made, the Office of Engineering will be forced to consider more stringent requirements for all projects, including traffic-control plans in the plans, standards, and estimates (PS&E) phase of development.

The PS&E phase should contain traffic-control plans and address the matter of safe location of contractor equipment, hazardous pavement dropoffs, and other instructions and requirements to provide protection in cases where the nature of the work creates unsafe conditions. Consideration should also be given to providing unit prices for maintaining, cleaning, and replacing traffic-control devices for projects that cover a long period of time. A notice of proposed rule making on traffic safety in highway and street zones was published in the Federal Register last year. In January a task group began the study of responses to this notice and the development of recommendations on further regulation development.

Only a minimum portion of FHWA's attempts to increase work zone safety is aimed at regulation. Many of our present work zone safety problems are caused by lack of knowledge on how to improve traffic operations at work sites.

The basic source of guidance for traffic control in work zones is Part VI of MUTCD, and this document does not cover everything. The criteria on placement and design of work site traffic control are generally vague. In some cases it is purposely vague so as to be applicable to a variety of conditions. But often the criteria are vague because of a lack of basic knowledge as

Figure 1. The construction-maintenance continuum.



to the best method of controlling traffic. The vagueness of MUTCD has been highlighted in a recently completed study by the General Accounting Office (GAO) as one of the major problems in improving work site safety. In the report summary GAO concludes:

> The Highway Administration's Manual on Uniform Traffic Control Devices described devices that can be used in construction zones. It does not contain enough information on how and when these devices should be used. Until uniform standards for using these devices are established, state planners, project officials, and federal inspectors will not have sufficient guidelines for safe highway worksites! As a result of these findings, the GAO report made as its first recommendation that FHWA: '. . . revise the Manual on Uniform Traffic Control Devices to include specific guidance on how and when to use traffic control devices in construction zones.'

The MUTCD criteria must be improved and FHWA hopes to gain much of the needed knowledge through research.

We have never really established driver needs to safely negotiate a work site. We do not even know how well the driver perceives our work site signs, such as the diamond-shaped warning signs, or the graphic and word messages they contain. Simple questions, such as how much advance warning is needed and how far in advance can the driver see and perceive the signs, are still unanswered. The problem becomes even more acute at night. We require colored reflectorized control devices and barricades, but does the driver perceive the color of the reflectorization? Does the driver recognize its significance? Does he or she really need or use the color coding we attempt to provide at night? Are graphic signs easier to distinguish and comprehend than word signs?

All we can say today is that the MUTCD provides uniformity in control techniques so the driver has at least a basic familiarity with what is expected. The underlying problem is that we have no idea whether the basic uniformity we provide is the most effective method of meeting the driver's needs.

We are presently debating in the national advisory committee the reflectivity requirements for signs and barricades. Most engineers agree that reflectivity of construction-traffic-control devices is desirable, but how much is needed? We do not have the knowledge to firmly say 40 or 80, but we know the driver must see the sign. He or she has visibility requirements regardless of whether the sign or barricade is new or old. Eventually we must stipulate the distance at which a sign or barricade must be visible and readable with low-beam headlights. This must be a maintained value—something the project manager or maintenance supervisor can use to evaluate the quality of traffic-control devices.

The problem for the driver is further complicated by the vast multitude of work site situations encountered. This is probably best illustrated by Figure 1. The time, complexity, cost, manpower, and control devices available in construction and maintenance activities vary considerably, but safety and operating needs are high regardless of activity.

Those responsible for work sites must provide a consistently high level of safety regardless of the nature of the work. The driver rarely knows the difference between a construction zone and a maintenance zone or utility work. All he or she knows is that there is a potential hazard, but the same degree of safety in driving is expected in all three classes of work sites and the driver should receive it.

The need to protect the driver at a consistently high level of safety requires that where traffic-control strategies are limited because of time or resources, the devices used to guide the driver must have greater visibility and comprehension. Criteria for new or additional devices must be developed through research. As an example, the steady-burn warning light probably provides the most effective nighttime visibility available. However, it is expensive and, where batteries are used, it must be checked frequently to assure its reliability. For minor or short-term work sites we need an inexpensive, convenient alternative to the steady-burn warning light. Since a variety of reflective materials is available, an alternative device must be practical.

The FHWA has initiated a number of research and development activities to improve our knowledge of safety needs at work sites and to develop better methods of protecting traffic. This research effort is already providing us with some answers. Crash tests with various types of barricades have led to the prohibition of timber barricades as a positive barrier. A number of other barriers are being tested and look like they could provide a relatively inexpensive and portable positive barrier for work sites. These studies should be completed within the next 2 years. Another area where research and development have shown an excellent payoff is in determining alternative methods to overcome the paint marking removal problem. The excess oxygen burner shows great promise. The use of raised pavement markers in lieu of painted markings was tested during the last construction season and appears to be quite effective in guiding traffic and practical for temporary markings on construction projects.

The ongoing National Cooperative Highway Research Program project to evaluate traffic controls for street and highway work zones should provide us with some much needed information on traffic-barrier spacing, temporary pavement markings, and effective methods to mark and make control devices reflective. We are not waiting for the results of these studies before developing new initiatives. We are presently initiating a major $500 000 study on the vital problem of driver needs in work zones. This effort, which will start this spring, should fill some of the knowledge gaps relating to the human factor in work site safety. We are also initiating a study to determine basic planning and scheduling requirements needed for short-term work sites.

There is also a continuing effort to develop new concepts and improvements for traffic control in work zones. We plan to be actively developing these new concepts over the next 4-year period and have budgeted another $1 million for this effort. FHWA has developed a training course on safety through construction zones, which will be offered by the National Highway Institute throughout the country and on a continuing basis at the U.S. Department of Transportation's Transportation Safety Institute in Oklahoma City, Oklahoma.

Progress has been made in work site safety but we have a long way to go. Improved methods in work site safety must be developed through research so that we can develop meaningful safety criteria based on facts. But we cannot wait for research results to make improvements. The problem is with us today, and we must take immediate action to reduce the present unnecessary accident toll. We can accomplish this through more stringent controls, more awareness of the problem on the part of work site management, and a sincere desire to enhance the safety of the motoring public. FHWA stands ready to assist and support the highway community in developing safer work sites in any way we can.

Publication of this paper sponsored by Committee on Traffic Safety in Maintenance and Construction Operations.

Abridgment

Liability for Improper Traffic Signaling, Signing, and Pavement Markings

Larry W. Thomas, Transportation Research Board

The liability for improper traffic signaling, signing, and pavement markings is an area of importance because of the increasing number of negligence claims brought against highway departments. In the past, the states generally had sovereign immunity and could not be sued. In recent years, however, this has changed as more and more states, by court decision or statute, have abolished or eroded immunity to a large extent. The states have a variety of approaches to the question of tort liability. Certain rules, however, seem to be applicable in most jurisdictions.

Although there has been a significant increase in tort litigation against highway departments, court decisions and recent tort claims acts recognize that states and state agencies should not be held liable for negligent performance of governmental functions that are discretionary in nature. The general view is that the state is not liable for negligence in the performance of functions that involve a high degree of discretion but is liable for negligence in the performance of ministerial or operational level tasks. The exemption from liability for duties discretionary in nature is rooted in the common law. It emerged from the law on personal liability of public officials, who also were not liable for negligence in the exercise of discretionary duties but were liable for the exercise of purely ministerial functions.

Any activity, of course, involves the exercise of discretion, but as used here, a discretionary duty is one involving the power to make choices among valid alternatives and to exercise independent judgment in choosing a course of action. Conversely, ministerial duties are more likely to involve clearly defined tasks that are to be executed with minimum leeway and individual judgment. Ministerial tasks are said not to require any evaluation or weighing of alternatives before performance of the assigned duty.

A case that illustrates executive activity that is discretionary in nature is Weiss v. Fote [7 N.Y. 2d 579, 167 N.E. 2d 63, 200 N.Y.S. 2d 409 (1960)]. In this case the issue was the adequacy of the clearance interval in a traffic light system that had been approved by the city board of safety after ample study and traffic checks. The court held that New York's general waiver of immunity did not extend to areas of lawfully authorized planning and that it would be improper to submit to a jury the reasonableness of the plan approved by the expert body.

Weiss and other cases hold that the decision to provide or withhold a certain service is discretionary in nature; thus, negligent design of a traffic light or the failure to erect a traffic light may be discretionary in nature and protected from liability. Immunity usually attaches to governmental decisions about signs, signals, or markings if the government shows that the plan, design, or program has been adopted after reasonable consideration and deliberation. Of course, the decisions should be made by a public body or official vested with authority to exercise discretion in formulating such decisions. The cases state that evidence should show that the decision was (a) reasonable, (b) duly prepared and approved, and (c) not arbitrary or capricious. Moreover, duty may require review of these decisions later to determine whether they are safe once implemented and in actual use. As one court has said, the public official must be cautious; the discretionary field of activity should not be used to justify the omission of obvious safeguards for the protection of the public.

Some decisions are clearly more discretionary than others, and court decisions differ on what falls within the discretionary field of activity. The trend appears to be that only decisions made at a policy level or decisions that involve a consideration of policy factors are discretionary. The result has been to narrow the duties that are discretionary; more decisions that once would have been immune from liability no longer enjoy that protection.

The narrowing of discretion is demonstrated in several cases construing tort claims legislation. These acts usually contain a provision that immunizes the public agency for negligence in the performance or failure to perform discretionary functions (the discretionary function exemption). This exemption has its roots in the exclusion from liability for discretionary activity previously discussed.

The courts have struggled to construe the tort claims acts' exemption from liability for a discretionary function and a landmark U.S. Supreme Court case has been used by lower courts for the development of the operational-planning test in an effort to give further meaning to the exemption. The majority of the courts hold that only decisions made at the planning level, rather than at the operational level, fall within the discretionary function exemption.

It would appear that the decision on whether to provide signs, signals, or markings is the exercise of immune discretion at the planning level; however, recent decisions hold that negligence thereafter in provision or in maintenance of them is less likely to be protected from liability.

In a New Jersey case [Catto v. Schnepp, 121 N.J. Super. 506, 298 A. 2d 74 (1972)], the plaintiff alleged that the state had negligently and improperly designed a curve and had failed to warn that a change in speed was necessary. The court ruled that the design of the road was discretionary in nature; furthermore, no independent liability attached for the failure to post a speed limit or other warning sign because these activities were within the discretionary judgment of the governing authority and, therefore, immune.

The New Jersey decision may be compared to the holding in an Alaska case [State v. l'Anson, 529 P. 2d 188 (Alaska 1974)], where the court ruled that, within the meaning of the discretionary function exemption of the Alaska Tort Claims Act, the state was liable for the failure to place traffic signs or paint lines on the highway at the entrance to campgrounds. The court held that the decisions that involved traffic signs or pavement markings were not broad policy decisions that came within the planning category. Two other decisions from Hawaii held that the failure to paint highway lines or provide highway warning signs are not discretionary acts and are not immune from liability.

Because of the discretionary nature of the decision, courts have held that, in the absence of statute, there is no general duty imposed on the department to install or provide highway lights, signs, or markings. The reason is that these decisions are legislative or quasi-judicial in nature and are customarily made by the legislative or executive branches of government. The courts are reluctant to permit second guessing of the authorities, who have the technical expertise to make these decisions.

Thus, some courts have held that the government, state or local, is not required to (a) place a traffic light at an intersection [Raven v. Coates, 125 So. 2d 770 (Fla. App. 1961)], (b) post signs and barricades at a curve [Andrus V. Lafayette v. Louisiana Dept. of Highways, 303 So. 2d 824 (La. App. 1975)], or (c) post a stop sign at a street intersection [Western Pennsylvania National Bank v. Ross, 345 F. 2d 525 (6th Cir. 1965)].

There is some authority to the contrary; for example, in Michigan the court held that a Michigan statute that requires that roads be kept in reasonable repair requires the government to install traffic-control signals [Dohrman v. Lawrence County, 143 N.W. 2d 865 (S.D. 1966)]

After the department has provided the signs, signals, or markings, it has assumed the duty to the public, who have a right to reasonably rely on them, and is obligated to maintain them in good serviceable condition. In addition, if the department is required by statute to maintain highways in a state of reasonable repair, its duty may include maintenance of traffic signals and stop signs [Williams v. State Highway Dept., 44 Mich. App. 51, 205 N.W. 2d 200 (1972)].

The department ordinarily must act on its own and provide, for example, highway warnings, traffic devices, or markings when it has notice of a hazardous or dangerous condition. The general view is that, in order to hold public authorities liable for injuries for failure to exercise ordinary care to keep roads and streets reasonably safe, it must appear that the authority knew, or had reasonable cause to know, of the defective condition a sufficient length of time prior to the accident to enable it to repair the road or alleviate the danger. The state need not have actual notice of the dangerous condition; notice may be imputed to the state if the danger is of such a nature that the department should have known of it or would have discovered it by being reasonably diligent.

The department's own records may indicate that a highway location is particularly dangerous and should be signed. In Smith v. State [12 Misc. 2d 156, 177 N.Y.S. 2d 102 (1958)] the traffic engineer, in a letter to the department of public works, had recommended W-160 oversize assembly signs at a particularly dangerous curve. He described the curvature and advised:

> This location has been the scene of many accidents of which speed was usually the contributing factor. Several years ago the curve was rebanked and a coarse mix added to the surface to decrease skidding and aid drivers to negotiate the curve. This improvement seemed to help but motorists still get into trouble when negotiating this curve.

The state was held liable for its failure to warn the decedent of the dangerous highway condition.

Most of the cases present a question of fact as to whether the highway location is so dangerous that the highway department should have acted, such as by providing traffic signs or warnings, signals, or pavement markings.

For example, in a Kentucky case [Commonwealth v. Automobile Club Insurance Co., 467 S.W. 2d 326, 329 (Ky. 1971)], the court held that a curve, shown to have a 52° turn for each 30.5 m (100 ft), with a total curvature of 117° from beginning to end, was a sharp or steep curve and sufficiently dangerous that the state should provide speed advisory signs, guardrails, or barriers near the curve.

The courts have held that the department is not compelled to place guardrails or curve signs at every curve along the highway, but that it must provide them at dangerous or unusual places on the highway to enable motorists, exercising ordinary care and prudence, to avoid injury to themselves and others. In addition, the state may have a duty to provide warnings of inherent dangers, such as obstructions or excavations in a highway or where a bridge has been destroyed or a highway terminated abruptly.

Some statutes require signs, signals, or markings only at dangerous locations. The California act defines a dangerous condition as one that creates a substantial (as distinguished from a minor, trivial, or insignificant) risk of injury when the road is used with due care and in a manner in which it is reasonably foreseeable that it will be used. The California statute was applied in Callahan v. San Francisco (15 Cal. App. 3d 374, 93 Cal. Rptr. 122). There the plaintiff was a passenger in an automobile on a street that dead-ended at an intersecting street. The weather was foggy and the T-intersection had no warning devices to advise that the road terminated abruptly with a cliff dropping into a lake. (The driver of the vehicle had been drag racing just prior to the intersection.)

The evidence was that there had been no prior accident at the intersection similar to the one that involved the plaintiff and that only 29 accidents (1 accident/ 685 000 vehicles) at the intersection had involved this direction of travel in 4.5 years. Thus, the court held as a matter of law that the city was not negligent and that the intersection was safe, except when a vehicle is driven at excessive or hazardous speed. Where a dangerous condition does not exist, the city is not required to provide warnings by signals, signs, or other markings.

With respect to traffic lights, authorities are split as to whether the state or other public agency is liable for failure to erect them, but most jurisdictions hold that the decision to provide or not to provide traffic lights is either the exercise of immune discretion or the performance of a purely governmental function.

An analysis of the traffic-light cases appears to support the following main conclusions:

1. The plaintiff is least likely to recover where a traffic sign or signal was removed from an intersection under proper authorization and where it was claimed that the traffic-control system at an intersection had been negligently planned or designed.
2. The plaintiff is most likely to recover for negligence where the highway authority failed within a reasonable time to replace a traffic sign that had been removed by unauthorized persons, to re-erect or repair a sign that had fallen down or had been knocked down or bent over, or to replace a burned-out bulb in an electric traffic signal. Ordinarily, the failure to keep traffic lights and signs in good working condition may result in liability of the department.
3. The cases are divided and hold both ways where, for example, there has been a failure to install any traffic signals or lights at an intersection alleged to be dangerous.

Considerable interest has been expressed concerning the liability of states arising out of pavement markings. State highway departments have been held liable for accidents caused by improper, inadequate, or misleading pavement markings, as noted earlier.

In a New York case [Dowley v. State, 61 N.Y.S. 2d 59 (Ct. Cl. 1946)], the claimant sued for negligence of the state in construction, maintenance, and safeguard of a state highway. Because of the surface appearance, the road appeared to proceed straight ahead, when, in fact, it curved to the east. No caution, slow, stop, curve, or other sign was on the highway. Moreover, no white line in the center of the highway indicated the highway curve. The court held that the evidence sustained a finding that the curve was dangerous and that the state was negligent in failing to provide proper warnings, barriers, and markings. Special pavement markings are not required at an intersection where, for example, the evidence does not establish the existence of a hazardous or dangerous condition. However, the highway department may be held liable for installation of highway signs that are themselves misleading and dangerous, or for failure to mark the pavement adequately to warn that a four-lane road becomes two lanes, for example.

Finally, states may have certain rules and regulations governing the installation or provision of signs, signals, or pavement markings. These regulations, and more particularly, the Manual on Uniform Traffic Control Devices, generally are admissible into evidence. The courts have held that the regulations are either evidence of the standard of care that should have been used or evidence that the department has failed to meet its own safety standards [State v. Watson, 7 Ariz. App. 81, 436 P. 2d 175 (1968)].

Publication of this paper sponsored by Legal Resources Group Council.

Status of Traffic Safety in Highway Construction Zones

Robert J. Paulsen, Howard Needles Tammen and Bergendoff, Kansas City, Missouri
Douglas W. Harwood and Jerry L. Graham, Midwest Research Institute, Kansas City, Missouri
John C. Glennon, Transportation Consulting Engineer, Overland Park, Kansas

Evidence is increasing that existing traffic-control practices do not always provide an adequate level of safety in construction zones. Synthesis of a number of accident studies reveals that the total accident experience in construction zones increases from 2 to 119 percent during the period of construction. The literature synthesis also indicates that the increases in accident experience are highly related to construction activity. A study in one state shows that accident experience decreases dramatically when construction-zone traffic-control practices are improved. The paper identifies methods by which more effective planning, design, and management of construction zones can improve traffic safety.

Highway construction zones provide traffic engineers with perhaps the greatest challenge in traffic control they face on any segment of the American highway system. Traffic control in a construction zone must permit the safe and efficient movement of traffic through the zone and at the same time provide a safe work area where construction activity can be conducted efficiently. The traffic-control plan must be tailored to fit not only the changing demands of traffic but also the changing demands of construction activity. Evidence is increasing that existing traffic-control practices do not always provide an adequate level of safety in construction zones.

The traffic-control devices used for highway maintenance and construction operations are specified by Part VI of the Manual on Uniform Traffic Control Devices (MUTCD) (1). These include regulatory and warning signs, hazard beacons and other lighting units, barricades, traffic cones, and flagpersons. MUTCD prescribes minimum standards for the application of these devices but does not relate the selection of a complete set of traffic controls to the geometric and traffic requirements of specific construction zone situations. In addition, new devices that are not included in the MUTCD, such as flashing arrow panels, have come into common use. Therefore, traffic engineers need a more comprehensive and formal procedure for establishing construction-zone traffic controls.

THE PROBLEM

Many construction projects are undertaken to reduce the number of accidents. An increase in accidents during construction activity may be inevitable on some projects, but construction-zone traffic-control practices should be adequate to ensure that the long-term accident reduction benefits are not inordinately offset by higher short-term accident rates during construction. The basis for evaluation of traffic safety in construction zones must be a comparison between accident experience before and during construction activity. Several such comparisons have been made.

The results of a 1965 study (2) of 10 randomly selected construction projects in California indicate that the total accident rate during construction increased by 21.4 percent above the rate experienced before construction. Even more alarming was the increase in the fatal accident rate of 132.4 percent during construction. After improved construction-zone traffic-control practices were put into effect, a second study of 31 projects made in 1970 showed an increase of only 7 percent in the total accident rate and 1.6 percent in the fatal accident rate. This important finding demonstrates the strong influence of traffic-control practices on construction zone safety.

Information furnished by the Georgia Department of Transportation on 207 two-lane highway resurfacing projects in Georgia shows a 61 percent increase in total accidents, a 67 percent increase in injury accidents, and a 68 percent increase in fatal accidents during construction.

Lisle, in a paper in this Record, presents the results of a recent comparison by the Virginia Highway and Transportation Research Council of the traffic-control practices in a construction zone on I-495 in Northern Virginia. He indicates a 119 percent increase in accident frequency over the preconstruction baseline. This project also experienced large increases in fatal and injury accident rates of 320 and 35 percent, respectively. However, the accident severity distribution shifted more toward property-damage accidents. The Virginia study also noted that, although the accident frequency increased throughout the 35.6-km (22.1-mile) project, interchanges and transitional areas experienced the highest increases.

Another recent study (3) analyzed the reports of nearly 3000 accidents that occurred in 21 construction zones on rural Interstate highways in Ohio. Accident experience before and after the construction activity were also analyzed and the following conclusions were made:

1. Accident rates before construction were lower than those during construction but higher than those after construction.
2. Safety upgrading construction projects on the rural Interstate system of Ohio generate traffic accidents, but these accidents are primarily minor in nature.
3. During the construction period, construction-related accidents are less severe than non-construction-related accidents.
4. A large number of improper merge and sideswipe accidents were in lane taper areas, occurred at night, and involved vehicles of the tractor trailer-bus class.
5. Many rear-end accidents were in lane closure areas, occurred during the daylight hours, and involved automobiles and motorcycles.
6. Large numbers of single-vehicle fixed-object accidents involved drums used for lane tapers and lane closures.

A recent study performed by Midwest Research Institute (4) for the Federal Highway Administration (FHWA) evaluated accident rates before and during construction on 79 projects in seven states. Conclusions from this study included the following:

1. The 79 construction zones experienced an average increase in accidents of about 7 percent; however, 31 percent of the projects experienced decreased accident rates during construction (this assumes that traffic volumes are equal before and during construction). Twenty-four percent of the projects experienced increases in accident rates of 50 percent or more.
2. Based on detailed analysis of three construction zones that experienced increased accident rates during construction, the increase in accidents was highly related to the construction.
3. Short duration and short-length construction projects experience higher accident rates. This finding may be the result of a concentration of construction-related accidents in lane taper and transition areas.
4. Bridge work and roadway reconstruction experienced the largest increases in accidents of any construction projects.
5. Although the accident rate was higher for urban construction projects, the percent of increase in accident rates was nearly equal for rural and urban projects. Accident rates for rural projects do, however, vary more than those for urban projects.
6. The number of night accidents increased during construction, but the proportion of night accidents to total accidents remained the same.
7. The proportion of fatal and injury accidents in construction zones is nearly equal to the accident experience before construction, with a slight shift toward less severe accidents during construction.
8. The presence of construction zones is more likely to increase fixed-object, rear-end, and head-on accidents but decrease right-angle, turning, and ran-off-road accidents.
9. The fixed-object accident rate is higher in stationary construction zones than in zones where traffic controls are moved periodically (daily, weekly, monthly).
10. Construction zones where speed limits have been reduced do not experience lower accident rates than other zones.

Finally, safety problems related to construction and maintenance activity involve construction workers as well as motorists. For example, data from the National Safety Council (5) indicate that state highway workers experience 1.7 times the all-industry average of work injuries per million person-hours worked. Street and maintenance workers in municipalities experience 5 times the all-industry average.

The total accident experience in construction zones has been observed to increase from 2 to 119 percent above that of the period before construction. Case studies by Midwest Research Institute found that such increases are highly related to construction activity. Coupled with the California finding that the number of accidents decreased dramatically when construction-zone traffic-control practices were improved, this indicates a great potential for increasing traffic safety in construction zones.

IMPROVEMENT OF TRAFFIC SAFETY IN CONSTRUCTION ZONES

Traffic safety in construction zones can be improved by two methods: (a) more effective planning and design of construction zones and (b) more effective management and operation of construction zones. Planning and design include those actions taken before construction begins to ensure that the most appropriate traffic-control devices are used in the most effective manner. Management and operations include those actions taken during the construction period to ensure that the traffic-control plan is adhered to or modified to be responsive to the changing demands of traffic and construction activity. More effective planning and management of construction-zone traffic control are needed to obtain an improvement in construction-zone accident experience.

PLANNING AND DESIGN OF CONSTRUCTION ZONES

Traffic-control plans and specifications are essential to provide safe and effective traffic control during construction, just as appropriate designs, plans, and specifications are necessary to successful construction of a roadway improvement. There are five logical steps that should be part of the construction-zone planning and design process:

1. Determine basic conditions, including construction plans, roadway geometrics, and traffic data;
2. Select the basic zone type and scheduling;
3. Formulate speed control strategy;
4. Determine geometric design elements; and
5. Select traffic-control devices and methods.

Basic Conditions

Before a traffic-control plan can be made, the basic conditions that will exist in the construction zone should be identified. Three categories of data are needed: construction data, roadway data, and traffic data. This information provides the foundation for the remainder of the planning and design process. The construction data needed include (a) the lateral location, (b) the longitudinal extent (length), and (c) the expected duration of construction activities.

The lateral location of construction activities determines the degree of interference with normal traffic operations. For example, activities located on the roadway reduce the amount of roadway available for travel. The extent of the impact on traffic operations depends on whether all or just a portion of the roadway is involved. Activities above or adjacent to the roadway and shoulder can also affect travel because curious motorists tend to slow the traffic stream as they enter any construction area (6). Overpass construction, installation of traffic-control devices, public utility construction, and even high-rise building construction can restrict traffic operations. Construction above the roadway may also affect truck traffic due to clearance problems (7).

Side effects of construction activity adjacent to the roadway may also influence traffic operations. Noise and dust are two such side effects. Dust can reduce capacity and create safety problems due to decreased visibility. Excessive noise can cause safety problems for both the motorist and the construction crew. Even when motorists' loss of hearing is minimal, communication among workers, and especially between flagpersons, can be seriously hampered by excessive noise. Therefore, flagpersons should not depend on verbal communication but rather should employ hand signals where excessive noise is expected.

Construction activity on the shoulder of the roadway, such as shoulder reconstruction and addition of lanes to the roadway, will usually affect traffic operations, depending on the amount of lateral clearance between obstructions and the edge of the traveled way. As the lateral clearance is reduced, vehicles tend to both shy away, reducing the available roadway, and slow down (8). This decreases the level of traffic service, decreases the capacity that could be critical under high-volume conditions, and may increase the accident potential through the creation of large speed differentials.

The length of a construction zone can affect the traffic operations in several ways. Short construction zones were found to have higher accident rates than long construction zones; however, drivers in excessively long zones could lose the awareness required to pass safely through the zone. Therefore, drivers should be reminded of the prevailing conditions repeatedly. For example, when a median crossover is used on a divided highway the MUTCD states that a "Two-way traffic sign should be used as needed at intervals to periodically remind drivers that they are on a two-way highway which contains opposing traffic." This is especially necessary for traffic in the direction that does not cross over the median. Often, when the zone is excessively long, large areas within the zone have no visible construction work for days or weeks. Drivers are unlikely to maintain reduced speeds and the required attentiveness when they do not see construction activity (9).

Longer construction zones may lead to higher frequencies of accidents due to the increased exposure. As the length of zone increases, the probability of a vehicle requiring an emergency stop also increases. If shoulders are eliminated and no other place is provided for emergency stops, the vehicle will be forced to stop in the traffic lane, thus becoming vulnerable to rear-end accidents (9). Longer construction zones usually require more traffic-control devices, thus increasing the probability of a hazardous condition if they are not maintained properly (9). In the determination of an appropriate construction zone length, it is important to consider the trade-off between the higher accident rates in short zones and the increased accident exposure in long zones.

The duration of construction activity affects traffic operations and safety in a construction zone in several ways:

1. A long construction period naturally involves greater traffic exposure to construction conditions than does a short construction period. This increased exposure can lead to an increased number of construction-related accidents.
2. Longer construction periods are more likely to involve traffic-control changes in response to the changing demands of construction activity.

One source indicates that motorists usually take a week to become accustomed to different traffic situations (7). As the duration of the construction activity increases, however, local drivers tend to become so familiar with the new conditions that they become complacent. Motorists often become irritated if construction seems to linger on, and they may lose respect for the traffic control (6).

The second category of data needed is roadway data, such as roadway cross-section, number and width of lanes, shoulder width, roadside obstacle clearance, median width, and horizontal and vertical alignment. These data are necessary to determine the type of work area and the roadway geometrics for the construction zone. For example, alignment and median width are important factors in determination of the location and geometrics of a median crossover. Also, the location of existing traffic-control devices, such as signs, signals, and markings, must be known so that they can be altered or deleted if necessary. In general, the same data required to design a new roadway should be employed in the design of the construction zone.

The third kind of data needed for construction-zone planning is traffic data. The normal traffic volume on the roadway will affect the ability to use various traffic controls in construction zones. Average daily traffic (ADT) is most often used in construction-zone planning, but as volumes become more critical, the amount of traffic during peak hours must also be considered. A previous study has established the following guidelines based on traffic volumes (6).

For two-lane roads (both directions):

1. If ADT is less than 1500 or if the peak-hour traffic is less than 150, maintain one lane; or
2. If ADT is greater than or equal to 1500 or the peak-hour traffic is 150 vehicles or more, maintain two lanes.

For four-lane undivided roads (both directions):

1. If ADT is less than 10 000 or peak-hour traffic is less than 1000, maintain one lane each direction; or
2. If ADT is 10 000 or more or peak-hour traffic is 1000 or more, maintain three lanes (two in the heavy direction).

The composition of the traffic flow is also important in the geometric design of a construction zone. Trucks and buses require wider lanes, and a large number of motorcycles may discourage use of rumble strips. Information on the number of pedestrians and their paths through the construction area is important so that construction, traffic, and pedestrians can all be separated and protected.

Various measures of vehicle speed are important to determine the required speed control strategy during construction. The posted speed limit is usually the most accessible piece of information but may not directly relate to actual operating conditions. A spot-speed study on the approach to the zone may be useful.

A good traffic-control plan should also reflect the accident experience of the zone before construction. Locations that have experienced a large number of accidents before construction may have particular problems that should be analyzed and addressed by the plan.

Basic Zone Selection and Scheduling

Once the basic conditions of construction, roadway, and traffic data are established, the type of zone and scheduling of the construction can be determined. The fundamental planning problem is one of separating the traffic and the construction activity. These activities can be separated in either space or time or both. Separation in space is accomplished by lane closure, crossover, temporary bypass, detour, or roadside work zone.

For a lane closure the construction in the work area uses one or more lanes of the roadway, leaving the remaining lanes open to traffic.

For a crossover traffic is channeled into one or more lanes of the roadway normally used for traffic in the opposite direction. On divided highways a temporary or existing connection through the median between the two directional roadways is used to channel traffic to the opposite side. On undivided roadways traffic is channeled across the old centerline of the roadway so that both directions of traffic are using the same side of the roadway.

For a temporary bypass a temporary road is built to carry traffic around the work area. The temporary bypass roadway may be either one-way or two-way.

For a detour the roadway is completely closed for either one or both directions and traffic is rerouted onto alternate routes.

For a roadside work zone the existing roadway is used but with some restrictions placed on it. An example would be shoulder work in which all traffic lanes are maintained.

Separation in time is accomplished by restricting the time that either the traffic or construction activity can occupy a specific section of roadway. A common strategy is the restriction of construction activity during hours of peak traffic flow. In other cases traffic is stopped for a period of time while construction activity occupies the traveled way. Another application of traffic pacing is the use of slow-moving lead vehicles to block all lanes of a roadway to create a gap in traffic so short-term construction activities can be done at the work site. In this case, the pacing is actually a way of time separation rather than a speed control strategy.

Speed Control Strategy

The third step in the planning and design of construction zones is the formulation of the speed control strategy. Two philosophies of speed control through construction zones are currently in widespread use. One philosophy says, "Speed in the construction zone should be similar to the speed on the highway before the start of the construction zone," and argues that changes in speed, per se, and large speed differentials, in particular, produce accidents. The second philosophy says, "The speed of traffic should be reduced in construction zones." This philosophy is based on the opinion that construction zones are intrinsically more hazardous than other sections of roadway and, therefore, traffic speeds should be reduced to provide a reasonable degree of safety for motorists and construction personnel. Conversations with highway officials in several states revealed that, while a majority of those interviewed think that speed reductions are necessary in almost all construction zones, a smaller number believe that speeds should not be reduced unless conditions dictate such a reduction.

If the objective of speed control is to maintain a normal speed through the construction zone, then a design speed equal to that of the approach to the construction zone should be used. All of the geometric design elements and traffic-control devices should be suitable for this design speed. For example, California specifies that, on roads with high approach speeds, detours should be designed to high standards (2). This principle should apply to all roads and its intent is to integrate the construction zone with the surrounding roadway without abrupt changes in design standards.

If the objective of speed control is to reduce traffic speeds in the construction zone, an effective method of speed reduction must be incorporated into the construction zone design. When speeds are actually reduced, a lower design speed can be used to determine geometric design elements and traffic-control devices needed. Of course, in some zones on low-volume highways, it may be necessary to stop traffic. In these zones it is important that vehicles be brought to a stop safely. Some commonly used speed reduction methods are advisory speed limits, regulatory speed limits, signal control, flagging, traffic pacing, and physical restriction of vehicle speeds by methods such as the Iowa weave and reduced lane widths.

The effectiveness of posting speed limits is regarded as poor. A study of construction-zone accidents stated (2), "It has been proved that posting of a speed limit does not cause traffic to slow to that speed. A majority of traffic behaves according to apparent conditions regardless of the posting." Especially where there is no visible construction activity, drivers are more likely to disregard reduced speed limits (7). Two sources indicated that drivers seemed to disregard speed limits unless a patrol vehicle was stationed at the construction zone (4, 6).

Geometric Design

The geometric design of the roadway passing through or around a construction zone should provide for safe, efficient travel with as little change as possible from the approach roadway. Any sudden change in geometric standards can result in inefficient and hazardous conditions. Lowering of geometric standards can contribute to increased accident rates (10).

Once the speed control strategy has been chosen, the construction travel way should be designed consistent with the geometric design standards required for the traffic speed. A California study (2) has indicated that drivers will not usually slow down while entering a construction zone, especially if they are used to sustained high speeds. This emphasizes the need to design the travel way through the construction zone for the speeds vehicles will travel, not for the speed one hopes they will travel.

Several principles that should be followed in the geometric design of construction zones are

1. Transition areas must be as nearly like the approach as possible; what differences there are must be clearly apparent (2);
2. A flat diagonal crossover is better than reverse curves with extensive superelevation (2);
3. Lateral obstructions located closer than 1.8 m (6 ft) from the edge of a traffic lane reduce its effective width (8);
4. Reduction of one geometric standard can sometimes be compensated for by improvement of another (2); and
5. Tapers for lane drops should not be contiguous with crossover of temporary bypass roadway transitions (2).

If standards consistent with the design speed cannot be attained due to right-of-way, cost, or other restrictions, then the speed control strategy should be changed. A roadway with reduced geometric standards can only be safe and efficient if the speed control strategy is successful in reducing speeds.

Traffic-Control Devices

A fifth step in the planning and design of construction zones is the selection of appropriate traffic-control devices. Devices, such as signs, signals, channelization devices, pavement markings, barriers, and lighting devices, are needed in construction zones to alert drivers to the impending conditions, warn them of hazards, and direct them through the proper path. The purpose of using standard signs in construction zones is to assist or direct the driver in making appropriate speed and path decisions. Since a driver can assimilate only a limited amount of information, it is preferable that each sign not contain more than two messages (11). Signs should not clutter the driving environment. If they must function during darkness, they should be as visible as they are during the day (6). In many cases, face-lit, nonreflective signs may be more visible than nonlit reflectorized signs.

In many cases, construction work makes it necessary to divert vehicles from the lanes they normally use. This situation requires that appropriate reflectorized pavement markings be installed and that inappropriate pavement markings be removed.

Timber barricades have been used in some construction zones to serve as both delineation devices and as a positive barrier (6). Such barricades were convenient because they take up little room but were mistakenly supposed by some agencies to be capable of redirecting errant vehicles. Lisle's paper in this Record on the Virginia Highway and Transportation Research Council study corrects this misimpression by demonstrating that the timber barricades were ineffective because 73.5 percent of all vehicles striking the devices either straddled or penetrated them. The Virginia report goes on to say that portable concrete traffic barriers with the safety shape are ideal for use as a protection and redirection device.

FHWA Notice N 5160.27 dated February 2, 1977, contains revised standards for the use of timber barricades, and states that "Timber barricades shall not be approved for use on direct federal or federal-aid projects as a positive barrier at any speed." The notice also states that timber barricades should be used for delineation only in urban areas where operating speeds of 32.2 km/h (20 mph) or less could be expected.

Recently, several new devices have been developed to aid in controlling traffic through construction areas:

1. Delineator poles made of elastomeric material, set in concrete base, and capable of withstanding bumper speeds up to 40 km/h (25 mph) (6): This device is especially useful in areas where traffic cones are knocked over repeatedly. These delineators also maintain higher reflectivity during rain than conventional posts.
2. Portable, 0.9 × 2.1-m (3 × 7-ft) changeable matrix message signs with 45.7 cm (18 in) characters (6): Changeable matrix message signs are very applicable to zones where traffic conditions are changeable. Portability of these signs allows for the freeing of construction equipment usually required for mounting of fixed traffic-control signs.
3. High-intensity reflectorized sheeting incorporating diagonal orange strips (6): This device is very useful when applied to barricades. The manufacturer claims it is nearly three times as bright as engineer-grade materials.
4. Improved equipment to erase inappropriate pavement markings (6): Inadequate removal of unnecessary pavement markings can result in very hazardous conditions if they lead the motorist on an inappropriate path. This new equipment removes the markings more effectively and leaves the pavement with as little scarring as possible.
5. Breakaway barricades (12): This device is assembled without bolts or cement to allow for instant breakaway and parts flying clear of impacting vehicles. Because of breakaway design, most of the parts will not be damaged by collision, and those that are can be easily replaced with interchangeable parts.

Additional research is to be conducted in the near future into the use of arrow boards and flood lighting. Also, an upcoming National Cooperative Highway Research Program (NCHRP) study will evaluate the effectiveness of various channelizing devices.

MANAGEMENT AND OPERATION OF CONSTRUCTION ZONES

The daily operation of the construction zone is even more important than the plan and design of the construction zone. Lackadaisical or inattentive supervision of the daily operations can negate the most complete and thorough plans. Also, even with the most thorough planning, changing field conditions may require immediate, unanticipated changes in the traffic-control strategy. One accident study has indicated that more than half of the accidents reported on road construction projects were caused by operational negligence (13). An Illinois accident study indicated (14), "Too many accident reports state that the driver was surprised by a barricade across the road or a flagperson stopping traffic without advance signs."

Public Information

Invaluable assistance in the management of construction traffic control on major facilities can be provided through advance use of public information. Various methods can be used to inform the public of anticipated delays or congestion resulting from construction activities. These methods include public hearings, press releases, special mailings, personal contacts, and special signs (6, 7, 15). The method and degree to which these techniques are used should vary according to the following project factors: duration, size, season, location, traffic volumes and mix, time of day, day of week, lane use, institutional constraints, available media and expertise, and funding sources (6). As an example, in areas with large tourist traffic, pamphlets can be handed out to alert drivers of the construction activity and show them alternative routes. Once the project is completed, mass media articles and letters to affected parties expressing appreciation for cooperation on the project will enhance the operation of future projects (6).

Training

An important aspect of the management of a construction zone is the training of the personnel who are working in the zone. The resident engineer must be well trained in traffic operations techniques in order to monitor and evaluate the effectiveness of the traffic control.

If flagging is used to control traffic in a construction zone, the flagperson is most directly responsible for controlling the actions of drivers approaching the zone. Therefore, flagpersons should be qualified and knowledgable in flagging procedures. The flagperson should be aware of various procedures, including:

1. Where he or she should be stationed,
2. How to slow traffic,
3. How to stop traffic,
4. How to coordinate traffic movements with another flagperson,
5. How to inform the public,
6. How to control for construction equipment movements,
7. How to handle emergency vehicles, and
8. How to warn construction workers of high-speed or out-of-control vehicles.

Most highway agencies have training programs for field supervisors and flagpersons. Some states even license flagpersons. A notebook designed to train government and contractor personnel in planning, designing, installing, and maintaining signing and marking installations in construction zones was developed by the U.S. Department of Transportation (16). This 1-week training course presents relevant information and then gives the participants an opportunity to use the information in work sessions. Training films have also been developed for these training sessions.

Modification of Traffic Control

As soon as the construction zone is opened to traffic, the operation of the zone should be evaluated. Standards used for the placement of devices may need to be altered because of some unique characteristic of the zone. Several methods are available to observe the operation of the zone, including (16) driving through the zone, viewing the zone from a high vantage point or from an airplane, and time-lapse monitoring. Operational characteristics that may indicate that the traffic-control strategy should be modified include: (a) accidents or near accidents, (b) damaged control devices, (c) skid marks, (d) unusually high or low speeds, (e) queues, and (f) drivers having difficulty in following the correct path. If modification is needed, the situation should be remedied immediately.

Another important aspect of evaluation and modification of construction zones is to make a night observation of controls in effect. California law requires a review of each major phase of change, including a nighttime viewing (2).

Removal of Inappropriate Traffic-Control Devices

An important aspect of efficient management of construction-zone operations is removal or alteration of inappropriate traffic-control devices when conditions warrant. Unfortunately, the public has become accustomed to inappropriate devices in construction zones, such as construction signs, uncovered existing signs, and pavement markings that do not relate to current conditions. These common conditions have led to a careless attitude among construction-zone motorists. FHWA Associate Administrator Howard Anderson recently stated (17), "The recent lack of public respect for the highway engineer is due in part to the public's most direct contact with us controlling traffic through construction sites."

A recent addition to the MUTCD states that markings that are "no longer applicable, which may create confusion in the minds of motorists, shall be removed or obliterated as soon as practicable." Painting over inappropriate markings can result in a highly reflective marking that may be even more visible under wet conditions than the existing markings. The most effective methods for removing inappropriate pavement markings include (18)

1. Sandblasting using air or water;
2. High-pressure water;
3. Steam or superheated water;
4. Mechanical devices such as grinders, sanders, scrapers, scarifiers, and wire brushes;
5. Solvents and chemicals; and
6. Burning.

The removal of inappropriate signs in construction zones is also important. When construction begins, the construction signing should be installed and existing signs that are inappropriate should be removed or covered. As the construction progresses, the signs should be reviewed periodically and whenever changes are made in the traffic-control strategy to ensure that the signs always correspond to the conditions that motorists will encounter. On moving operations, such as resurfacing, warning signs should be moved frequently in order for the traffic control to keep pace with the construction activity.

Maintenance of Traffic-Control Devices

Traffic-control devices must be kept in good condition and in the proper location so that they perform their intended function. Proper maintenance of the devices will help to minimize accident litigation potential, check vandalism, and accommodate adverse environmental conditions (16).

Maintenance of traffic-control devices on very large construction projects can be a substantial part of the project costs. For one construction project on the Dan Ryan Expressway in Chicago, the contractors maintained the devices on a continuous 24-h/d basis by use of a two-person crew equipped with a two-way radio. This crew replaced an average of 70 to 100 barricades/d (7). In California, a contractor was required to survey all traffic-control devices, 24 h/d, every day of the week, for the entire length of the project, and to make any necessary temporary repairs (7). This extensive maintenance effort resulted in a great reduction in the number of accidents that usually accompanied construction projects in that state. Cost of the surveillance was about 2 percent of the project cost.

Generally, the following general guidelines should be followed in the maintenance of traffic-control devices (6, 16):

1. Replace devices damaged from the weather, traffic, or construction activity;
2. Replace missing devices;
3. Remove devices no longer needed;
4. Replace obsolete devices;
5. Clean dirty signs;
6. Remove weeds, shrubbery, construction materials or equipment, and spoil that obscure devices;
7. Repaint faded pavement markings if they are to be used for an extended period of time;
8. Check flasher and delineation light charge levels daily; and
9. Maintain an adequate inventory of devices.

CONCLUSIONS

The traffic-safety problem associated with traffic-control practices in at least some construction zones can be alleviated by improved traffic-control practices. All phases of traffic control in construction zones can be improved, including planning, design, and management. More effective planning and design of construction-zone traffic control should require a step-by-step planning process including (a) collection of roadway, traffic, and construction data; (b) selection of basic zone type and scheduling; (c) formulation of a speed control strategy; (d) determination of geometric design elements; and (e) selection of traffic-control devices and methods.

More effective management of construction-zone traffic control should include (a) improved public information, (b) training of field personnel, (c) review and modification of traffic control, (d) removal of inappropriate devices, and (e) improved maintenance of traffic-control devices.

ACKNOWLEDGMENT

This paper is based on a review of literature and current practices conducted by Midwest Research Institute as part of a Federal Highway Administration contract entitled, "Design and Operating Speeds for Construction Zones." The findings and conclusions of this paper are our own and do not necessarily represent the views of the Federal Highway Administration.

REFERENCES

1. Manual of Uniform Traffic Control Devices for Streets and Highways. Federal Highway Administration, 1971.
2. Construction Zone, Detour and Temporary Connection Accidents. California Business and Transportation Agency, Department of Public Works, June 1972.
3. D. J. Migletz. Analysis of Traffic Accidents Occurring on Ohio's Rural Freeways During Safety Upgrading Construction Projects. Ohio State Univ., M.S. thesis, 1977.
4. J. L. Graham, R. J. Paulsen, and J. C. Glennon. Accidents and Speed Studies in Construction Zones. Federal Highway Administration, Final Rept., DOT-FH-11-8121, June 1977.
5. Public Employee Safety Guide—Street and Highway Maintenance. National Safety Council, 1974.
6. Traffic Controls for Construction and Maintenance Worksites. American Public Works Association; Federal Highway Administration, Final Rept., Dec. 1975.
7. Highway Focus. Federal Highway Administration, Vol. 6, No. 4, Dec. 1974.
8. Highway Capacity Manual. Highway Research Board, Special Rept. 87, 1965.
9. L. Smith. Safe Traffic Control Through Highway Work Areas. Center for Auto Safety, Jan. 21, 1976.
10. J. K. Kihlberg and K. J. Tharp. Accident Rates as Related to Design Elements of Rural Highways. NCHRP, Rept. 47, 1968.
11. S. F. Hulbert. Human Factors and Traffic Engineering. Traffic Engineering, Sept. 1968.
12. Federally Coordinated Program of Highway Research and Development. Federal Highway Administration, 1975.
13. It Pays to Minimize Traffic Hazards During Road Construction. Public Works, Oct. 1963.
14. W. A. Frick. Traffic Protection for Highway Work Areas. 58th Annual Purdue Road School, Engineering Bulletin, Purdue Univ., Engineering Extension Series, No. 138, April 1972.
15. Traffic Control for Freeway Maintenance. NCHRP, Synthesis of Highway Practice 1, 1969.
16. Traffic Control for Street and Highway Construction and Maintenance Operations. Federal Highway Administration, Sept. 1975.
17. H. L. Anderson. Let's Try to Dispel Some Highway Safety Myths. Traffic Engineering, Dec. 1976.
18. The Obliteration of Pavement Markings. Federal Highway Administration, FHWA Notice N 5100.14, Dec. 5, 1975.

Publication of this paper sponsored by Committee on Traffic Safety in Maintenance and Construction Operations.

Crash Test Evaluation of Temporary Traffic Barriers

Maurice E. Bronstad and C. E. Kimball, Southwest Research Institute, San Antonio

In and around highway construction zones, delineation devices as well as barriers are used to control and restrict the flow of traffic. The need for positive containment barriers was recognized by the Federal Highway Administration. The Federal Highway Administration further recognized that the use of many temporary barrier devices was not based on documented performance. Accordingly, three temporary barriers were selected for crash test evaluation: (a) 250 x 250-mm (10 x 10-in) timber barrier, (b) W-beam-barrel barrier, and (c) type X curb. These barriers were subjected to controlled impacts with full-sized 2040-kg (4500-lb) automobiles impacting at angles from 7° to 16° at speeds from 56 km/h (35 mph) to 90 km/h (56 mph). Results indicate that the first and third barrier designs had minimal redirection-containment capacity, and performance was judged to be poor. The W-beam-barrel concept performed well during a 72-km/h (45-mph), 15° angle impact; however, the system was penetrated during a 93-km/h (57.6-mph), 16° angle impact.

In or around highway construction zones, delineation devices, barricades, and barriers are used to control and restrict the flow of traffic. The term barrier as used in this paper denotes a device with certain capacity to contain and redirect impacting vehicles. Barricade devices that have minimal strength requirements (e.g., environment) should be much less formidable or hazardous when impacted than a barrier. This distinction between a barrier and a barricade device should be clearly understood.

This paper is concerned with crash test evaluation of some currently used temporary barriers. These barriers were being used without knowledge of containment capacity, and the purpose of the tests was to ascertain performance limits of these selected devices.

BACKGROUND

There are many traffic barriers with known capacities for containment and redirection; however, these barriers are primarily used for permanent installations. There is a need for barriers that are portable to readily accommodate movement during the course of highway construction. Due to the unique requirements of portability, these barriers must accomplish their function without benefit of foundation restraint that is costly to either install or remove.

Three currently used temporary barriers were selected by the Federal Highway Administration (FHWA) for evaluation by crash test. The three barriers, as described in Figure 1, are (a) 250 × 250-mm (10 × 10 in) timber barrier, (b) W-beam-barrel barrier, and (c) type X curb.

All of these barriers are currently in use, although the timber barrier has been banned by FHWA from further applications (1).

TEST PROGRAM

The selected temporary barriers were known not to be of sufficient strength to meet the current barrier strength test requirements set by the National Cooperative Highway Research Program (NCHRP) (2). Since there are no criteria for temporary barriers, test conditions were selected based on what was believed to represent the upper limit of barrier performance. Full-sized sedans weighing approximately 2000 kg (4500 lb) were selected for the evaluations.

The timber barrier was evaluated for both 7° and 15° angle impacts at speeds from 56 to 62 km/h (35 to 39 mph). The W-beam-barrel barrier was evaluated in three 15° angle tests at speeds of 56, 72, and 88 km/h (35, 45, and 55 mph). The type X curb was evaluated in a 15° angle test at 56 km/h (35 mph).

The crash tests in this program were performed with vehicles running under power with guidance provided by a guide channel that captivated the right wheels of the vehicle. Vehicle ignition and brakes were controlled through a tether line, which also carried the signals from strain gauge accelerometers located in the longitudinal and lateral (or transverse) directions of the vehicle. These transducers were mounted near the vehicle center of gravity (c.g.). Vehicle ignition was turned off just prior to impact. Brakes were not applied in any of these tests. Both high-speed and real-time cameras were used to document the impact events.

Data were derived from two primary sources: (a) micromotion analysis of high-speed film and (b) accelerometers. Data were taken from film using a Vanguard motion analyzer and then processed by the SwRI DATA IV motion analysis computer program.

Data from the strain gauge accelerometers were recorded at 1.5 m/s (60 in/s) on magnetic tape and replayed through SAE J211 class 60 specification filters; the signals were displayed on oscillograph charts.

RESULTS

Results of the test series are summarized in Table 1.

Test TB-1, Timber Barrier

Impact conditions for the vehicle were 61 km/h (38.0 mph) and a 7° angle. The vehicle's left front tire contacted the barrier approximately 13.1 m (43 ft) from the upstream end and immediately climbed up and over the base, as shown in Figure 2. After straddling the barrier, one of the steel strap splices released, allowing the barrier section to pivot and imparting redirection to the vehicle. The vehicle came to rest 1.2 m (4 ft) from the downstream end of the barrier, as shown in Figure 3. The vehicle sustained only minor damage; damage to the upper barrier rails downstream of the impact was total. The 250 × 250-mm (10 × 10-in) base sections were widely displaced, as shown in Figure 3.

Test TB-2, Timber Barrier

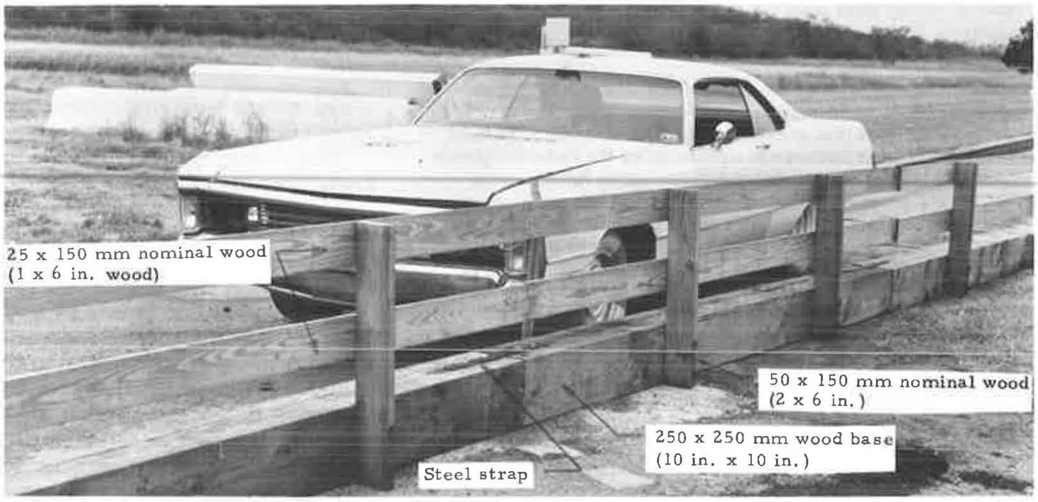
Vehicle impact conditions were 55.3 km/h (34.6 mph) and a 15° angle. The vehicle's left-front tire contacted the barrier 14.6 m (48 ft) from the upstream end. As shown in Figure 4, the vehicle vaulted over the base and with little redirection continued over and through the barrier. Two of the base sections were displaced, as shown in Figure 5. The vehicle came to rest with the rear end 6.1 m (20 ft) behind the barrier.

Vehicle damage resulted from spearing of the grill by one of the upper rail members. There was considerable damage to the vehicle front suspension, transmission, and rear-end (differential) assembly.

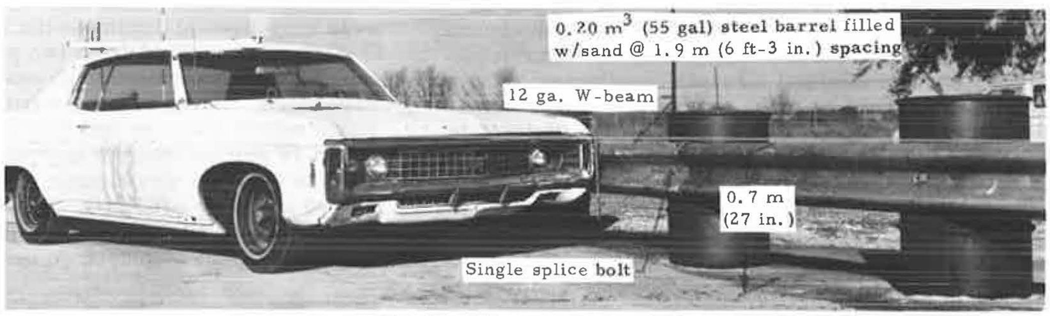
Test TB-3, W-Beam-Barrel Barrier

Vehicle impact conditions were 57 km/h (35.5 mph) and a 14.3° impact angle. As shown in Figure 6, the barrels

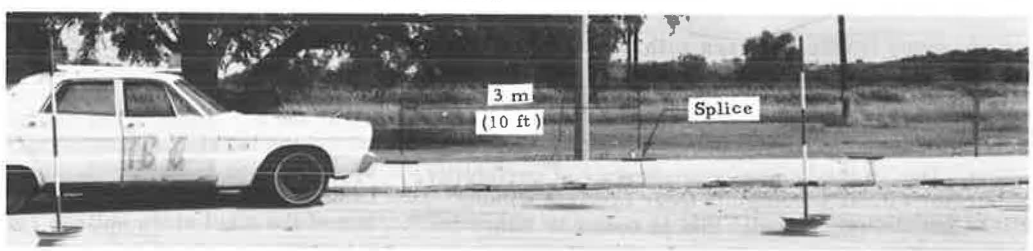
Figure 1. Temporary barrier test installations.



(a) Timber barrier
[Test installation length = 43.9 m (144 ft)]



(b) W-beam/barrel barrier
[Test installation length = 30.5 m (100 ft)]



(c) Type X concrete curb
[Test installation length = 30.5 m (100 ft)]

Table 1. Summary of crash test results.

Test	Barrier	Vehicle Weight (kg)	Impact Speed (km/h)	Impact Angle (degrees)	Maximum Average (50 m/s) Accelerations Obtained From High-Speed Cine: Longitudinal (g)	Lateral (g)	Barrier Maximum Lateral Displacement (m)	Remarks
TB-1	Timber	2040	61.0	6.9	-0.7	-1.6	4.6	Vehicle redirected, straddled barrier
TB-2	Timber	2040	55.3	15.5	-1.1	-2.4	4.0	Vehicle penetrated barrier
TB-3	W-beam/barrel	1954	57.3	14.3	-0.6	-1.9	1.2	Vehicle redirected
TB-4	W-beam/barrel	1954	73.1	14.6	-1.2	-2.7	1.8	Vehicle redirected
TB-5	W-beam/barrel	2008	92.7	15.8	-2.5	-2.2	10.1	Vehicle penetrated barrier
TB-6	Type X curb	1970	56.3	8.1	-2.1	-1.1	0.3	Vehicle mounted barrier, remained on top; abrupt deceleration caused by snagging on exposed splice plates

Note: 1 kg = 2.2 lb; 1 km/h = 0.6 mph; 1 m/s = 3.3 ft/s; 1 m = 3.3 ft.

in the impact area immediately tipped away from the vehicle as it was smoothly redirected. Barrels adjacent to the impact area subsequently began to tip, and similar to a domino effect, the barrels rotated over on their sides, as shown in Figures 6 and 7. Although there was wheel contact with three barrels, no abrupt decelerations were observed.

The vehicle sustained minor sheet metal damage; otherwise it was undamaged. Although the entire installation was displaced, as shown in Figure 7, it was easily restored to an upright position for test TB-4.

Test TB-4, W-Beam-Barrel Barrier

Vehicle impact conditions were 73 km/h (45.4 mph) and a 14.6° angle. As shown in Figure 8, the vehicle impacted the installation 15.2 m (50 ft) from the upstream end, and barrels in the impact area immediately tipped away from the redirected vehicle. As in test TB-3, the barrels out of the impact area rotated sequentially until the entire installation was pushed over. Vehicle contact with six barrels was noted; however, no snagging or abrupt deceleration occurred.

The vehicle sustained minor sheet metal damage to left-front and rear fenders, as shown in Figure 9. In ad-

Figure 2. Test TB-1 sequential photographs.

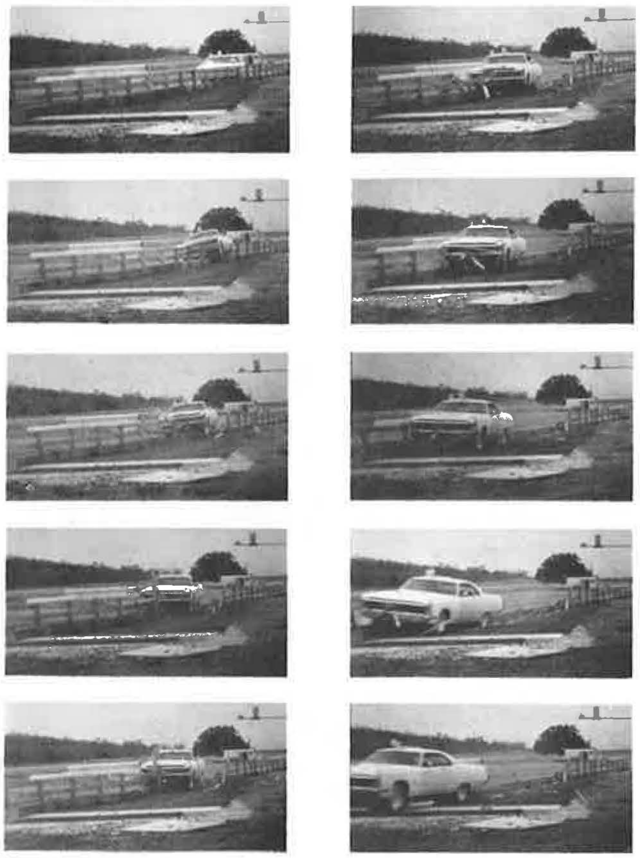


Figure 3. Test TB-1 vehicle and barrier damage.

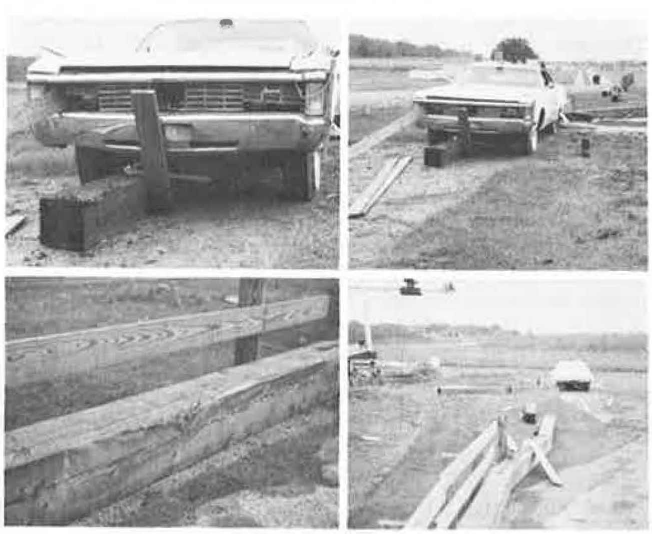


Figure 4. Test TB-2 sequential photographs.

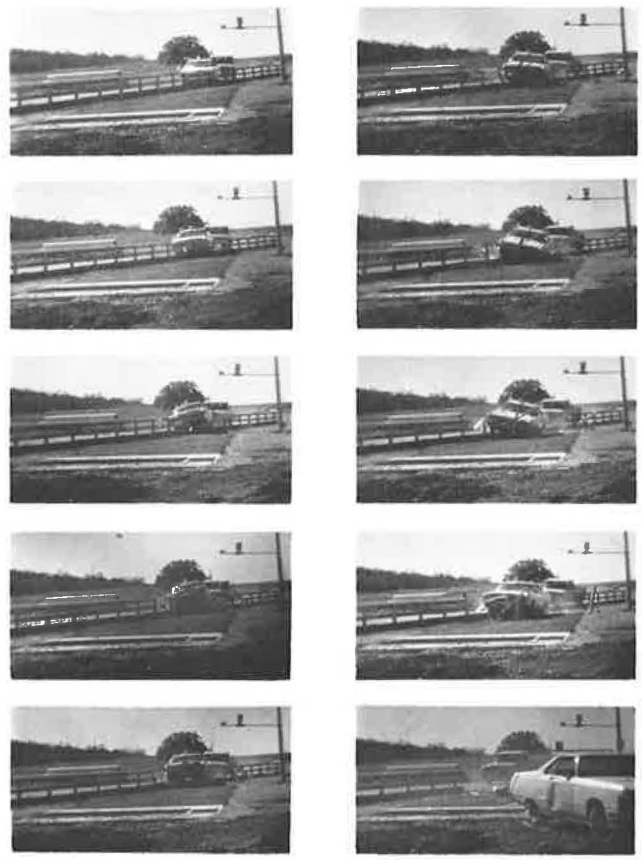


Figure 5. Test TB-2 vehicle and barrier damage.

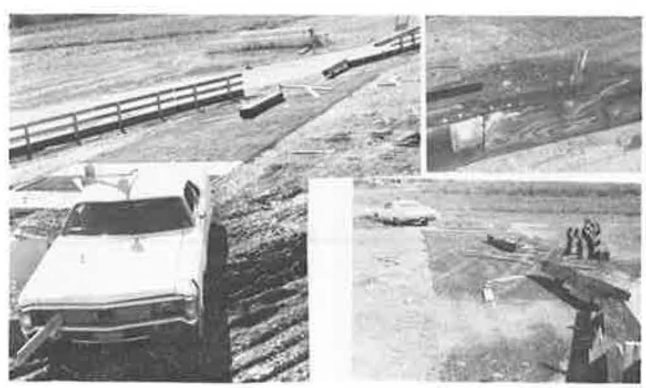


Figure 6. Test TB-3 sequential photographs.

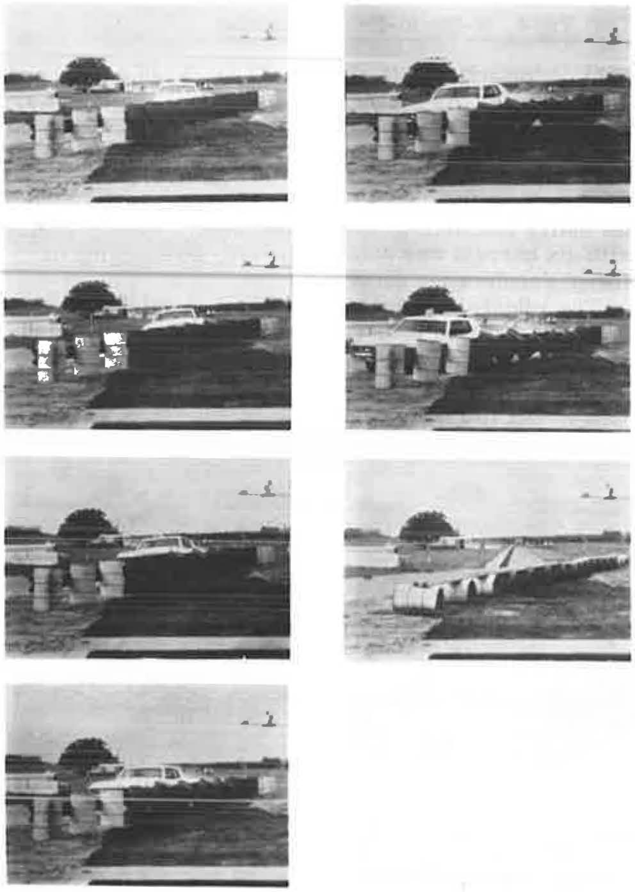


Figure 7. Test TB-3 vehicle and barrier damage.

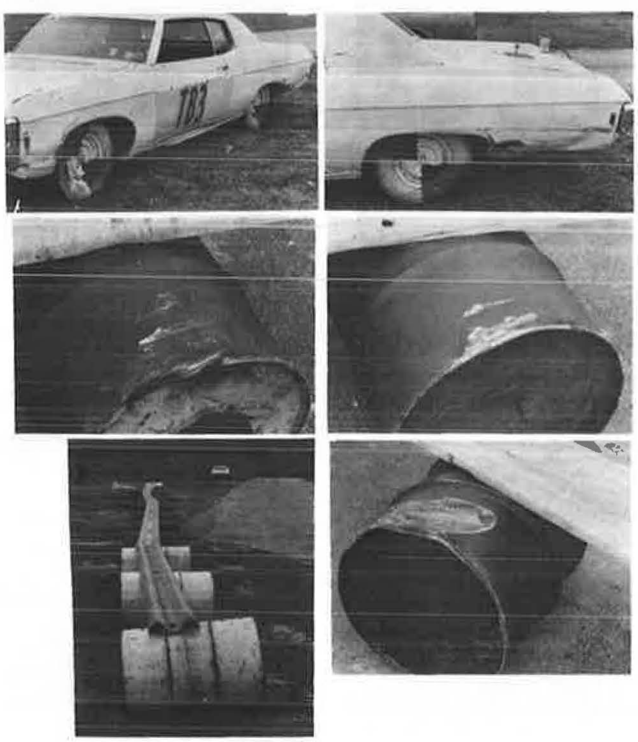


Figure 8. Test TB-4 sequential photographs.

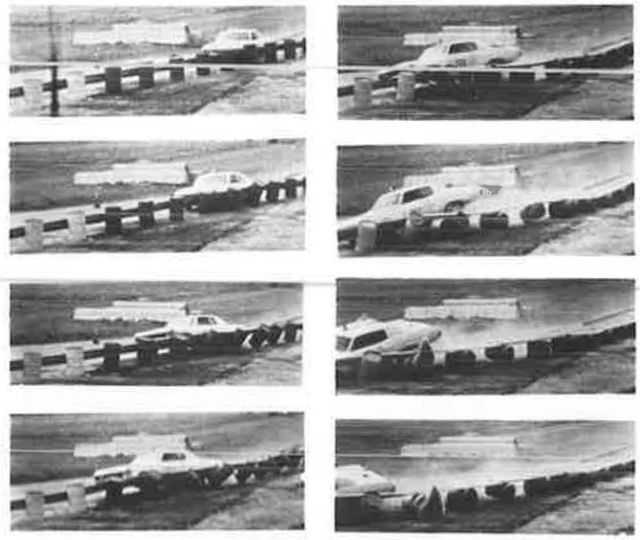
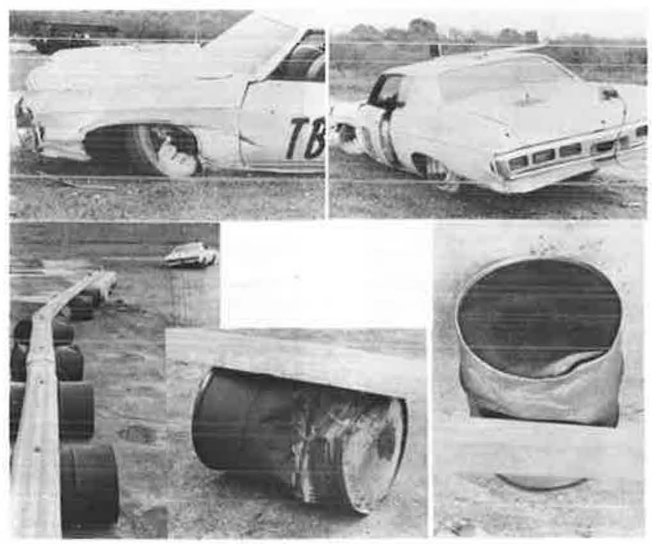


Figure 9. Test TB-4 vehicle and barrier damage.



dition, the lower ball joint at left-front wheel was separated and both left tires were punctured during impact. Damage to the installation was limited to three barrels, which were replaced prior to the next test.

Test TB-5, W-Beam-Barrel Barrier

Vehicle impact conditions were 92.7 km/h (57.6 mph) and a 15.8° impact angle. As seen in the sequential photograph of Figure 10, the vehicle pocketed slightly, and then, from an orientation approximately parallel to the barrier, vaulted over the barrier. As the W-beam splice connection failed, the vehicle climbed over the barrels in front. Although the vehicle was airborne and unstable, it did not roll over and came to rest as shown in Figure 11.

Considerable sheet metal and suspension damage was sustained by the vehicle's left-front quadrant. In addition, the rear transmission mount and differential housing attachments failed. Barrier damage was extensive, as shown in Figure 11.

Test TB-6, Type X Curb

Vehicle impact conditions were 56 km/h (35 mph) and an 8.1° angle. Initial impact was 9.8 m (32 ft) from the upstream end. As shown in Figure 12, the left wheels immediately climbed up the sloped curb face. The vehicle pitched (nose up) initially, and then as it straddled the barrier, the front underside snagged on one of the 25-mm

Figure 10. Test TB-5 sequential photographs.

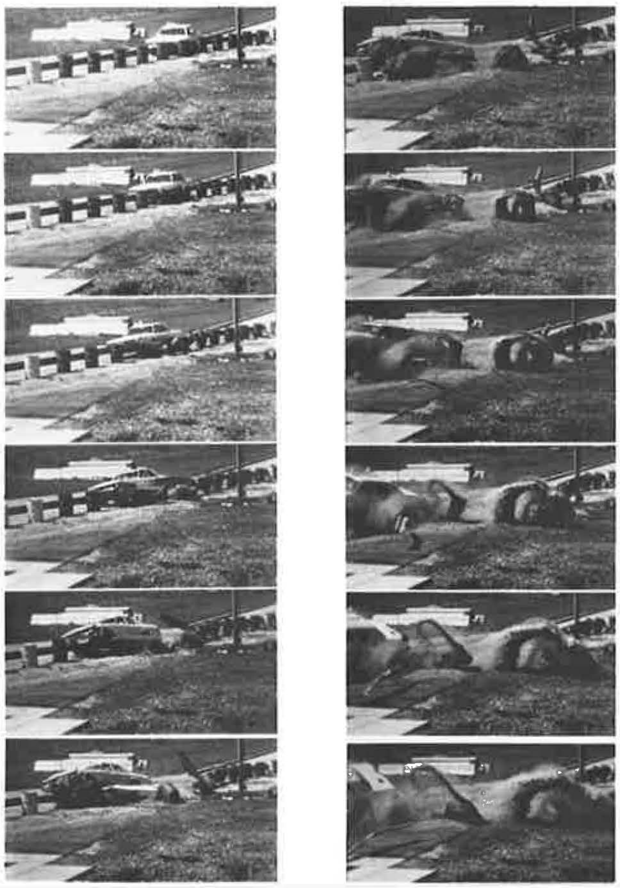


Figure 11. Test TB-5 vehicle and barrier damage.

Figure 12. Test TB-6 sequential photographs.

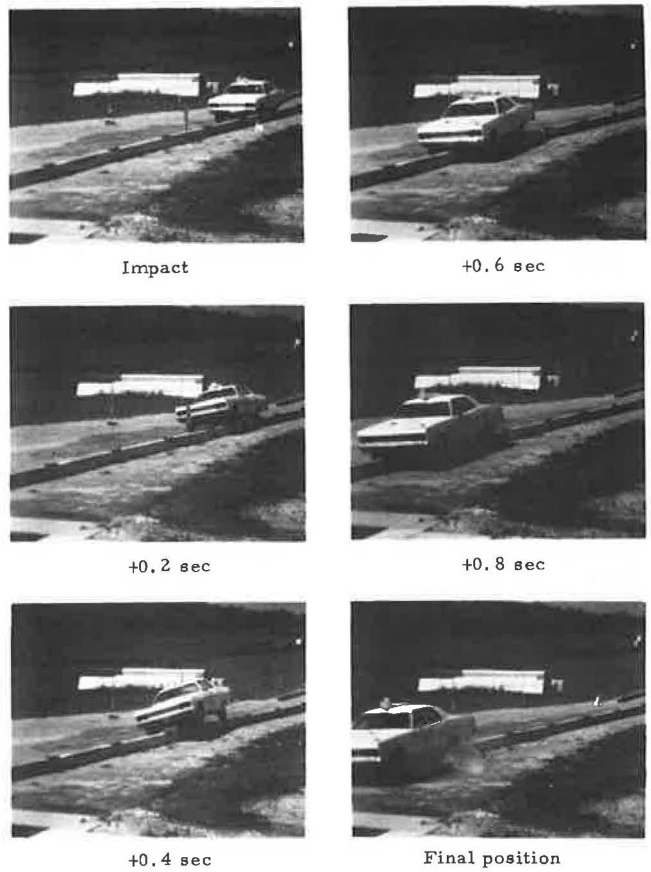


Figure 13. Test TB-6 vehicle and barrier damage.

(1-in) thick splice plates. Significant deceleration forces were then applied to the vehicle by this splice plate and the one immediately downstream. These forces were sufficient to prevent the vehicle from proceeding over the barrier; however, considerable damage to the vehicle's underside and three barrier sections was observed. Final position of the vehicle and the barrier damage are shown in Figure 13.

CONCLUSIONS

Based on the findings of these crash tests, the following conclusions can be made:

1. The 250 × 250-mm (10 × 10-in) timber barrier tested has minimal redirection capability. The upper rail members are not functional and exhibit a potential for spearing both vehicle and occupants. The lower 250 × 250-mm base is readily mounted by vehicles at nominal speeds and angles. Use of this barrier for containment and redirection is not recommended. The 250 × 250-mm base with upper railings removed could be used for very low speed operations, where speeds and impact angles are low and traffic consists of automobiles only.
2. The W-beam-barrel concept evaluated in this program is an effective containment barrier for impacts characterized by a 2040-kg (4500-lb) vehicle impacting at 73 km/h (45 mph) and an angle of 15°.
3. The type X curb is ineffective in redirecting vehicles. The curb is readily mounted and even at angles of 8° it does not appear to be capable of redirecting a 2040-kg vehicle impacting at 56 km/h (35 mph). The fact that the test vehicle did not completely go over the test barrier is attributed to the deceleration force imparted to the vehicle by the splice plate snagging previously cited. This snagging is undesirable in that it causes severe damage to both vehicle and barrier segments. In addition it cannot be considered as a repeatable means of decelerating a vehicle due to the intermittent spacing of the splices.

ACKNOWLEDGMENTS

We recognize the contribution of Morton Oskard of the Office of Research, Federal Highway Administration. Also recognized is the Office of Highway Safety of the Federal Highway Administration for its contribution. For Southwest Research Institute, the work of Glenn Deel, Robert Guillot, Bobby Johnson, Charlie Berger, and Jane Baker is recognized.

REFERENCES

1. News Release. Federal Highway Administration, FHWA 9-77, March 3, 1977.
2. M. E. Bronstad and J. D. Michie. Recommended Procedures of Vehicle Crash Testing of Highway Appurtenances. NCHRP, Rept. 153, 1974.

Publication of this paper sponsored by Committee on Traffic Safety in Maintenance and Construction Operations.

Evaluation of Timber Barricades and Precast Concrete Traffic Barriers for Use in Highway Construction Areas

Frank N. Lisle, Virginia Highway and Transportation Research Council, Charlottesville

This paper summarizes the results of a study of the performance of the timber barricade and a comparison of its characteristics and performance with those of the precast concrete traffic barrier. The study included (a) a traffic accident analysis of the construction zone on I-495 where the timber barricade was employed; (b) a comparison of the technical, operational, and economic feasibility of the timber barricade and the precast concrete traffic barrier; and (c) a review of the legal requirements for temporary barrier systems. The frequency of accident occurrence during construction on I-495 was approximately 119 percent higher than that before construction. Of the reported crashes during construction, 52.5 percent involved vehicle contact with the timber barricades. Of the vehicles involved in crashes with the barricades, 73.5 percent straddled or penetrated the barricades. Thus, on the I-495 site, the timber barricades were ineffective as positive barriers. From the technical, operational, and economic analyses, the precast concrete traffic barrier appeared to be superior to the timber barricade. Since the completion of this study, the Federal Highway Administration has banned the use of the timber barricade as a positive barrier on any federal or federal-aid project.

This paper summarizes the results of a study requested in August 1975 by the Virginia Department of Highways and Transportation to evaluate the performance of the timber barricade employed to separate freeway traffic and construction activities in the widening of I-495 in northern Virginia (1). The department further requested that the characteristics and performance of the timber barricade be compared to those of the New Jersey-shaped precast concrete traffic barrier (PCTB) to determine whether the PCTB could be subsituted for the timber barricade in future projects.

The evaluation covered three major areas: (a) accident analysis, (b) barricade and barrier feasibility, and (c) legal requirements for temporary barriers. Data for the first area were obtained on three widening projects on the Virginia portion of I-495 where the timber barricades were employed. I-495 is the beltway for Washington, D.C., and carries a traffic volume in the range of 80 000 to 100 000 vehicles/d. Two of the projects, 12.30 km (7.64 miles) and 10.73 km (6.67 miles) in length, included the addition of two lanes in each direction to an existing four-lane roadway. The third project, 12.54 km (7.79 miles) in length, included the addition of one lane in each direction to an existing six-lane roadway. Information for the second area of study was obtained from Virginia's experience with the timber barricades and the experience of other states along with Virginia's limited experience with the PCTBs. The third area included results of an examination of federal statutes and rules that might be interpreted as either approving or forbidding the use of the timber barricade or the PCTB.

ACCIDENT ANALYSIS

The accident analysis consisted of (a) a general review of the accident experience on I-495 before and during construction to determine the magnitude of the traffic safety problem associated with construction and (b) an examination of the accident data on I-495 for periods before and during construction to determine the effects of construction on traffic accident characteristics and the role of the timber barricade in vehicle crashes. The numbers of reported accidents by month were reviewed (see Figure 1) before selecting an approach that would show the magnitude of the traffic safety problem on I-495. From January through October 1973 the numbers of accidents per month were found to fluctuate around an average of 96. In November 1973, a decrease in the number of accidents was noted, which corresponded with the start of the energy crisis. Work on the first construction contract was initiated in February 1974, and a rise in the number of accidents was noted. This rise may be attributed to the construction activities, to a decrease in the effects of the energy crisis, or to both. Similar rises were noted for the start of work on the second and third construction contracts in May and November 1974.

A review of the data presented in Figure 1 reveals that the effects of the energy crisis and the effects of the construction activities on the three projects initiated at different times could not be segregated in an analysis of the entire I-495 roadway. To eliminate the effect of different starting times, each segment was analyzed separately. To separate the effects of the energy crisis, it was necessary to identify a control roadway that was affected by the energy crisis but not by major construction. I-95 was chosen as the best available control roadway since it is similar to I-495 in geographic location and most roadway characteristics, with the exception of a major construction project. The traffic volume on I-95 was somewhat lower than that on I-495, but remained relatively constant at 31.3 percent of that on I-495 for the 5-year period from 1970 through 1974. Note that this period includes the energy crisis.

Also considered was the possibility that, due to unavoidable differences in Interstate roadways, the energy crisis could have affected various Interstate roadways differently, and therefore, I-95 would not be a viable control. However, the effects of the energy shortage were found to be quite consistent across Virginia's Interstates and I-495 in Maryland. The total accident rate on the Maryland portion of I-495 dropped by 30.1 percent from 1973 to 1974. Similar drops were found for I-95 in Virginia (30.6 percent), for I-66 (30.4 percent), and for the average for all Virginia Interstate roadways excluding I-495 (32.0 percent). Thus, it appeared that I-95 was a suitable control.

Using I-95 as a control roadway to separate the effects of the energy shortage, and analyzing each construction contract section separately to eliminate the effect of different starting times, it was determined that the accident experience on I-495 during construction was 119 percent greater than during the preconstruction period. This increase is statistically significant at the 99 percent confidence level (t-test).

Changes in the Distribution of Accident Characteristics on I-495

The second phase in the accident analysis was an analysis of the reported accidents on I-495 before and during construction to determine (a) the effects of construction on traffic accident characteristics and (b) the role of the timber barricade in vehicle crashes.

State accident reports were compiled by accident date and location to provide a comparison of crash data for periods before and during construction. Because of the staggered starting times for the three construction projects, different time periods were used for the road segments. To avoid seasonal fluctuations, the months before construction were matched to the months during construction. The selection of the study periods in this manner provided 7 months before and 7 months during construction for the first project, 9 months for the second project, and 4 months for the third project. Note that the effects of the energy crisis were not factored out of this analysis as was done for that in the previous section.

The analysis of the distribution of crashes by crash severity (see Table 1) showed a significant shift in crash severity from injury accidents before construction toward property-damage-only accidents during construction (chi-square = 12.41, $p < 0.01$). Note that the increase in the total number of traffic crashes calculated in this section (from 433 to 862) is 99 percent as compared to the 119 percent determined in the previous section. This difference is attributed to the effects of the energy crisis. In essence, the numbers of accidents in the before-construction periods selected for this analysis underestimate the effects of the energy crisis in reducing the number of accidents.

The analysis of the distribution of crashes by type of collision (see Table 2) reveals that there was a significant shift from rear-end collisions before construction to fixed-object collisions during construction (chi-square = 140.35, $p < 0.01$).

Driver inattention was the major causative factor in accidents before and during construction (see Table 3). However, there was a significant shift in the distribution of accidents by major causative factor (chi-square = 58.00, $p < 0.05$). The increase in the number of accidents in which driving under the influence of alcohol was the major causative factor contributed to this significant shift.

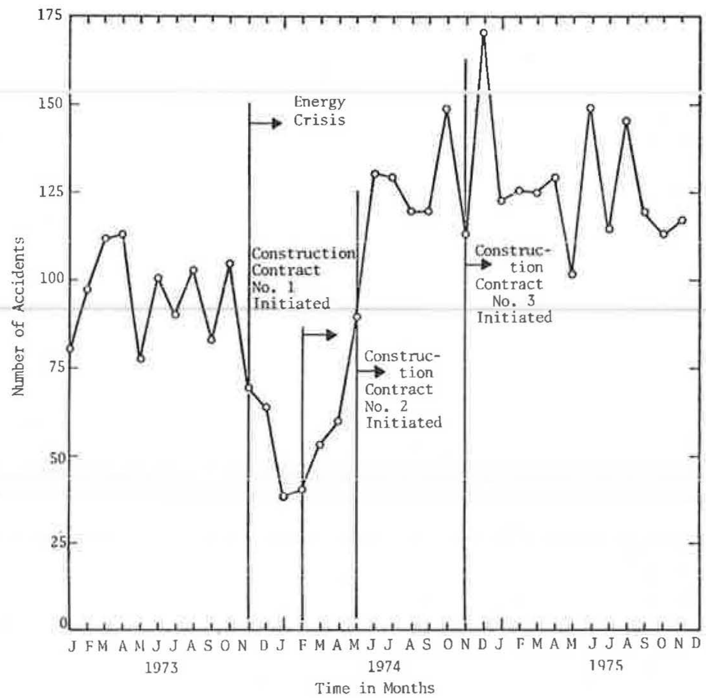
The distribution of accidents by time of day (see Table 4) shifted significantly from peak volume time periods before construction toward the hours of darkness during construction (chi-square = 16.49, $p < 0.01$).

A survey of crashes on I-495 by location revealed a number of high accident locations. The histogram in Figure 2 shows accidents for the second construction project for the study periods before and during construction. Four clusters of accidents are noted in the histogram. These clusters occurred around mileposts 8, 10, 12, and 14, and they correspond to interchanges for I-95, VA-620, VA-236, and US-50, respectively. The data presented in Figure 2 indicate that more accidents per mile occurred at interchanges than within any other section of roadway, independent of construction.

Role of the Timber Barricade

The timber barricade is constructed of a 25 × 25-cm

Figure 1. Number of accidents on I-495 by month.



(10 × 10-in) base and two horizontal railings at heights of 85 cm (34 in) and 55 cm (22 in) supported by two vertical 5 × 15-cm (2 × 6-in) posts (see Figure 3). The barricades were placed on the edge of the traveled way with the 3-m (10-ft) dimension parallel to the direction of traffic. Adjacent barricades were connected by steel straps bolted to their bases. The barricades were not attached to the roadway surface. The general crash data for the period during construction indicated that timber barricades were involved in 52.5 percent of all reported traffic crashes. An average of seven barricades were damaged or destroyed for each accident in which the barricade was involved.

The analysis of the distribution of accidents by crash severity during construction (see Table 5) revealed that there was no significant difference in the crash severity between barricade- and nonbarricade-involved crashes (chi-square = 3.18, not significant). Thus, the involvement of the timber barricade in crashes during construction does not appear to be associated with the severity of the crash.

As can be seen in Table 6, there was a significant difference in the distribution of crashes during construction by type of collision (chi-square = 502.61, $p < 0.01$). The accidents involving the timber barricade were associated with a high incidence of fixed-object accidents (most of the fixed objects being the timber barricades) and most of the nonbarricade accidents were associated with rear-end and sideswipe crashes.

With reference to Table 7, there was a significant difference in the distribution of crashes during construction by major causative factor (chi-square = 234.26, $p < 0.01$). Driving under the influence ranked number one as the major causative factor in barricade-involved accidents and driver inattention ranked number one in nonbarricade-involved accidents. Note that the location of the timber barricade adjacent to the traveled roadway may have been the prime factor in the increase in the number of accidents associated with driving under the influence of alcohol.

As can be seen in Table 8, there was a significant difference in the distribution of crashes during construction by time of day (chi-square = 86.54, $p < 0.01$). The accidents involving the timber barricade were associated with the hours of darkness and nonbarricade accidents were more frequent during the middle of the day.

The effectiveness of the timber barricades in keeping vehicular traffic out of the work area was also studied. For all vehicles striking the barricade in reported accidents, 26.5 percent were arrested and redirected, 28.2 percent straddled it, and 45.3 percent penetrated it (see Table 9). Since 73.5 percent of vehicles that contacted the timber barricade either straddled or penetrated it, the apparent conclusion is that the barricade was not effective in keeping vehicular traffic out of the work area.

Traffic volume counts taken on I-495 during construction indicated that 81 to 85 percent of the traffic volume consisted of automobiles, 12 to 13 percent of trucks, and 3 to 7 percent of tractor trailers. Note in Table 9 that 81 percent of the vehicles involved in barricade crashes were automobiles, 16 percent were trucks, and 2 percent were tractor trailers. Thus the percentage of vehicle involvement with the timber barricade by vehicle type is approximately equivalent to its percentage of the vehicle mix.

BARRICADE AND BARRIER FEASIBILITY

A comparison of the characteristics and performance of a timber barricade and a New Jersey-shaped PCTB was made to determine whether a concrete barrier could be substituted for a timber barricade as a temporary barrier in a construction zone. Ideally, the comparison should have been based on the results of accident experiences on I-495, where the timber barricades were employed, and accident experiences on another construction project similar to I-495, where the PCTBs were employed. However, at the time this study was conducted, Virginia had had very little experience with the PCTBs in construction zones. Therefore, the comparison of the two devices was made in terms of their technical, operational, and economic feasibility. Technical feasibility refers to the ability of the device to perform a particular task; operational feasibility refers to the successful use of a device in performing its intended task; and economic feasibility refers to the dollar value in benefits achieved by using a particular device.

Technical Feasibility

The purpose of the timber barricade is to form a barrier between the construction work area and the traveled roadway. As shown in Figure 3, the timber barricade is constructed of a timber base with two vertical posts, which support two horizontal rails. The posts and rails in the upper portion are intended mainly for delineation of the road edge. Thus, restraint or redirection of errant vehicles must be performed primarily by the timber base.

The California Division of Highways conducted initial testing of curb configurations and their effects on impacting vehicles in 1953 (2). One design tested was approximately 23-cm (9-in) high and had a 0° batter, or vertical face. This design closely resembles the 25-cm (10-in) vertically faced curb of the timber barricade. In the tests, the 23-cm curb served reasonably well as a barrier, but its performance was not consistent. The automobile tended to climb the curb. This curb inflicted severe damage on the wheel rims, which had to be repaired after each test because the tires deformed on impact and allowed the rims to bite into the curb. Actual curb mounting occurred at 32 km/h (20 mph) and an impact angle of 15° with the 23-cm curb.

These findings indicate that the timber barricade is not designed to redirect errant vehicles under freeway operating conditions. Further, these findings were reinforced by the accident analysis on I-495, where it was found that 73.5 percent of the vehicles that contacted the timber barricade straddled or penetrated it.

The PCTB is a New Jersey-shaped portable concrete barrier designed to restrain and redirect vehicles on impact (see Figure 4). The PCTB's use as a temporary barrier followed from the successful use of the New Jersey-shaped concrete median barrier (CMB) in restraining and redirecting vehicles on impact. (The term CMB as used here refers to a permanent installation of the concrete median barrier on the completed roadway.) The ability of the PCTB to safely restrain and redirect vehicles on impact lies in the design characteristics of its forerunner, the CMB.

Results from crash tests performed in California (3) and Texas (4, 5) indicate that the CMB is effective in safely redirecting an impacting vehicle at high speeds in combination with impact angles of less than 15°. At angles of 15° and greater, the impact with the CMB becomes a fixed-object accident rather than a side-swipe accident.

Operational Feasibility

The timber barricade is relatively simple to construct. The timber base is rough hewn, and the post and rail members are made of standard-sized lumber. The 3-m (10-ft) barricade weighs 68 to 91 kg (150 to 200 lb) and can be handled by two people, although common practice is to use a forklift or crane. The structures are easily transported to the work site and installation is rapid; 600 m (2000 ft) of barricade can be placed in a work day.

Maintenance has been a problem. The white-painted barricade rapidly collects road grime. The reflective devices and lights attached to the structure dull rapidly and must be cleaned. The barricades are severely damaged when vehicles strike and mount the curb, and the whole barricade system must be monitored around the clock to make certain that the units are properly positioned.

In the past few years, many states have used PCTBs as temporary traffic-control devices during construction and have found them to be reasonably portable and to perform satisfactorily with little maintenance. The manufacture of PCTBs requires about 2 person-hours of direct labor for each unit. Eight units can be carried per truck to the job site, where a small crane is required to unload and place the 900-kg (2-ton) units on the road edge. More than 400 m (1300 ft) of PCTBs can be placed each day. Various types of end connections have been used, including a tongue-and-groove design, various I-bolt and pin connections, and a wire rope and lock con-

Table 1. Distribution of crashes by crash severity.

	Before Construction		During Construction	
Crash Severity	Number	Percent	Number	Percent
Fatal	2	0.5	8	0.9
Injury	100	23.1	130	15.1
Property damage only	331	76.4	724	84.0
Total	433	100.0	862	100.0

Table 2. Distribution of crashes by type of collision.

	Before Construction		During Construction	
Type of Collision	Number	Percent	Number	Percent
Rear end	222	51.3	243	28.2
Fixed object	83	19.2	448	52.0
Sideswipe	84	19.4	135	15.6
Angle	12	2.7	16	1.9
All others	32	7.4	20	2.3
Total	433	100.0	862	100.0

Table 3. Distribution of crashes by major causative factor.

	Before Construction		During Construction	
Major Factor	Number	Percent	Number	Percent
Driver handicap (i.e., asleep)	13	3.0	32	3.7
Driving under the influence	36	8.3	174	20.2
Speeding	34	7.9	91	10.6
Inattention	280	64.7	415	48.1
Vehicle defective	17	3.9	31	3.6
Road slick	16	3.7	19	2.2
Forced off road	13	3.0	68	7.9
All others	24	5.5	32	3.7
Total	433	100.0	862	100.0

Table 4. Distribution of crashes by time of day.

	Before Construction		During Construction	
Time Period	Number	Percent	Number	Percent
Early morning (12:00 m.n. to 7:00 a.m.)	68	15.7	189	21.9
Morning peak (7:00 a.m. to 9:00 a.m.)	65	15.0	88	10.2
Midday (9:00 a.m. to 4:00 p.m.)	140	32.3	269	31.2
Afternoon peak (4:00 p.m. to 6:00 p.m.)	77	17.8	118	13.7
Evening (6:00 p.m. to 12:00 m.n.)	83	19.2	198	23.0
Total	433	100.0	862	100.0

Figure 2. Accident histogram for construction project no. 2.

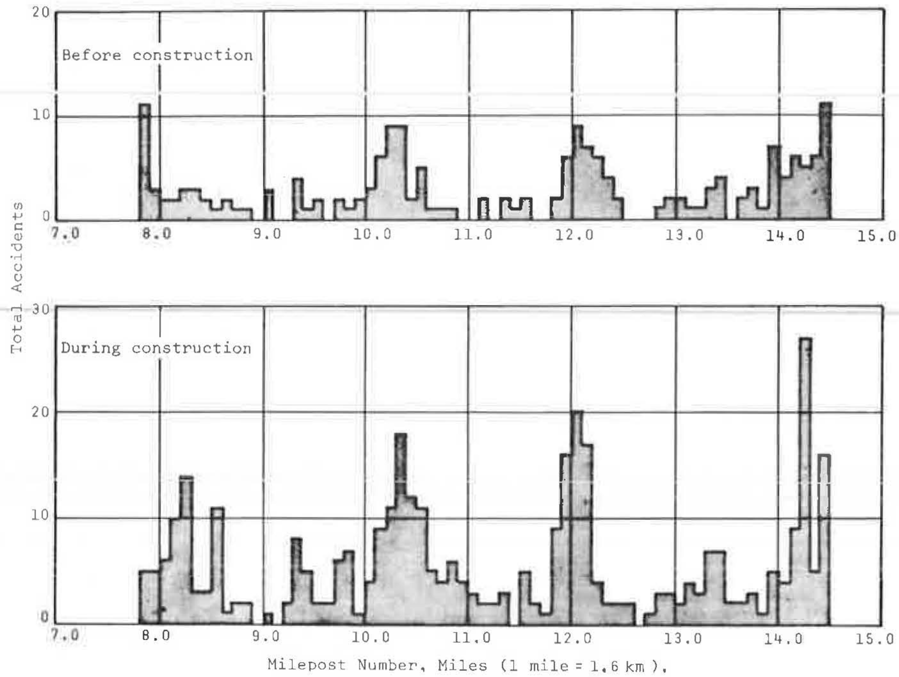
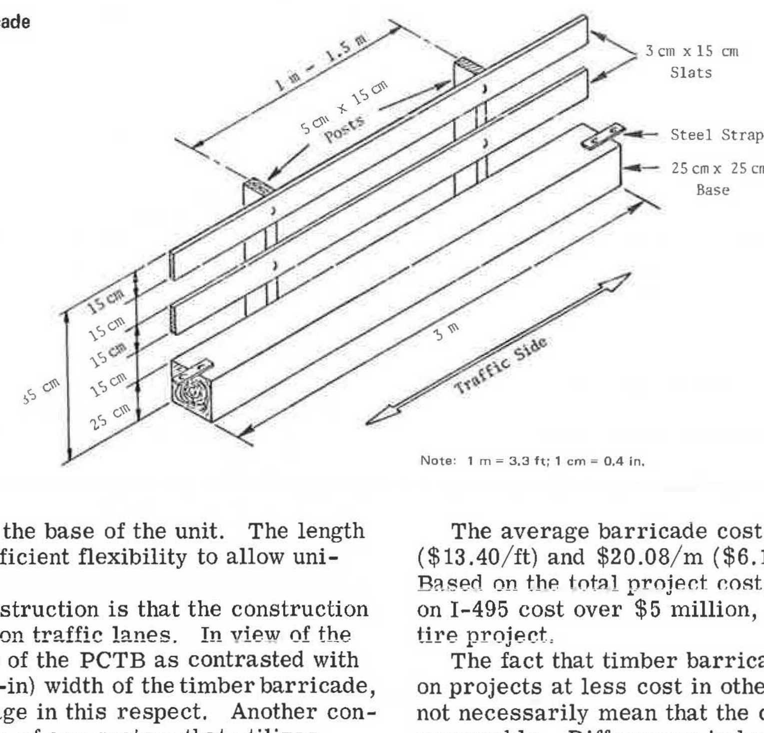


Figure 3. Typical timber barricade used on I-495.



Note: 1 m = 3.3 ft; 1 cm = 0.4 in.

nection through holes in the base of the unit. The length of the units provides sufficient flexibility to allow uniform alignment.

A concern during construction is that the construction operation will encroach on traffic lanes. In view of the 61-cm (24-in) wide base of the PCTB as contrasted with the narrower 41-cm (16-in) width of the timber barricade, the latter has an advantage in this respect. Another concern is for the continuity of any system that utilizes PCTBs. An opening in the system would create a fixed-object hazard. The use of a few selected openings in the PCTB system with an appropriate taper section or cushioning device should minimize this hazard.

Economic Feasibility

Timber barricades have been used on many construction projects in Virginia in recent years. Their costs have varied; \$22.97/m (\$7.00/ft) for furnishing, maintaining, and relocating them is representative of most costs in 1973. More current experience in Virginia displayed a price of \$24.61/m (\$7.50/ft) for furnishing and maintaining the barricades and an additional \$4.92/m (\$1.50/ft) for relocating them.

The average barricade cost for I-495 was \$43.96/m (\$13.40/ft) and \$20.08/m (\$6.12/ft) for relocation. Based on the total project cost, the timber barricades on I-495 cost over \$5 million, or 6.6 percent of the entire project.

The fact that timber barricades have been furnished on projects at less cost in other parts of the state does not necessarily mean that the costs on I-495 were unreasonable. Differences in local material costs and labor rates significantly affect the cost of barricades. The length of time to complete construction is also important, since longer projects require more maintenance. Another factor that affects the cost of maintenance is the volume of traffic using the roadway. Still another possible reason for the high cost of barricades is the practice of unbalanced bidding by contractors, since the barricades were one of the first items to be worked on.

CMBs have been used for many years as permanent positive barriers to separate opposing traffic on high-speed roadways. However, only recently have PCTBs been manufactured for temporary use during construction. Because of this relatively new practice, prices vary widely. The summary of cost information given in Table 10 is not a complete list of all projects that have used PCTBs but is representative of the historical data. Note that the larger projects, where economies of scale may have come into play, experienced the best prices.

Given the price experience of Virginia and other states and the current estimates by Virginia precasters, the temporary New Jersey-shaped concrete barrier could be purchased for $50 to $65/m ($16 to $20/ft), including delivery to the site, initial placement, and maintenance. The actual price would depend on the volume purchased and the lead time available to the barrier manufacturer. Indications from the construction industry are that relocation expenses during construction would be comparable to that charged for moving the timber barricade on I-495, approximately $20/m ($6/ft). A lower price may be realized if the units were rented from the precasters, since the previous prices are based on state ownership of the barriers when the project is completed.

Table 5. Distribution of crashes during construction by severity.

	Crashes Involving Barricade		Crashes Not Involving Barricade	
Crash Severity	Number	Percent	Number	Percent
Fatal	4	0.9	4	1.0
Injury	59	13.0	71	17.3
Property damage only	390	86.1	334	81.7
Total	453	100.0	409	100.0

Table 6. Distribution of crashes during construction by type of collision.

	Crashes Involving Barricade		Crashes Not Involving Barricade	
Type of Collision	Number	Percent	Number	Percent
Rear end	11	2.4	232	56.7
Fixed object	396	87.4	52	12.7
Sideswipe	40	8.9	95	23.2
Angle	3	0.7	13	3.2
All others	3	0.7	17	4.2
Total	453	100.0	409	100.0

Table 7. Distribution of crashes during construction by major causative factor.

	Crashes Involving Barricade		Crashes Not Involving Barricade	
Major Factor	Number	Percent	Number	Percent
Driver handicap (i.e., asleep)	26	5.7	6	1.5
Driving under the influence	142	31.4	32	7.9
Speeding	62	13.7	29	7.1
Inattention	113	24.9	302	73.8
Vehicle defective	21	4.6	10	2.4
Road slick	7	1.5	12	2.9
Forced off road	63	13.9	5	1.2
All others	19	4.3	13	3.2
Total	453	100.0	409	100.0

Table 8. Distribution of crashes during construction by time of day.

	Crashes Involving Barricade		Crashes Not Involving Barricade	
Time Period	Number	Percent	Number	Percent
Early morning (12:00 m.n. p.m. to 7:00 a.m.)	148	32.7	41	10.1
Morning peak (7:00 a.m. to 9:00 a.m.)	34	7.5	54	13.2
Midday (9:00 a.m. to 4:00 p.m.)	111	24.5	150	30.6
Afternoon peak (4:00 p.m. to 6:00 p.m.)	43	9.5	75	18.3
Evening (6:00 p.m. to 12:00 m.n.)	117	25.8	81	19.8
Total	453	100.0	409	100.0

LEGAL REQUIREMENTS

In order to receive funds under the federal-aid system, a state must comply with two acts of Congress: the Federal-Aid Highway Act of 1973 as amended and the Highway Safety Act of 1973. The former requires, among other things, that road design be conducive to safety and that states comply with U.S. Department of Transportation (DOT) safety standards. The latter requires that states comply with uniform safety standards set by DOT.

Federal-Aid Highway Act of 1973

The Federal Highway Administration standards promulgated under the Federal-Aid Highway Act of 1973 are contained in the Federal-Aid Highway Program Manual (FHPM) (6). These rules are binding. The FHPM sets forth a number of specifications relating to items ranging from highway markers to pavement design; however, it offers no specifications for temporary barriers used during construction. The manual does, however, list all other publications that are applicable to federal-aid highway projects. These other publications are separated into three groups: (a) standards and specifications, (b) policies, and (c) guidelines. There are 12 publications in the first group, 7 in the second, and 17 in the third. The FHPM (6) provides that "approval may be given to plans, specifications, and estimates that are found to be in conformance with [these references]." Further, it states that "approval may be given to designs on a project basis which do not conform [to the first and second groups] only after due consideration is given to all project conditions such as maximum service and safety benefits for the dollar invested." The publications in the last group, guides, "are not project requirements and no specific approval for deviations from the guides is required."

The following publications, cited in the FHPM, are directly or indirectly applicable to the subject at hand.

1. Standards and Specifications—Part VI of the Manual on Uniform Traffic Control Devices (MUTCD) (7);
2. Policies—A Policy on Design of Urban Highways and Arterial Streets 1973 (8); and
3. Guides—Highway Design and Operational Practices Related to Highway Safety (9) and Guide for Selecting, Locating, and Designing Traffic Barriers (10).

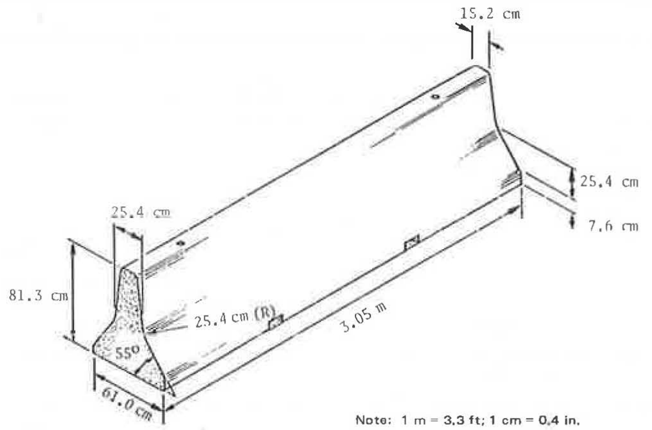
Part VI of the MUTCD is the only federal standard to provide specific information concerning practices in traffic operations. The MUTCD states that the logical goals for traffic-control devices in the construction zone are to guide drivers, minimize damage to errant vehicles, and protect workers. However, the manual does not identify any device that can fulfill the goals it sets forth for a situation similar to the widening of I-495.

A Policy on Design of Urban Highways and Arterial Streets lists the geometrics desirable in the final design of freeways, arterial streets, collector and local streets, and interchanges, along with various other pieces of information, such as provisions for buses and parking. It has a brief section called "Maintaining Traffic During Construction," but it concerns itself largely with capacity considerations and refers the reader to the MUTCD.

Highway Design and Operational Practices Related to Highway Safety deals generally with the safety of finished roads, such as forgiving roadsides and traffic operations. It includes a chapter entitled "Construction and Maintenance Operations," which indicates the necessity for a clear recovery area or positive barriers between work areas and passing traffic.

The Guide for Selecting, Locating, and Designing Traffic Barriers superseded National Cooperative Highway Research Program Report 118 in May 1977 as the guide to be used in selection, location, and design of permanent traffic barriers. The basic criteria for selecting and locating permanent traffic barriers can also be applied when using temporary barriers in work areas.

Figure 4. A New Jersey-shaped precast concrete traffic barrier.



Note: 1 m = 3.3 ft; 1 cm = 0.4 in.

Highway Safety Act of 1973

Pursuant to the Highway Safety Act of 1973, 18 uniform safety standards have been promulgated by the Federal Highway Administration and the National Highway Traffic Safety Administration. Highway Safety Program Standard 12, Highway Design, Construction and Mainteenance (11), requires that every state shall have a program of highway design, construction, and maintenance to improve highway safety. Further, it states that the program shall provide, as a minimum, that "there is guidance, warning, and regulation of traffic approaching and traveling over construction of repair sites and detours." The extremely general nature of this regulation was not designed to require or bar the use of any reasonable device.

Occupational Safety and Health Administration

The Occupational Safety and Health Administration (OSHA) has also promulgated rules for worker protection at roadside construction activities. The Safety and Health Regulations for Construction (29 Code of Federal Regulations § 1926) dictates that no contractor shall require any laborer to work in surroundings hazardous or dangerous to his or her safety, as determined by OSHA regulations. Those regulations require that, for the protection of employees, barricades shall conform to the requirements of the MUTCD, and further that, if signs, signals, and barricades do not provide the necessary protection adjacent to a highway, flagmen or other appropriate traffic controls shall be provided.

Subsequent FHWA Action

At the time this study was conducted, there were no

Table 9. Extent of vehicle contact with timber barricade.

	Arrested and Redirected		Straddled		Penetrated		Total Involved	
Vehicle	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Automobile	103	27.6	99	26.6	170	45.7	372	81.4
Truck	15	20.5	25	34.2	33	45.2	73	16.0
Tractor trailer	2	22.2	4	44.4	3	33.3	9	2.0
All others	1	33.3	1	33.3	1	33.3	3	0.6
Total	121	26.5	129	28.2	207	45.3	457	100.0

Table 10. Historical cost experience of PCTBs.

Year	State	Quantity (m)	Price ($/m)	Delivery ($)	Placement ($)	Removal ($)	Comments
1969	California	8475	16.40	U	U	U	Price may include delivery, placement, and removal but information was unavailable
1970	Idaho	U	23.62 to 26.25	I	6.56 to 7.87	U	Idaho was first state to employ concrete barriers for temporary use (1968)
1972	Illinois	U	39.37 to 65.62	I	4.76 to 34.34	U	Project was on Illinois Tollway
1974	North Carolina	3350	57.41	I	I	4.10 (est.)	Will be moved into permanent median position
1974	Washington	N/A	24.57	5.35	U	U	Contractor produces for inventory. State is responsible for placement and removal
1974	Oregon	N/A	15.16	5.68	U	U	Contractor produces for inventory. State is responsible for placement and removal
1974	Florida	1750	65.62	I	I	I	Price included delivery, placement, and four moves during construction
1974	Florida	3960	36.09	I	I	I	Price included delivery, placement, and four moves during construction
1974	Virginia	80	130.00	I	I	I	Barriers are now being used on another project at no cost
1975	Washington	N/A	40.06	I	I	I	Precaster retains ownership
1975	Oregon	N/A	26.90	I	I	I	Precaster retains ownership
1975	Virginia	15 to 30	82.02	I	I	U	Bridge parapet bolted to the deck
1975	Virginia	400	71.03	I	I	U	Removal is assumed to be included

Notes: 1 m = 3.3 ft.
I = included, U = unknown.

federal requirements that would prohibit the use of the timber barricades or the PCTBs. However, the Federal Highway Administration, aware of the study results on I-495, contracted with the Southwest Research Institute to conduct crash tests on the timber barricade. The crash tests were conducted in November 1976 and confirmed the study results. Based on this information, the Federal Highway Administration issued FHWA Notice N 5160.27 on February 2, 1977, which states in part,

> It has been concluded that effective immediately, 'Timber Barricades' shall not be approved for use on direct federal or federal-aid projects as a positive barrier at any speed.

CONCLUSIONS

The more than doubling in the frequency of accident occurrence during the construction study period reflects a need for improved control of traffic through high-volume, high-speed roadway segments undergoing construction. The high concentration of accidents at interchanges identifies them as roadway locations where extreme care should be exercised in the selection, installation, and maintenance of traffic-control devices. Though 52.5 percent of the reported crashes for the construction study period involved vehicle contact with the timber barricades, the possible degree to which the barricades contributed to the overall increase in accidents is not known.

The timber barricades did not prove to be effective as positive barriers for the traffic conditions in the I-495 construction zone, since 73.5 percent of the vehicles impacting the barricades straddled or penetrated them. Because of the lack of information on the performance characteristics of the PCTB in construction zones, crash tests and field evaluations are needed. There is a need for a national guide to aid in the selection and use of temporary barrier systems in construction zones.

ACKNOWLEDGMENTS

Bernard J. Reilly and Melvin D. Beale, graduate assistants at the time of the study, made significant contributions to the study. The study was sponsored jointly by the Virginia Department of Highways and Transportation and the Highway Safety Division of Virginia. The opinions, findings, and conclusions expressed in this paper are mine and not necessarily those of the sponsoring agencies.

REFERENCES

1. F. N. Lisle, B. J. Reilly, and M. D. Beale. Evaluation of Timber Barricades and Precast Concrete Traffic Barriers for Use in Highway Construction Areas. Virginia Highway and Transportation Research Council, Sept. 1976.
2. J. L. Beaton and H. Peterson. A Report on Dynamic Testing of Various Designs of Highway Bridge Curbing. California Division of Highways, Dec. 1953.
3. E. F. Nordlin and J. J. Falson. Dynamic Tests of the California Type 20 Bridge Barrier Rail. HRB, Highway Research Record 348, 1971.
4. E. R. Post and T. J. Hirsch. Truck Tests on Texas Concrete Median Barrier. HRB, Highway Research Record 460, 1973.
5. E. R. Post, T. J. Hirsch, and G. G. Hayes. Vehicle Crash Test and Evaluation of Median Barriers for Texas Highways. HRB, Highway Research Record 460, 1973.
6. Federal-Aid Highway Program Manual. Federal Highway Administration, Vol. 6, Chapt. 2, Sect. 1, Subsect. 1, Oct. 1973.
7. Manual on Uniform Traffic Control Devices for Streets and Highways. Federal Highway Administration, 1971.
8. A Policy on Design of Urban Highways and Arterial Streets. American Association of State Highway Officials, Washington, DC, 1973.
9. Highway Design and Operational Practices Related to Highway Safety. American Association of State Highway and Transportation Officials, Washington, DC, 2nd ed., 1974.
10. Guide for Selecting, Locating, and Designing Traffic Barriers. American Association of State Highway and Transportation Officials, Washington, DC, 1977.
11. Highway Safety Program Standard 12: Highway Design, Construction, and Maintenance. Federal Highway Administration, Feb. 1974.

Publication of this paper sponsored by Committee on Traffic Safety in Maintenance and Construction Operations.

Accident Analyses of Highway Construction Zones

Jerry L. Graham, Midwest Research Institute, Kansas City, Missouri
Robert J. Paulsen, Howard Needles Tammen and Bergendoff, Kansas City, Missouri
John C. Glennon, Transportation Consulting Engineer, Overland Park, Kansas

Accident analyses were conducted for 79 construction projects in seven states. Results indicate an overall increase in the accident rate of 6.8 percent. Examination of accident rate differentials reveals that 31 percent of the projects experienced decreased accident rates during construction and that 24 percent of the projects experienced rate increases of 50 percent or more. Case study analyses of three projects with rate increases of 40 percent or more indicate that construction-related accidents were responsible for the accident rate increases.

Accident analyses were conducted by Midwest Research Institute as part of a larger investigation (1) aimed at developing design and operational criteria for safe and efficient traffic operations in construction zones. The accident study portion of the research examined the accident experience of construction zone roadways before and during construction. Data from seven states were used in the analysis. Trips were made to each state to obtain data. The data were classified into two major categories—construction data and accident data. Construction data include the type of construction, length, duration, traffic volumes, and traffic controls used. Accident data were reduced into several categories, such as type, location, time of occurrence, and severity. Forms were developed for recording both types of data to ensure uniformity of the data from each state.

The data were analyzed in four stages: (a) a comparison of the number of accidents before and during construction, (b) accident rates before and during construction, (c) a regression analysis with construction-zone characteristics as independent variables and accident rates during construction as dependent variables, and (d) three construction project case studies that included determination of construction-related accidents.

DATA COLLECTION AND REDUCTION

A data collection plan was developed prior to state visits. In order to choose projects that would provide a reasonable number of accidents, project selection criteria were developed that specified a minimum product that should be obtained when the length and the duration are multiplied. These criteria, developed from typical accident rates, were presented in a previous report (2).

The collection of project data on the initial visit to a state usually requires trips to district highway department offices. In most visits, current projects were visited and photographed to obtain a perspective on the relation of controls shown on the traffic-control plans and controls that were being used in the field. The table below gives the general categories of the 79 construction-zone sites selected for analysis.

Highway	Number of Projects Urban	Rural	Total
Six- to eight-lane Interstate	11	0	11
Four-lane Interstate	5	19	24
Four-lane divided	6	12	18
Five-lane undivided	3	0	3
Four-lane undivided	3	1	4
Two-lane	3	16	19
Total	31	48	79

Accident data for the period of construction and the period 1 year before construction began were requested for each project. Where possible, accident reports were requested for the period during construction and computer printout line summaries were requested for the period before construction. In some states, only hard copies of construction-related accidents were available or the state could only furnish hard copies on two or three projects.

The first stage of the analysis compared the number of accidents during construction with the number of accidents during the year before construction began. Where the construction period was 1 year or less, the comparison was performed simply on a month-to-month correspondence. Where the construction period exceeded 1 year, the accident numbers before construction were expanded by the ratio of the duration of construction to the duration of the period before. One drawback to this expansion is that it ignores the effect that seasons of the year have on accident types, severity, surface condition, percentage of night accidents, and total accident numbers. However, since only 27 percent of the projects are affected by the expansion, the seasonal effects were minimal when the total accident set was analyzed.

Table 1 illustrates the total number of accidents and percent change for all projects. The table shows a 7.5 percent increase in construction accidents. Fixed-object, rear-end, head-on, and turning accidents experienced large increases; however, ran-off-road accidents declined substantially. The number of night accidents increased by 9.4 percent. However, the percentage of night accidents to total accidents remained 30 percent both before and during construction. Accident severity had similar results. Although the number of fatal and injury accidents increased by about 5 percent, the percentage of these accidents to the total number of accidents remained a constant 29 percent both before and during construction. Also, rural accidents increased slightly more than urban accidents.

The rank order of the states by the percentage increase in accidents during construction is shown below.

State	Increase in Accidents During Construction Period (%)	Rank
6	-3.4	1
2	-1.0	2
5	+9.6	3
1	+9.9	4
3	+11.6	5
4	+21.0	6
7	+37.6	7

State numbers are used instead of names to keep the state identities anonymous. Two states actually experienced slight decreases in the number of accidents during construction; however, the percentage increase in accident numbers is sensitive to the type of projects in the state and the number of accidents before construction that are considered.

The accident numbers were further analyzed by a time-trend analysis of the month-by-month accident totals. For each project, the monthly differences between accidents during construction and those in the corresponding months in the year before construction were totaled. The month-by-month accident differentials were used to determine whether there was a time-trend effect in the construction-zone accident experience. Since only 1 year of data on accidents before construction were collected, a maximum of 12 monthly differentials were analyzed. For projects that lasted more than 1 year, data after the first 12 months of construction were not considered.

In addition to the time trend, the monthly differentials were also analyzed to determine the variability of accidents in construction zones among states, areas (urban or rural), and levels of speed reduction (speed reduction or no speed reduction). Only 65 of the 79 projects studied were used in this analysis, because the before data in state 2 were not broken down on a month-by-month basis.

The natural framework for the data is the (hierarchical) analysis of variance (AOV) model. Since some cells of this framework are missing, and since the sample sizes are unbalanced throughout, the AOV required is complicated. In order to produce working estimates of variable effects with a minimum of effort, an approximate AOV was executed in phases.

The AOV considers monthly responses as replicates, i.e., independent duplicate observations of accident dif-

Table 1. Total construction-zone accidents.

Item	Before	During	Change (%)
Total accidents	8172	8785	+7.5
Night accidents[a]	2454	2685	+9.4
Severity[a]			
Property damage only	4718	5226	+10.7
Injury	2369	2488	+5.0
Fatality	62	58	-6.5
	7149	7772	
Accident class			
Right angle	720	585	-18.8
Rear end	2614	3048	+16.6
Sideswipe	939	850	-9.6
Head on	99	114	+15.2
Turning	480	552	+15.0
Ran off road	706	520	-26.3
Roll	204	225	+10.3
Animal	84	102	+21.4
Fixed object	941	1307	+38.9
Fixed object (construction equipment)	-	120	N/A
Other	1385	1362	-1.7
	8172	8785	
Surface[a]			
Dry	4190	4870	+16.2
Wet	1467	1443	-1.6
Ice or snow	706	548	-22.4
Unknown	786	911	+15.6
	7149	7772	
Area			
Urban	4873	5149	+6
Rural	3299	3636	+10
	8172	8785	

[a]Includes data from six states only.

ferential. In practice, the sequence of monthly observations within any project might be correlated to time if, for example, the effect of construction is relatively immediate but tapers off after a few months.

Therefore, prior to the AOV, an examination of the monthly accident differential versus time (in months) was undertaken. The Spearman rank correlation coefficient (r_s) was computed for the 65 projects, with the result that no significant trends were observed. Only five of the 65 r_s's were statistically significant at $\alpha = 0.05$, and, of these, three were positive and two were negative. Also, the overall incidence of positive and negative r_s's was not significantly different from an equal partition [$X^2(1) = 2.46$]. These computations indicate no general or long-term association between construction effect and time after construction. Also, a comparison of the first month's response to their expected rank under the hypothesis of no significant short-term effect yielded an insignificant test statistic ($Z = 0.57$).

The overall average accident differential of +1.60 is significantly greater than zero ($t = 4.75$, $p < 0.01$). That is to say, on the average the construction zone caused a significant increase of 1.60 accidents/month. The increase is greater in zones with a speed reduction (5.58 versus 1.11) and greater in urban locations (6.22 versus 1.19).

State 5 had the worst record (9.21), state 3 was next (3.09), and the other four states were less (0.58 to 1.37). No state exhibited a negative accident differential, although states 1 and 6 are not significantly different from zero. The average monthly accident differential was 1.60, but the average accident differential by project was 2.11. Apparently, the shorter duration construction projects caused more incremental accidents than the projects that lasted 1 year or more.

ACCIDENT RATE COMPARISONS

Although comparative analyses using accident numbers provide useful information, the change in accident rates from the period before to the period during construction is a more meaningful measure of the effects of construction. Although data were available to compute accident rates for the before period (length, duration, accident number, and traffic volumes), for only two projects were traffic volume data available for the period during construction.

Two factors are of primary concern for an estimation of construction traffic volumes based on the before data. One is the expected annual increase in average daily traffic (ADT) on the subject projects. The other is the expected decrease in traffic volumes during construction caused by a reduction in the number of lanes, by a decrease in average speed, by a general annoyance to the traveling public, or by a combination of all three.

Since most of the construction projects sampled occurred in either 1974 or 1975, the before periods were 1973 and 1974 respectively. National statistics have shown that traffic volumes for these years were quite similar due to the energy crisis. Thus, on many projects the reduction effect of construction probably outweighed the annual increase in traffic volumes, resulting in an overall drop in traffic volumes.

The two projects that had traffic volume data for the period during construction were six-lane urban freeways, where two lanes were closed in each direction. Also, several entrance ramps were closed on each project. These projects experienced traffic reductions of 60 and 35 percent. Although these projects were unique in having two lanes closed, they do indicate that on similar projects traffic volumes probably decreased significantly.

Two-lane resurfacing and rural Interstate projects were also a significant percentage of the total number of projects analyzed. These projects probably did not experience any significant drop in traffic volumes. State 6 consisted entirely of rural Interstate projects during 1972. Traffic volumes from 1971 through 1973 in this state increased 10 percent annually. For this state, the accident rate increase may be overstated.

In conclusion, the construction projects probably had lower traffic volumes than in their respective periods before construction. Thus, the increases in construction accident rates are probably somewhat greater than the results indicate.

Although the lack of traffic volume data during the construction period forced a computation of construction accident rates using traffic volumes before construction, the accident rate analysis did provide a method for comparison of accidents before and during construction by using only documented accident data, not expanded numbers. Before data used were (a) 1-year prior to construction for projects of 1 year or longer and (b) corresponding months before construction for projects shorter than 1 year. Since four of the 79 projects had no before data, only the 75 projects with before and during data were used. Table 2 ranks the states by increase in construction accident rate. This table is very similar to the listing of the increase in accident numbers in Table 1, but does show some changes in the rankings. Probably the most interesting result is the large increase in accident rate experienced by state 4.

Although Table 2 shows only a 6.8 percent overall increase in accident rates, a more interesting analysis is the distribution of accident rate increases. Figure 1 shows that 31 percent of the projects experienced decreased accident rates during construction, while 24 percent of the projects experienced rate increases of 50 percent or more.

Table 3 shows how the type of road affects accident rates. For example, six- or eight-lane divided roadways reduced to one lane in each direction experienced a rate increase of 114.6 percent, but those reduced to two lanes in each direction experienced only a 5.3 percent increase. Two-lane highways reduced to one lane had a 30.7 percent rate increase, but those shifted to a new alignment had a 14.3 percent decrease. And finally, four-lane divided Interstate highways reduced to two-lane, two-way roads experienced an increase of 147.2 percent during construction, but those in which one lane was closed in each direction experienced a 68.6 percent increase in their accident rate. Unfortunately, only two projects were reduced to two-lane, two-way, so the reliability of these data is questionable.

The table below illustrates the mean accident rates for the various work area roadway types. The mean accident rate is the number of accidents per 100 000 000 vehicle-km (1 km = 0.6 mile).

Work Area Roadway	Number of Projects	Mean Accident Rate
Lane closure	48	127.64
Crossover	4	134.55
Temporary bypass	0	—
Detour	0	—
Lane closure and crossover	5	90.18
Lane closure and temporary bypass	4	317.49
Lane closure and detour	10	179.17
Crossover and detour	3	46.3
Temporary bypass and detour	1	262.09

Lane closures with temporary bypass roadways experienced the highest accident rate followed by temporary bypass roadways with detours. However, further investigation showed that the lane closure with temporary bypass roadway had a mean accident rate before construction of 453.23/100 million vehicle-km; thus the accident rate decreased by 30 percent during construction. Also, the temporary bypass with detour work area roadway had an accident rate of 69.68/100 million vehicle km before construction; thus its construction accident rate went up substantially. However, since the work area roadway types were distributed so disproportionately (over 60 percent were lane closures), no major conclusions can be drawn from this analysis.

Table 4 illustrates the mean accident rates for the various types of construction. The construction types were distributed relatively evenly; bridge work and reconstruction of existing roadways experienced the highest percentage accident rate increases. The former had a substantial increase in raw accident rate of 61.24/100 million vehicle-km.

The table below illustrates the percentage increase in accident rates of urban and rural projects. The mean accident rate is the number of accidents per 100 000 000 vehicle-km (1 km = 0.6 mile).

Area	Mean Accident Rate: Before Construction	Mean Accident Rate: During Construction	Change (%)
Urban	170.96	190.44	+11.4
Rural	87.78	96.62	+10.1

This analysis shows that urban projects experienced a slightly higher percentage increase in accident rates. Also, their increase in accident numbers (31.16) was higher than that for rural projects (14.14).

Table 5 illustrates the severity rate experienced by state and by the total data set. States 4 and 7 experienced the largest increases in injury accident rates. Overall, the property-damage-only accident rate increased by a slightly higher percentage than the injury

Table 2. State ranking by increase in mean accident rate.

State	Number of Projects	Mean Accident Rate[a]: Before	Mean Accident Rate[a]: During	Change (%)	Rank
2	9	142.21	129.33	-9.1	1
6	15	75.13	72.95	-2.9	2
1	16	167.65	181.68	+8.4	3
3	10	178.96	143.63	+10.4	4
5	10	118.31	135.95	+28.2	5
7	5	130.49	179.61	+37.6	6
4	10	165.78	267.75	+163.16	7
Total	75	127.45	136.09	+6.8	

Note: 1 km = 0.6 mile.
[a]Number of accidents per 100 000 000 vehicle-km.

Figure 1. Project accident rate change.

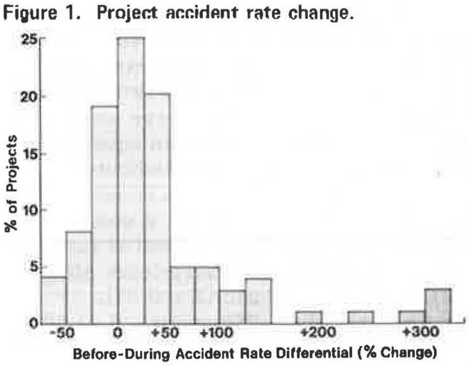


Table 3. Effect of degrading various road types.

Roadway	Number of Projects	Mean Accident Rate[a]: Before Construction	Mean Accident Rate[a]: During Construction	Change (%)
Six- or eight-lane Interstate reduced to two lanes each direction	8	121.23	127.64	+5.3
Six- or eight-lane Interstate reduced to one lane each direction	3	142.44	305.76	+114.6
Four-lane Interstate reduced to one lane each direction	22	85.10	143.47	+68.6
Four-lane Interstate reduced to two lanes, two-way	2	25.43	62.86	+147.2
Four-lane divided reduced to one lane each direction	5	196.71	225.91	+14.8
Four-lane divided reduced to two lanes, two-way	5	110.68	128.23	+15.9
Four-lane divided on new alignment	6	155.68	125.33	-19.5
Four-lane undivided reduced to two lanes	3	500.91	476.24	-4.9
Five-lane undivided with two-way left turn lane reduced to two lanes	3	305.15	485.09	+59.0
Two-lane reduced to one lane	7	227.14	297.33	+30.7
Two-lane on new alignment	11	397.98	340.96	-14.3
Total	75			

Note: 1 km = 0.6 mile.
[a]Number of accidents per 100 000 000 vehicle-km.

Table 4. Mean accident rate by type of construction.

Construction	Number of Projects	Mean Accident Rate[a] Before Construction	During Construction	Change (%)
Resurfacing, pavement patching	26	92.33	99.40	+7.7
Bridge work	5	55.17	82.79	+50.1
Median barrier work	15	116.97	127.42	+8.9
Widening of existing roadway	12	360.69	370.76	+2.8
Upgrading to Interstate standards	9	104.78	121.65	+16.1
Reconstruction of existing roadway	2	174.36	232.48	+33.3
Construction of new roadway (new alignment)	5	133.43	133.92	+0.4
Other	1	85.85	85.85	0.0

Note: 1 km = 0.6 mile.
[a]Number of accidents per 100 000 000 vehicle-km.

Table 5. Mean accident severity rates by states.

State[a]	Number of Projects	Property Damage Only[b] Before	During	Δ (%)	Injury[b] Before	During	Δ (%)	Fatal[b] Before	During	Δ (%)
1	16	133.45	146.73	+9.9	33.14	34.44	+3.9	1.05	0.51	-51.8
3	10	116.28	127.12	+9.3	59.38	65.25	+9.9	0.98	0.87	-7.9
4	10	122.35	200.29	+63.7	42.98	56.50	+33.0	0.95	0.42	-55.9
5	10	67.1	78.81	+17.4	49.79	55.43	+11.3	1.42	1.71	+20.3
6	15	50.98	49.16	-3.6	23.13	22.91	-1.0	1.03	0.89	-13.4
7	5	92.61	126.28	+36.4	37.89	53.64	+41.7	0	0	0
Total	66	76.81	80.63	+5.0	37.07	38.48	+3.8	0.99	0.90	-8.9

Note: 1 km = 0.6 mile.
[a]Data were not available for state 2.
[b]Number of accidents per 100 000 000 vehicle-km.

rate, and the fatal accident rate decreased.

Accident rate comparisons were also made between projects that had reduced lane widths and projects that maintained normal lane widths. The six projects with reduced lane widths during construction experienced a 17.6 percent increase in accident rates during construction and the 69 projects with normal lane widths experienced a 6.6 percent increase in accident rates during construction. Projects with and without speed reductions were also compared. Urban projects showed a 14.0 percent increase without speed reductions and a 6.0 percent increase with speed reductions. Rural projects, however, showed a 2.6 percent increase without speed reductions and a 16.4 percent increase with speed reductions.

REGRESSION ANALYSIS

The third stage of the analysis involved multiple regression analysis of the data using 17 independent variables and computing their relationship to 17 various accident rates during construction (dependent variables). The list of independent and dependent variables used in the multiple regressions is given below (note that Y_1, the total accident rate, was for the period during construction only).

Independent Variables	Dependent Variables
X_1 = state number (1 to 7)	Y_1 = total accident rate
X_2 = project number (1 to 79)	Y_2 = night accident rate
X_3 = project length	Y_3 = property-damage-only accident rate
X_4 = duration (days)	Y_4 = injury accident rate
X_5 = road type	Y_5 = fatal accident rate
X_6 = primary construction road type	Y_6 = nonreportable accident rate
X_7 = secondary construction road type	Y_7 = right-angle accident rate
X_8 = primary work area road type	Y_8 = rear-end accident rate
X_9 = secondary work area road type	Y_9 = sideswipe accident rate
	Y_{10} = head-on accident rate
	Y_{11} = turning accident rate
X_{10} = type of construction	Y_{12} = ran-off-road accident rate
X_{11} = area (urban, rural)	Y_{13} = overturning accident rate
X_{12} = normal speed limit	Y_{14} = animal accident rate
X_{13} = speed reduction	Y_{15} = fixed-object accident rate
X_{14} = daily traffic effect	Y_{16} = fixed-object (construction device) accident rate
X_{15} = control status	Y_{17} = other accident rate
X_{16} = lane width (normal, reduced)	
X_{17} = traffic control method	

The initial screening regression run indicated strong correlations between many of the dependent variables. For this reason, several dependent variables were eliminated from further regressions. Also, several of the independent variables were moderately correlated. This correlation of independent variables was largely due to the way the independent variables were chosen, and changes in the classification of the variables for later regressions were made based on these results.

The 17 dependent variables account for about 38 percent of the variability of the total accident rate (adjusted R^2 = 0.385) and considerably less for the other dependent variables studied.

Based on the initial regression, it was apparent that many of the dependent variables were highly correlated and, therefore, a subset of the variables could be used in further investigations. This regression also revealed some problems of moderately correlated independent variables. For these reasons, another set of regressions were run, using only total accident rate and other dependent variables that seemed to differ radically from total accident rate. The independent variables were adjusted to remove those that were significantly correlated.

Table 6 gives the general results of the second multiple regression. For the regression of total accident rate, the original 17 variables were reduced to 6. However, the adjusted R^2 value only changed from 0.385 to

0.236. The order of the independent variables indicates that normal speed limit accounts for the largest portion of the variability of total accident rate, and that construction road type (primary) accounts for the least portion of the variability of the six independent variables. The prediction of the fatal accident rate and other accident rate were both very poor, indicating the lack of relationships between the construction-zone variables and fatal accident rate. Two other accident rates in Table 6 are of particular interest: fixed-object accident rate and the construction-object accident rate. The control status variable that refers to the way the work area moves within the construction zone is an important contributor to both types of fixed-object accident rates.

Further investigations were made by conducting linear regressions of both length and duration versus the total accident rate. A regression was done on the total project set and for each road type and construction road type and also by urban and rural projects. The results of the regressions are shown in Table 7.

In general, both the length and duration regression lines had negative slopes, indicating that the long length and duration projects normally had lower accident rates. Many of the regressions broken down by type of road and construction road were hampered by small sample sizes.

Table 6. Second multiple regression.

Dependent Variables	Adjusted R^2	Independent Variables (most to least important)
Total accident rate	0.236	Normal speed limit, area type, zone type, state, project, construction road type (primary)
Fatal accident rate	0.000	State, construction road type (primary), project
Overturn accident rate	0.342	State, type of construction, project
Animal accident rate	0.214	Length, project, state
Fixed-object accident rate	0.225	Construction road type (primary), control status, type of construction, project, state
Construction-object accident rate	0.273	Control status, project, traffic control devices and methods, daily traffic effect, state
Other accident rate	0.000	Zone type, construction road type (primary), state, project

CONSTRUCTION PROJECT CASE STUDIES

Three case studies of selected construction projects were performed. Each of the case studies presented findings about an individual project. The projects were not selected randomly. Hard copy accident reports were scanned, and the projects chosen were those that demonstrated a reasonably high number of construction-related accidents. The projects were chosen this way because this stage of the analysis was aimed at getting an idea of why accidents happen in construction zones.

Table 8 gives the results of the three case studies. Each study experienced an above average increase in the number of accidents during construction. The mean accident and fatality rates are given below in accidents per 100 000 000 vehicle-km (1 km = 0.6 mile).

Table 7. Linear regression results.

Regression	b	a	r^2	n
Length versus total accident rate (all projects)	-10.87	376.20	0.06	79
Duration versus total accident rate (all projects)	-0.23	362.28	0.03	79
Length versus total accident rate				
Six- or eight-lane Interstate	12.30	241.40	0.05	12
Four-lane Interstate	-4.39	197.65	0.22	24
Four-lane divided	7.26	200.61	0.07	15
Four-lane undivided	373.37	-21.37	1.00	2[a]
Five-lane undivided with two-way left-turn lane	-148.14	1 572.50	0.84	3
Four-lane combined divided and undivided	20.13	76.81	0.33	4
Two-lane	-23.80	520.93	0.08	19
Duration versus total accident rate				
Six- or eight-lane Interstate	-0.78	460.76	0.29	12
Four-lane Interstate	-0.14	197.00	0.13	24
Four-lane divided	-0.10	280.95	0.02	15
Four-lane undivided	-49.53	14 469.0	1.00	2[a]
Five-lane undivided two-way left-turn lane	6.89	11.62	0.84	3
Four-lane combined divided and undivided	-0.07	166.14	0.73	4
Two-lane	0.10	353.80	0.01	19
Length versus total accident rate				
Two-way, two-lane reduced to one lane	-38.52	750.79	0.29	7
Four-lane divided reduced to one lane each direction	0.11	171.42	0.00	29
Four-lane divided reduced to two lanes each direction	-19.38	314.25	0.17	7
Six- or eight-lane divided reduced to two lanes each direction	-1.26	290.47	0.00	8
Six- or eight-lane divided reduced to one lane each direction	-4.00	536.77	0.04	3
Four-lane undivided reduced to two lanes	386.00	-313.71	0.55	5
Four-lane divided maintained, but on new alignment or mainline shift	-20.22	325.33	0.32	6
Two-lane highway maintained, but on new alignment or mainline shift	-20.10	425.81	0.05	12
Five-lane undivided with two-way left-turn lane reduced to two lanes	-119.57	1 335.34	1.00	2[a]
Duration versus total accident rate				
Two-way, two-lane reduced to one lane	0.48	367.51	0.02	7
Four-lane divided reduced to one lane each direction	-0.21	237.40	0.07	29
Four-lane divided reduced to two-way, two lanes	-0.15	281.10	0.14	7
Six- or eight-lane divided reduced to two lanes each direction	-0.56	388.74	0.17	8
Six- or eight-lane divided reduced to one lane each direction	-1.68	616.53	0.10	3
Four-lane undivided reduced to two lanes	-0.79	891.10	0.25	5
Four-lane divided maintained, but on new alignment or mainline shift	0.13	180.58	0.03	6
Two-lane highway maintained, but on new alignment or mainline shift	0.17	261.63	0.03	12
Five-lane undivided with two-way left-turn lane reduced to two lanes	15.89	-825.97	1.00	2[a]
Length versus total accident rate				
Urban	-10.78	485.66	0.01	31
Rural	-4.77	251.30	0.03	48
Duration versus total accident rate				
Urban	-0.25	486.75	0.02	31
Rural	-0.05	226.14	0.00	48

[a]Inadequate sample size.

Case	Mean Accident Rate		Mean Fatality Rate	
	Before Construction	During Construction	Before Construction	During Construction
1	33.8	47.5	0.8	1.4
2	116	270	–	–
3	116	326	–	–

The percentage of night accidents decreased in all three cases. The percentage of the types of accidents varied between the three studies. In all of the studies the percent of property-damage-only accidents increased during construction. All of the projects studied had a large proportion of accidents that were construction related. In case 1, 36 of 102 accidents were construction related; in case 2, 78 of 103 accidents were construction related; and in case 3, 8 of 14 accidents were construction related.

The determination of construction-related accidents was a central part of the case studies. The accident was judged construction related by reading the accident report and asking, "Was the accident precipitated or affected by the construction?" Or from the opposite point of view, "Would the accident have happened and been as severe if there were no construction under way?" Although judgment was involved, the judgments were made by experienced traffic safety personnel after thorough study of the project.

In each of the projects, the number of construction-related accidents was at least equal to the increase in accidents from the period before to the period during construction. In case 2, the construction-related number is high because of a high number of rear-end accidents that occurred when queues formed during the construction. Even if the rear-end accidents had not been classified as construction related, the other 29 construction-related accidents would be near the increase in accidents comparing the before and during periods.

The general impression gained from the case studies was that the accident experience of a roadway not only increases during construction, but also the overall characteristics of the accident histories are different from those of the periods before construction.

In the first two case studies, there was a definite predominant accident type, which if remedied could have reduced the number of accidents in the zone. In the first case study, accidents involving timber barricades were prevalent throughout the construction period. In the second case study the rear-end accident was predominant. Fixed-object and head-on or sideswipe accidents were nearly the entire set of construction-related accidents in the third case study.

Table 8. Case study summaries.

Accident	Before Construction (%)	During Construction (%)	Rate of Change (%)
Case 1 accidents			
Night	50	44	-6
Rear end and sideswipe	40	21	-19
Fixed object	15	38	+23
Head on	0	2	+2
Property damage only	38	57	+19
Injury	60	40	-20
Fatality	2	3	+1
Total accident increase	-	-	+42
Case 2 accidents			
Night	43	28	-15
Rear end and sideswipe	33	50	+17
Fixed object	16	9	-7
Head on	-	-	-
Property damage only	68	79	+11
Injury	32	21	-11
Fatality	-	-	-
Total accident increase	-	-	+49
Case 3 accidents			
Night	60	50	-10
Rear end and sideswipe	60	14	-46
Fixed object	0	44	+44
Head on	0	21	+21
Property damage only	60	86	+26
Injury	40	14	-26
Fatality	-	-	-
Total accident increase	-	-	+180

SUMMARY

Accidents occurring both before and during construction were analyzed using several methods. These included analysis of the time-trend effect of monthly accident differentials, total accident number analysis, accident rate analysis, and case studies of individual projects. In addition, regression analysis was performed on the construction accident rates.

The time-trend analysis showed that construction zones caused an average increase of 1.60 accidents/month. The total number of accidents increased by 7.5 percent and the accident rate increased by 6.8 percent. Thirty-one percent of the projects studied experienced decreases in accidents during construction; 24 percent experienced rate increases of more than 50 percent. The percent differences may be understated because of the lack of data about traffic volume during construction. The analyses assumed that traffic volumes were equal before and during construction; however, for many projects, the traffic volumes during construction were probably lower than those before construction. Three case studies of zones experiencing large increases in accident rates revealed that most of the increase was due to construction-related accidents.

Both the number of accidents and accident rate analyses showed very little difference in the distribution of accident severity in the comparison. However, both analyses showed a slight shift toward property-damage-only accidents. Both analyses show a great degree of variability in the number and rate of fatal accidents. This was supported by the regression analysis, in which there was very little correlation between the construction-zone variables and the fatal accident rate.

The proportion of night accidents to the total number of accidents remained relatively constant in both the number of accidents and accident rate analyses. Again, this was supported by a relatively high degree of correlation between night accident rates and total accident rates in the regression analysis. The linear regression analysis also indicated a strong correlation between traffic-control devices and construction fixed-object accidents and a poor correlation between construction-zone variables and ran-off-road accidents. Accident number analysis showed a substantial increase in fixed-object, head-on, and rear-end accidents, but a decrease in ran-off-road and sideswipe accidents.

The time-trend analysis showed that projects where speed limits were reduced (by regulatory or advisory signs) had higher monthly accident differentials than those without speed reductions. The accident rate analysis also showed that those projects with speed reductions had a slightly higher percentage accident rate increase. According to the linear regression analysis the project speed limit, which is highly correlated with area type, accounts for the largest portion of the total accident rate variability.

Road type accounted for 4 of the 30 highest correlations between construction zone and accident variables in the linear regression analysis. Accident rate analysis resulted in some interesting results concerning road types. Six- or eight-lane Interstate projects reduced to one lane in each direction had accident rate increases of over 100 percent, but those reduced to two lanes in each direction had increases of only 5 percent. The case studies showed that the one-lane projects experience a great number of rear-end accidents. Four-lane divided Interstate projects reduced to two-lane, two-way had percentage increases more than double those in which the roadway was simply reduced to one lane in each direction. Five-lane undivided highways with two-way left-turn lanes reduced to two lanes during construction experienced the largest accident rate increase of all road types. And finally, two-lane roads reduced to one-way alternating operations experienced worse construction accident rates than those placed on new alignment during construction.

The time-trend analysis indicated a much higher monthly increase in accidents in urban areas. However, since urban areas normally have higher accident numbers, this does not necessarily mean their construction accident experience is any worse. The linear regression analysis indicated a moderately high correlation between area type and total accident rate. The accident number and accident rate analyses both showed that construction accidents went up by a similar percentage in urban and rural areas.

The time-trend analysis showed that the first month after construction begins is not significantly different than the other months of construction and that construction zones do not necessarily have better accident experiences over time. The linear regression analysis showed a negative correlation between the length and duration of projects and the accident rate; thus, the longer the duration of a project (both in time and space), the lower the accident rate.

The accident rate analysis indicated that bridge work, followed by reconstruction of existing roadway (on the same alignment), experienced the largest percentage accident rate increases. Case studies of projects with large rate increases before to during construction showed a definite predominant accident type for each of the studies.

ACKNOWLEDGMENT

This paper is based on work done as part of a Federal Highway Administration contract entitled, "Design and Operating Speeds for Construction Zones." The findings and conclusions of this paper are our own and do not necessarily represent the views of the Federal Highway Administration. The statistical analyses reported in this paper were conducted by Michael C. Sharp, senior statistician, of Midwest Research Institute.

REFERENCES

1. J. L. Graham, R. J. Paulsen, and J. C. Glennon. Accident and Speed Studies in Construction Zones. Federal Highway Administration, Rept. FHWA-RD-77-80, June 1977.
2. J. A. Fee and others. Interstate System Accident Research Study—1. U.S. Department of Transportation, Oct. 1970.

Publication of this paper sponsored by Committee on Traffic Safety in Maintenance and Construction Operations.

Computer Model for Liquefied Natural Gas and Liquefied Propane Gas Risk Simulation

F. B. Silvestro and M. J. Mazurowski, Ecology and Environment Inc., Buffalo

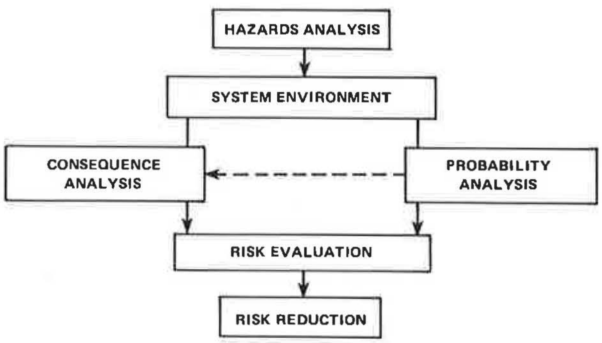
Early in 1971, the National Transportation Safety Board recommended a general framework for risk analysis of hazardous materials. The HAZ-EX computer program was developed to provide analysis of the risk to the public associated with the transportation of hazardous materials. The purpose of the program is to give project designers safety information on routes and sites during the planning stages of a project. The HAZ-EX program is a modular design whereby each module is an element of the risk analysis. The elements range from the simulation of spill dynamics to human injury criteria. The advantage of a modular approach is that updated data or alternative phenomenon descriptions can be inserted. The program capability includes material storage and ship, pipeline, truck, and rail transportation modes. Program-effects analysis capability includes prediction of injury due to toxicity, radioactivity, flammability, and explosivity. By selection of the appropriate combinations of modules, rapid comparisons can be made of site, transportation mode, transportation routes, and system alternatives. The HAZ-EX program has been applied to the storage and bulk transportation of liquefied natural gas and liquefied propane gas. The use of realistic injury and damage criteria as well as accurate physical phenomena description are extremely important. The advantage of a computerized model is speed. A few pages of computer output can apprise decision makers of the safety aspects of a proposed movement of hazardous materials. If a working definition of acceptable risks were then available, the reviewer could be easily satisfied as to the acceptability of an applicant's plans as proposed or whether modifications would be necessary. The efficacy of modifications can be evaluated by rerunning the model.

Liquefied gases will be an important source of energy in the coming decade. Liquefied natural gas (LNG) and liquefied propane gas (LPG) both offer environmentally sound response flexibility, especially since the technology has been developed to ship these products in bulk as cryogenic, or pseudo-cryogenic in the case of LPG, products rather than as liquids under pressure. However, such proposals have not been without controversy. A recent press report succinctly states the issues that must be addressed, "Critics... of the proposal... want to be certain it is as safe as possible." Hence, an important aspect of import and transshipment proposals for LNG and LPG is an understanding by project planners and systems designers of the attendant hazards and public risk of these products as they move through the transportation (including storage) network. While the products may be in varying states, the physical and chemical properties of the products of concern relate primarily to, hypothetically, spilled product. How such material properties could pose a threat and how such a threat can be eliminated or minimized is the object of hazards and risk analyses.

We developed an approach and an analytic computer program, called HAZ-EX, to systematically evaluate the transportation and storage of hazardous materials. The computer program design is consistent with the general framework recommended by the National Transportation Safety Board in that emphasis is placed on the initial and intermediate steps of the analysis (1).

The HAZ-EX program is a modular design, whereby each module is an element of the risk analysis. The elements range from the simulation of spill dynamics to human injury criteria. The program capability includes material storage and ship, pipeline, truck, and rail transportation modes. Program effects analysis capability includes prediction of injury due to toxicity, radioactivity, flammability, and explosivity. By selection of the appropriate combinations of modules, rapid comparisons can be made of site, transportation modes, transportation routes, and system alternatives.

Figure 1. Analytic approach.



The HAZ-EX program has been applied to the storage and bulk transportation of LNG and LPG as cryogenics. Exposure to injury and damage from thermal radiation, vapor cloud travel, and detonation were of interest. The use of realistic injury and damage criteria as well as accurate physical phenomena description are also extremely important. The first step of a hazards analysis (see Figure 1) is a hypercritical examination of the proposed transportation and storage system, the properties of the hazardous material, a definition of failure or accidental events, and a detailed description of the environment in which the project would be implemented, i.e., the system environment. The methodology of fault-tree and failure mode analysis is applicable in this approach (2). The output of the analysis is the definition of credible accidents or failure events.

The system environment refers to the aggregate of all external factors that could possibly affect the system or be affected by the system and its credible failure events. The system environment may include factors such as traffic patterns, demography, land use planning, precipitation, wind speed distribution, failure or accident statistics of similar existing systems, severe storm and flood occurrences, and seismicity. The environment in which the proposed system is to operate may, to a large extent, determine the probability of accidents or failure events and their consequences. The importance of such data cannot be overstated with respect

Figure 2. Hazards consequence analysis.

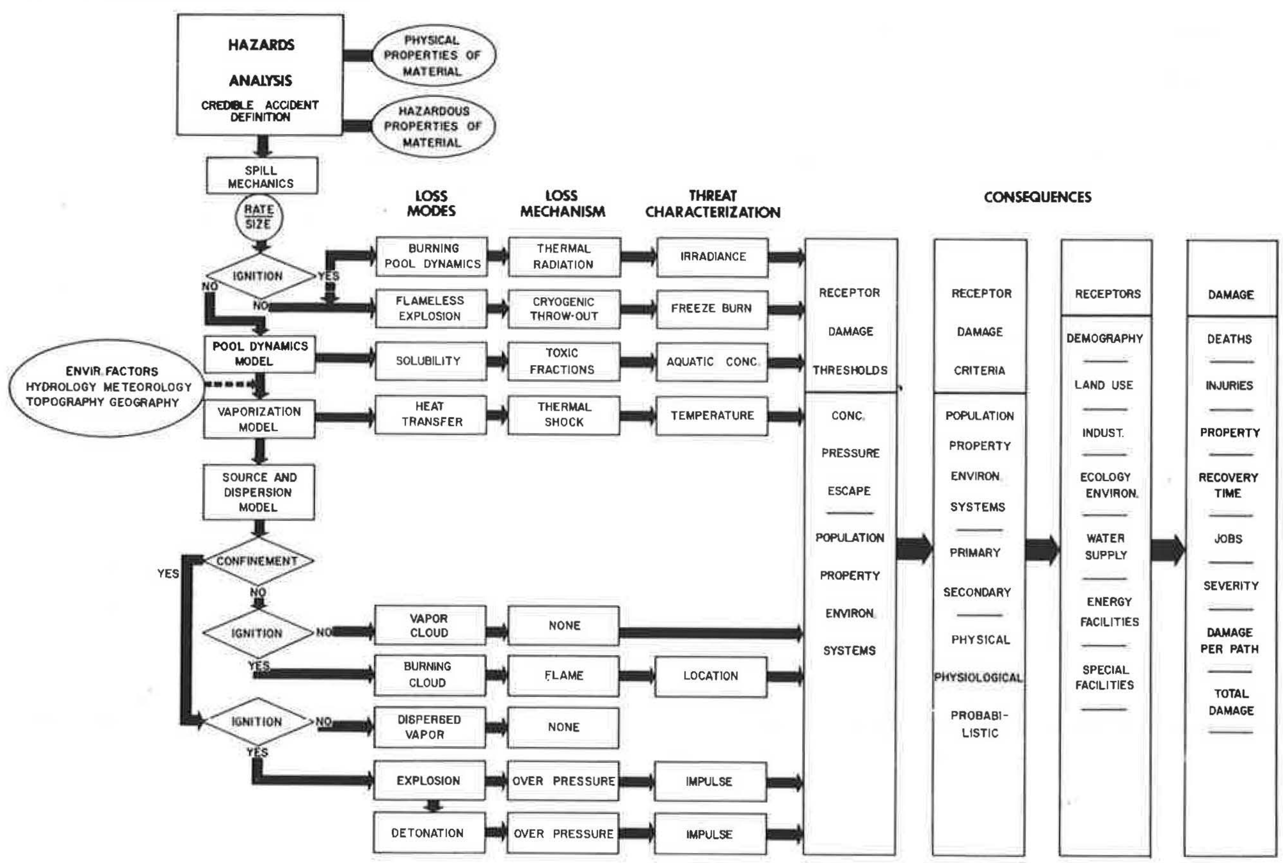


Table 1. Elements of risk analysis.

Hazard	Consequence	Probability	Risk	Evaluation and Mitigation
Material properties	Physical spill models	Spill producing accidents	Exposure to damage	Identify peaks
Project definition	Loss modes	Spill size, rate	Damage	Everyday activities
Accident statistics	Loss mechanisms	Environmental conditions	Exposure range	Other materials
Transportation corridor	Threat characterization	Design conditions	Probable range of damage	Other activities
Fault tree	Damage thresholds	Loss modes		Sensitivity
Accident scenarios	Damage criteria	Damage severity		Operational guidelines
Mitigating factors	Physiological models			
Regulatory requirements	Definition of receptors			
Credible accident scenarios	Damage			
	Damage occurrence			
	Temporal relations			
	Possible range of effects			

to routing, siting, and operating an LNG-LPG system.

The analysis of the consequences of credible accidents is perhaps the most controversial aspect of a risk analysis. In this step of the analysis the dynamics of a spill or product release are described (i.e., modeled) and the implications to population and property are determined. The various pathways and elements of the consequence analysis for LNG and LPG can be viewed in the form of a logic diagram (Figure 2). For each credible accident, the appropriate spill, spread, vaporization, and dispersion models are available in the HAZ-EX program to describe spills in water, releases from pressured pipelines, and releases from ruptured tank trucks. When and whether or not ignition or confinement occurs in the development of the accident scenario are important factors in determining which and perhaps how many loss mechanisms could be realized. The various branch points in the sequence are of course probabilistic in nature and to a great extent depend on the event that causes the release and the environment in which it occurs. For example, in a collision scenario in which a cargo tank of a cryogenic LNG or LPG tanker was penetrated, immediate ignition would likely occur. Based on oil tanker experiences, the probability of ignition is between 0.9 and 1.0 (the certain event). The probability of immediate ignition is not as high for accidents involving pressurized tank trucks, rail cars, and liquid pipelines, since failure of the containment vessel attributed to nonpenetrating damage is an additional consideration, as are rocket effects of the containment vessel in some cases.

Each path in the consequence tree leads to a characterization of the threat element (Figure 2). In the HAZ-EX program, the threat characterization expresses the relation between the loss mechanism and spatial-temporal distance. Accurate threat characterization is a necessary ingredient of a safe, yet realistic, system design.

Once the threat is known, the consequences of hypothetical accidents can be examined. The outcome is the damage. For some threats precise data on specification of thresholds or criteria may be lacking, and it may be somewhat tempting to be conservative and accept low-threshold criteria in order to be on the safe side when dealing with long-term exposure to materials whose threats may be unknown, cumulative, and unavoidable. There is no similarity to LNG-LPG where the threats are well enough known to allow definition of effective mitigation actions and the assignment of mitigation priorities in order to achieve a safe project. Nevertheless, such guidelines must be predicated on realistic damage criteria or else the planners and designers will be misled.

Some of the guidelines, for example, suggest the use of a thermal radiation criteria of 5-s exposure to 17 MW/m^2 (1500 $Btu/ft^2 \cdot s$) in order to determine a safe distance. Experimental data indicate that exposure to such a level for five times the duration on bare skin leads to blistering, somewhat akin to common sunburn (3). The above concept is not only conservative but also technically flawed. A dosage approach is technically more correct and more realistic in that the human response to the threat (i.e., to flee or seek shelter in a shadow) and subsequently the determination of the need and form of countermeasures can be evaluated. The vulnerability model and the effective dosage approach of determining resulting physiological effects is employed in the HAZ-EX program (4). However, the dosage concept is used carefully in the HAZ-EX program since there is a threshold irradiance level below which no significant injury will occur. For LNG-LPG fires involving even massive, unconfined spills of 25 000 m^3 (32 700 yd^3), the time duration of a fire would only be about 6 to 8 min. Hence, in the HAZ-EX program the threshold level is taken as 14 MW/m^2 (1230 $Btu/ft^2 \cdot s$). Time-integrated exposures above this level are used to determine human fatalities for those who take no protective action and to determine the availability of time and the need to flee or seek shelter.

PROBABILITY ANALYSIS

In the development of an accident and the determination of its safety impacts, probabilistic concepts enter in a number of ways. When and where a spill could occur, what environmental conditions could exist, and the response of receptors are questions for which the answers are probabilistic in nature. In terms of the ultimate risk values, probability values enter both as multiplicative and additive factors. An uncertainty in a specific probability factor may relate to uncertainty in the result in a complicated way; indeed, a significant uncertainty in a specific probability value may be of no significance in the result. One of the advantages of a computerized approach such as HAZ-EX, is the ability to perform sensitivity analyses rapidly.

Determination of some of the needed probability values is relatively straightforward, e.g., reliable wind velocity probabilities can be obtained from sources such as the STAR program (5). Others, especially where and when, and also how large, a spill could occur are not so straightforward. The salient probability aspects in the overall context of the risk methodology presented here is of a general nature; however, the items are slated specifically toward LNG-LPG analyses (see Table 1). The probability item indicated as design conditions is particularly relevant with respect to flammable vapor clouds composed of methane or propane gas (and perhaps certain other gaseous products). Specifically, the possible range of effects for vapor clouds relates to parameters such as soil moisture state, if a spill were on ground, wind velocity, and atmospheric stability.

RISK

Once the hazard, consequence, and probability analyses have been completed, the computation of the risk is anticlimactic and straightforward. The distinctions between the risk of exposure to damage and the risk of damage is perhaps most evident if the question of human injury and fatality risk is examined. The risk of exposure would be a numerical probability value on an annual per person basis of being within the possible range of effects, whereas the risk of damage for the exposed population is the annual per person probability of being injured or fatally injured. The difference between the two relates to fatality thresholds, protection, and countermeasures. The range of effects, perhaps both distance and time, associated with either risk measure is useful for analysis of transportation corridors.

A comparison of the project risk values or peaks to other activities and a sensitivity analysis comprise the risk evaluation step of the analytic approach. In the evaluation step, sensitivity analyses will pinpoint critical areas or perhaps assumptions requiring further scrutiny.

The discovery of risk peaks and an examination of their origin points the way for needed mitigation actions, including perhaps operational restrictions. A risk peak is a combination of circumstances of either or both consequence and probability origin that contributes a significant portion of the risk. The computerized HAZ-EX program is of significant value in identifying and pinpointing peaks and risk reduction considerations.

In summary then, a few pages from the computer output can apprise decision makers of the safety aspects of the proposal. If a working definition of acceptable risks were then available, the reviewer could be easily satisfied as to the acceptability of the applicant's plans as proposed or whether modifications would be necessary.

REFERENCES

1. Special Study—Risk Concepts in Dangerous Goods Transportation Regulations. National Transportation Safety Board, Jan. 1971.
2. H. Napedensky. Risk Assessment, Methodologies. LNG Risk Assessment Symposium, Institute of Gas Technology, Chicago, Feb. 10, 1977.
3. A. Stoll and C. Greene. Relationship Between Pain and Tissue Damage Due to Thermal Radiation. Journal of Applied Physiology, Vol. 14, No. 3, 1959, pp. 373-382.
4. Vulnerability Model. U.S. Coast Guard, U.S Department of Transportation, Rept. CG-D-136-75, June 1975.
5. STAR Program. National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Asheville, NC.

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

Crash Testing of Nuclear Fuel Shipping Containers

Robert M. Jefferson and H. Richard Yoshimura, Sandia Laboratories, Albuquerque

In an attempt to understand the dynamics of extra severe transportation accidents and to evaluate state-of-the-art computational techniques for predicting the dynamic response of shipping casks involved in vehicular system crashes, a program was organized to investigate these areas. This program, which began in 1975, encompasses the following distinct major efforts. The first of these uses computational methods to predict the effects of the accident environment and, subsequently, to calculate the damage incurred by a container as the result of such an accident. The second phase involves the testing of one-eighth-scale models of transportation systems. Through the use of instrumentation and high-speed motion photography, the accident environments and physical damage mechanisms are studied in detail. After correlating the results of these first two phases, a full-scale event, involving representative hardware, is conducted. To date two of the three selected test scenarios have been completed. Results of the program to this point indicate that both computational techniques and scale modeling are viable engineering approaches for the study of accident environments and physical damage to shipping casks.

For the past several years the U.S. Energy Research and Development Administration (ERDA) through the Division of Environmental Control Technology has pursued a coordinated program to address the problems and perspectives of the transportation of radioactive materials. A part of that program has been the collection and analysis of data on the frequency and severity of accidents involving trains, highway vehicles, and aircraft within the United States. Significant correlations of these data, along with the basic data collection, are contained in the Transportation Environment Data Bank at Sandia Laboratories (1). This information has been used in a variety of programs.

As significant as this data collection is in the determination of the risk of exposure to accidents in the transportation segments of the nuclear fuel cycles, it does not relate the severity of the accident to the damage inflicted on the containers used to ship radioactive materials. ERDA recognized this need and initiated programs to evaluate that relationship. The first such program involved testing of full-scale casks in severe environments at Oak Ridge and Sandia. Following successful completion of these tests, full-scale testing of complete cask transport systems in highway and rail transport modes was initiated.

When these two programs are completed, it should be possible to predict the probability of causing various levels of damage to shipping containers as the result of transportation accidents. The remaining step is to correlate package damage and release fractions (i.e., the consequences of damage). Although the transportation tests conducted to date have resulted in no release of contents or release of only some portion of the coolant, concerns have been expressed as to what would happen if the cask were to be breached by accident or by any other means. Future programs may be required to provide these correlations. However, it should be noted that some currently used models assume releases of 1, 10, and 100 percent of volatiles and gases as accident severity increases to the extreme (2). But, even with such conservative release fractions, the risk to the public is still found to be very low.

PRELIMINARY TESTING

To prepare for full-scale testing of spent nuclear fuel shipping systems, we conducted drop tests of obsolete spent-fuel casks to demonstrate the integrity of containers in severe environments (3). In 1975, two lead-shielded containers were dropped 610 m from a helicopter onto undisturbed soil at Sandia's Edgewood, New Mexico, test site to determine damage caused by an extreme accident environment. Both of the containers used in this test were considered obsolete because they did not meet current fire requirements.

One cask, a simple cylindrical unit weighing 3 Mg, used for handling irradiated test capsules, penetrated 2.4 m into the hard prairie after impact at 396 km/h. The cask suffered no measurable deformation. At Oak Ridge National Laboratory, an identical cask was subjected to the standard drop test of 9 m onto an unyielding surface at their drop-tower facility (4). This cask suffered significantly more deformation and lead slumping due to the high deceleration forces incurred at impact. Weld failures also occurred in the outer shell of the cask as the result of the 9-m drop. However, this cask would have still safely contained the contents without release.

The second cask, a simple cylindrical unit mounted on a rectangular base plate weighing 7.4 Mg, had previously been used to ship and store spent fuel from an Oak Ridge research reactor. It penetrated 1.3 m after impact at 371 km/h. This cask experienced superficial deformation that would not have resulted in release of contents. The lead shielding slumped 20 mm as the result of deceleration forces during impact. Matching tests to the regulatory specification were not conducted on this cask.

These tests revealed that although the velocities were substantially higher, impact onto the hard prairie soil damaged the casks much less than the impact onto unyielding targets used in the 3-m regulatory drop test.

Objectives

Little information exists on the response of casks to the environments to which they might be subjected in actual accidents, since at the time of an accident casks are not generally instrumented nor are cameras available to record events. As part of the program, therefore, full-scale shipping casks and transport systems were subjected to very severe accident environments.

The test program has two major objectives:

1. To assess and demonstrate the validity of ERDA's analytical and scale-modeling programs for prediction of damage in accident conditions by comparison of predicted results with actual test results, and
2. To gain quantitative knowledge of extreme accident environments by measurement of the response of full-scale hardware under actual crash conditions.

The tests were not intended to validate present regulatory standards promulgated by federal agencies.

The full-scale test program was approached in three separate phases:

1. Mathematical analyses,
2. Scale-model tests, and
3. Full-scale tests.

Once the accident scenarios were chosen, the effects of this environment on the cask transport system were determined by both quasi-static and dynamic structural analyses. Calculations of the strength of materials estimated the static strength of critical parts of the structure. The dynamics of the system were studied by a previously validated and tested lumped-parameter computer code. Once the system dynamics were understood, parametric and sensitivity studies on the transport system were readily made. Damage to the cask was calculated with a finite-element code using input parameters estimated from the lumped-parameter code calculations.

The second phase of the program used scaling techniques to assess the damage to the container and transport systems in ⅛ scale. Structural models of the cask and transport system were constructed and subjected to scaled crashes. Results of the scale-model tests were then correlated with the analytical studies.

Full-scale testing to confirm the results was the final phase of the program. Since full-scale crash tests are spectacular events, considerable interest has been generated in the program. All tests were observed by representatives from industry and the government, private citizens, and the media.

Test Scenarios

In selection of test scenarios, primary consideration was given to exposing the cask to very severe accident environments, amenability of the test to analyses and scale-model testing, and test costs. Response to the concerns of government, industry, and the public was also considered. A serious effort was made to select test scenarios that could be conceived as realistic and yet, on the basis of accident data on hand, were extremely severe. Substantial consideration was also given to the ability of test engineers to conduct the test properly without failures resulting from problems with the test setup. For instance, rail car roll-over and broadside skids with tractor-trailer rigs into massive barriers, which are difficult to perform in a repeatable manner, were rejected as unfeasible. Test scenarios were also considered that would trade an increase in severity for simplifications in the calculation and testing procedures.

On the basis of these criteria, the selected accident scenarios were

1. Crashes of a tractor-trailer rig carrying a spent nuclear fuel cask into a massive concrete barrier at 100 and 130 km/h,
2. High-speed (130 km/h) impact of a locomotive into a truck-mounted spent nuclear fuel cask at a simulated grade crossing, and
3. Impact at 130 km/h of a special rail car carrying a spent nuclear fuel cask, followed by exposure to a fire.

ANALYSES

Before the full-scale tests were conducted, extensive analyses were performed to predict the response of the systems. These analyses considered the impact of

Figure 1. SHOCK tractor-trailer model.

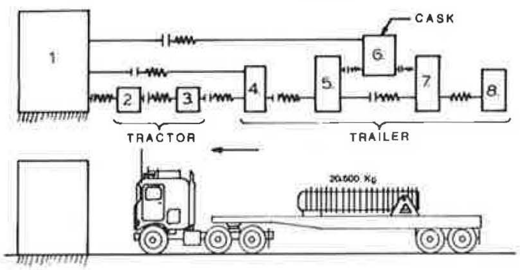


Figure 2. Analytical and scale model results for HONDO mesh: (a) undeformed and (b) deformed.

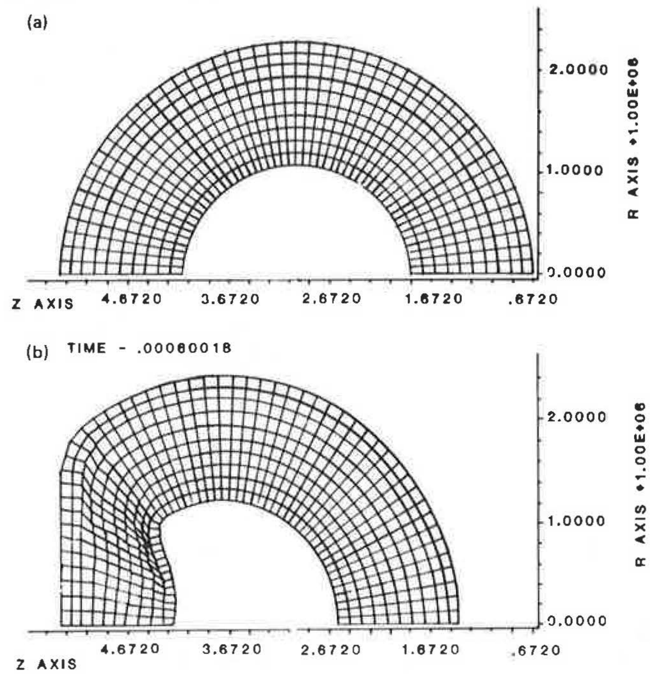
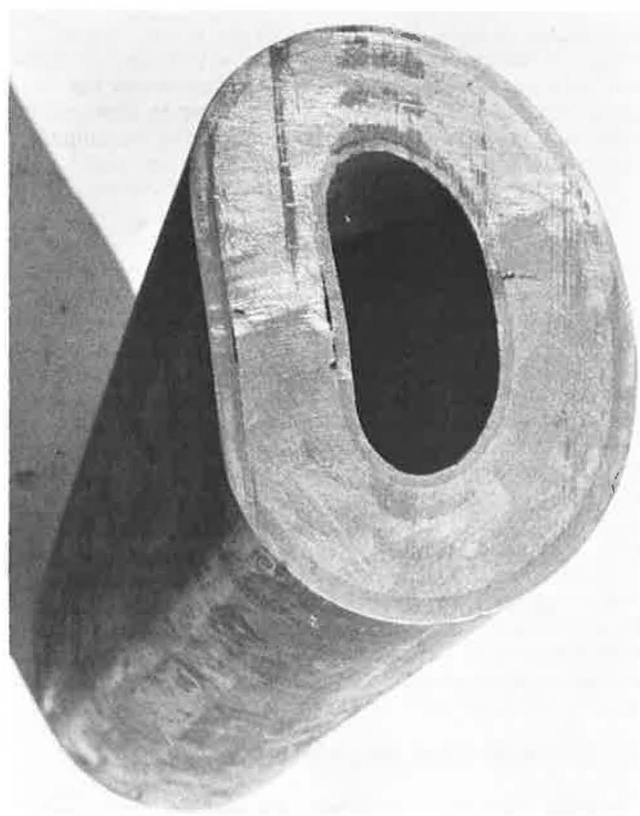


Figure 3. Cask deformation.



isolated casks on unyielding surfaces and entire transportation systems, including the impact of the cask on the same surface. In the first instance, the analyses gave insight into the generic behavior of lead-shielded casks. In the second, the analyses helped predict the behavior of the cask and transport system when subjected to the transportation accident environment.

The full-scale tests were analyzed by validated computer codes, including both lumped-parameter and dynamic finite-element models.

Lumped-Parameter Model (SHOCK code)

The overall systems were analyzed by SHOCK (5), a one-dimensional lumped-parameter code. With this code the system is represented by discrete masses and couplings. The coupling definitions are based on analytical estimates of the load-displacement behavior of the structure. Large permanent deformations are approximated by a hysteresis coupling. In addition to a hysteresis coupling, linear springs are also used in the models to represent elastic behavior.

Mathematical models for the three full-scale tests were constructed using this SHOCK code (6). Figure 1 illustrates the model for the tractor-trailer impact. Here the system, including the target, is modeled with eight discrete masses and ten couplings. Mass 1 (the target) is held fixed, and the remaining masses are given initial velocities equal to the velocity of the test impact. In this model, coupling 3 and 4 represent the tractor-trailer kingpin connection, and couplings 5 and 6 and 6 and 7 simulate the cask tiedowns. Couplings 1 and 4 and 1 and 6 represent the interactions between the end of the trailer and the target and between the cask and target. These are given appropriate amounts of travel without loading. The rest of the couplings represent frame elements.

Dynamic Finite-Element Modeling (HONDO code)

To better understand the generic behavior of casks subjected to severe impacts, some finite-element modeling was performed. Initially, a side impact was analyzed with the HONDO (7) code to understand the dynamics of a side-on cask impact into an unyielding surface. HONDO is a dynamic finite-element program that can model large deformations in two-dimensional or axis-symmetric solids. For the problem of a side impact, the code was modified to restrain node movement past the plane. The cask body was assumed to be in a state of plane strain and was given an initial velocity equal to the impact velocity.

Figure 2a illustrates the mesh for a model cask (6). The cask cross section, including the outer and inner shells and the lead shielding, is modeled. Figure 2b illustrates the severely deformed mesh after a 130 km/h side-on impact.

Figure 3 illustrates the $^1/_8$-scale model cross section after a side-on impact into a steel target at the same velocity. As can be seen, quantitative agreement is good between the code and the scale-model results.

SCALE-MODEL TESTING

Evaluation of damage from free drops of full-scale shipping containers into essentially unyielding surfaces has been previously used as one of the bases for qualifying spent-fuel casks. Such testing is expensive, particularly since simpler, less expensive techniques are available. Many studies have shown the applicability of scale-modeling techniques for studying the structural response of structures impacting into hard surfaces (8, 9). Recently, scale-modeling techniques have been applied to study the structural response of shipping cask systems subjected to severe transport environments. These techniques are described in greater detail elsewhere (10).

In order for scale-model testing to be useful, parametric and dimensional analyses must be conducted. On this basis, the scale hardware can be designed either as replica models (which are exact geometric material models) or as adequate models (which, while allowing some geometrical simplifications, will produce meaningful results). Both replica and adequate models have been used in this program.

Scale-model testing of the casks took two forms. Casks without their associated transport systems were subjected to varied impact conditions to gain a better understanding of damage mechanisms. Later the cask and its entire transport vehicle were modeled and tested to determine the total system response.

FULL-SCALE TEST EQUIPMENT

Financial constraints affected both test definition and equipment procurement. Because current-generation spent-fuel shipping casks cost from $500 000 for truck casks to $3.5 million for rail casks, it was necessary to use used or retired equipment. Out-of-service and older shipping cask systems, used commercial truck tractors, and a military surplus locomotive were obtained and modified to make them more representative of current designs. The casks used in the test program were similar in weight to modern casks; where they differ, the weight difference has been shown to be of little importance in the accident environment. In some cases, modifications such as impact limiters were made on the casks to make them more representative of current equipment. Every effort was made to obtain transport vehicles for the test program that were similar in both structure and weight to those actually in service. Therefore, the use of obsolete transport equipment had no effect on the results of the test program since computer analyses and scale-model test techniques are equally valid on both old and new equipment.

The three casks used in this test series, although differing in size, are of the same basic construction. Each has an inner and outer steel shell, with the annular region between filled with lead for shielding. In each case, the head is attached to the cask body with bolts. The casks used weigh from 20 to 62 Mg.

Truck-Cask Impact Tests

In the truck-cask impact tests, an obsolete spent-fuel cask weighing 20.5 Mg was obtained complete with its normal transport trailer and tiedowns. In its original configuration, the cask was mounted with the head facing the rear of the trailer. Since most modern casks are shipped head forward, this test cask was reversed on the trailer to simulate current transport conditions. The cask was attached to the tiedown structure by bolted connections at the base and head of the cask. In reversing the cask, the original bolted and welded connections were duplicated to secure the tiedown structure to the trailer. Balsa-wood impact limiters designed by the techniques currently in use were added to the cask to evaluate the effectiveness of impact-limiting devices in accident situations.

A standard cabover, tandem-axle, diesel-powered tractor was procured for the test. Although the tractor was considered obsolete and worn out, the structural members of the tractor were in excellent condition. An identical tractor and trailer, complete with tiedown structure, was obtained for the higher velocity test to replace the rig demolished in the first crash. The cask, which was practically undamaged in the first test, was equipped with a new front-impact limiter and reused in the second test.

The impact target used in these tests was designed to be massive and rigid. It consisted of a heavily reinforced 626 Mg concrete structure, backed by more than 1580 Mg of earth. For all practical purposes, considering the masses and velocities involved in the tests, the target is essentially unyielding. An object of this size and weight is rarely, if ever, found along normal truck routes. To save costs, this target is also to be used in the special rail car impact test.

Grade-Crossing Test

For the grade-crossing test, a 23-Mg cask, complete with trailer and tiedown structure, was obtained. The cask, similar in construction to the cask used in head-on barrier tests, was mounted on the trailer by a band tiedown system, as shown in Figure 4. A tandem-axle, gasoline-powered tractor supported the cask and trailer during the test.

A military surplus 109-Mg diesel-electric locomotive was obtained for the grade-crossing test. This locomotive was originally powered by a V-12 diesel engine through six traction motors in two three-axle trucks. Since the engine needed extensive repairs and was not required to accelerate the locomotive to the test speed, the pinion gears were removed to allow the locomotive to free-wheel. The weight of the engine and alternator in this design is supported by two I-beams that extended to the length of the locomotive. Although lighter in weight, the locomotive construction is quite similar to that of modern locomotives.

Impact and Fire Test of a Rail Car and Cask

In the impact and fire test of a rail car and cask system, a 68.2-Mg rail car with a 61.8-Mg rail cask has been obtained for testing. This cask, while similar in construction to those tested earlier, is larger and capable of containing more spent-fuel elements. The special rail car system, which is equipped with three-axle trucks, is shown in Figure 5. Secondary cooling systems are shown at both ends of the car.

PROGRAM RESULTS

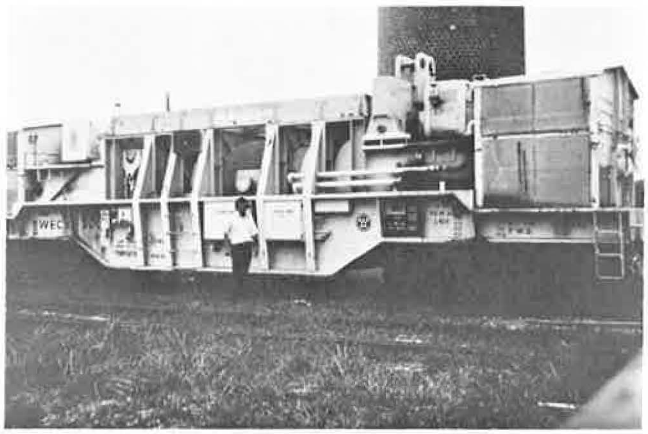
Truck-Cask Tests at 100 km/h

The basic dynamic response of the truck-cask tests was investigated analytically by a mathematical lumped-parameter model using the SHOCK code. As previously described, computational results from this model estimated expected deformations, displacement time, and velocity time histories for the transport system components.

A parametric study was performed to obtain information over a possible range of system responses.

Figure 4. 15 x 140 cask used in grade-crossing test.

Figure 5. Rail car system.



Most notably, the strength of the tiedown structure was varied to depict the reasonable limits of responses.

As indicated on Figure 6, when the tiedown is assumed to either not fail or fail late in the impact (favorable), the cask was continuously slowed as the components of the transport system crushed. Under these conditions, the container should impact the wall at less than 48 km/h (13.3 m/s).

In the worst-case condition (unfavorable) the tiedown structure in the SHOCK model was intentionally weakened so that the container would break away early in the impact, with little reduction in velocity. This resulted in the prediction of a large velocity change at impact with the wall, as shown in Figure 6. Such a large velocity change would crush the impact limiter and cause cask deformation. The favorable response condition was determined to be the more realistic case. From the graph, the cask impact velocity with the target would be about half of the initial velocity of the system. In this case, the impact limiter, designed for the 9-m drop test (impact velocity 13.4 m/s), would reduce the velocity of the cask even further, resulting in no structural deformation to the cask. The code predicted only partial crushup of the impact limiter.

Scale-Model Test

A $\frac{1}{8}$-scale model of the cask transport system shown in Figure 7 was tested at our rocket sled track facility. To assess damage to the cask structure, an adequate model (excluding fins) of the cask and impact limiter was constructed. The tractor-trailer model was designed with emphasis on the major masses and structural elements. Only those elements expected to contribute

Figure 6. SHOCK predictions.

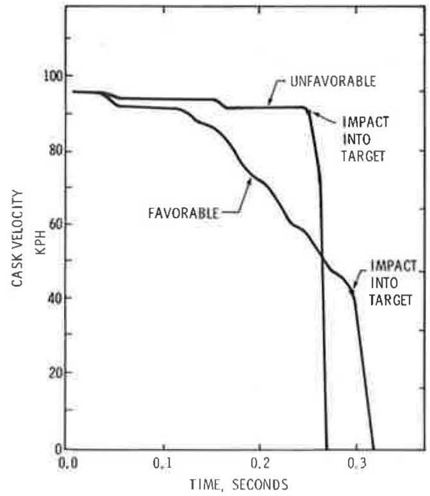
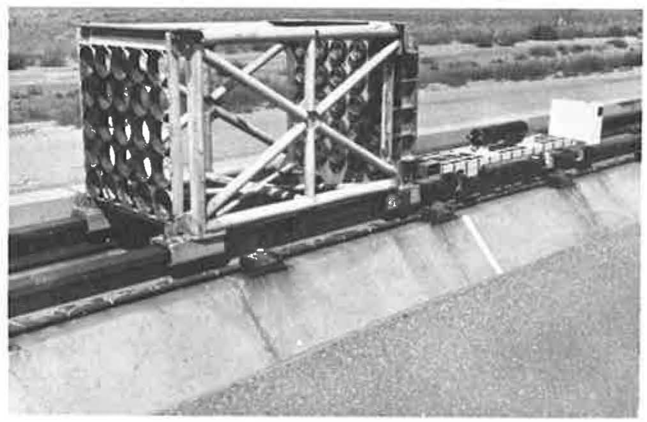


Figure 7. Cask transport model.



significantly to the cask dynamics were included. The model, therefore, simulated the major dynamics and resultant damage expected in the full-scale test.

Using a rocket, the model transport system was propelled into a scaled concrete wall at 97 km/h. A posttest view of the damage is shown in Figure 8. Scale-model results agreed closely with analytical predictions. High-speed data films showed that the transport and cask system response closely followed that predicted in the case where the tiedown did not fail. The impact limiter was partially crushed, and the cask was undamaged, except for minor deformations around the tiedown attachment points.

Full-Scale Test

The first tractor-trailer test was conducted on January 18, 1977. Before testing, the cask was loaded with an unirradiated Savannah Core II reactor fuel assembly ballasted to the weight of a conventional pressurized water reactor (PWR) fuel assembly. The thermal environment of a normal spent-fuel cask, which contains an irradiated spent-fuel subassembly, was simulated by heating the test cask to 66°C. About 160 kg of water coolant were included in the cask to simulate its normal shipping environment. Rocket motors propelled the transport system up to speed, after which the tractor-

Figure 8. Posttest damage—scale-model test.

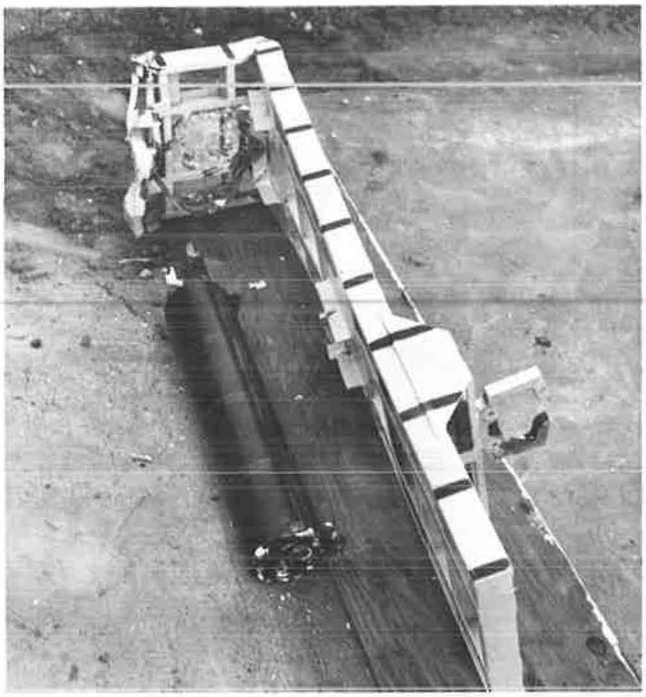


Figure 9. Posttest accident view—97.8-km/h test.

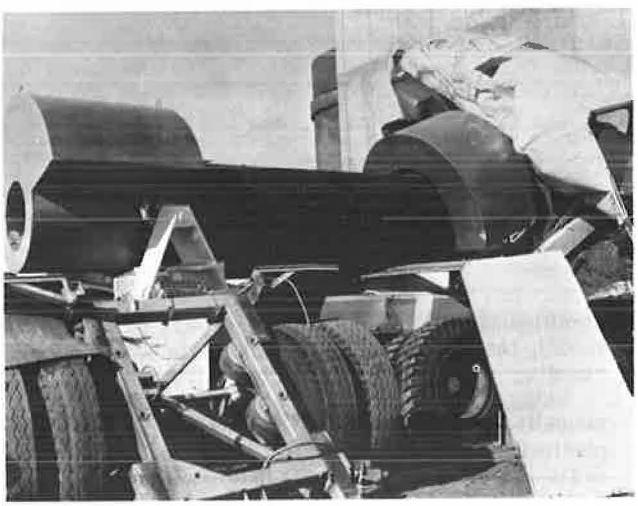


Figure 10. Comparison of SHOCK results.

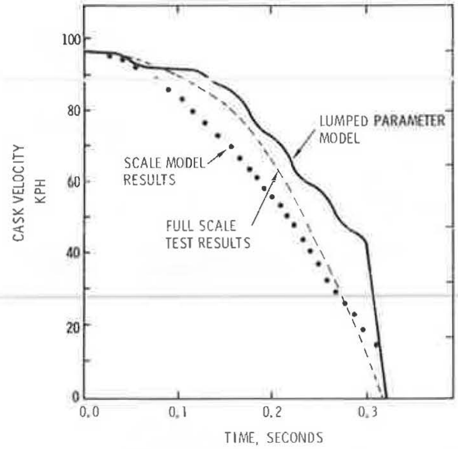
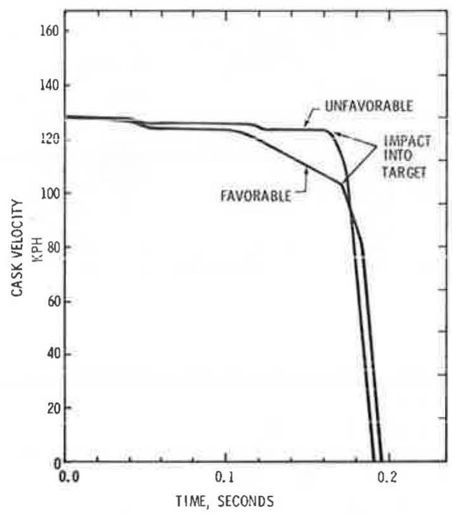


Figure 11. Pretest SHOCK comparison—130-km/h test.



trailer rig, guided by rails, coasted into the impact zone at 97.8 km/h.

As predicted by the conclusions drawn from both the analytical and scale-model test results, the tractor was completely destroyed in the crash. The tractor's fifth-wheel attachment failed, and the trailer moved forward through the cab to impact the wall. Crushing and buckling upwards, the trailer and other crushed structure gradually reduced the velocity of the cask to about half of its original impact velocity. The impact limiter then contacted the bent trailer and other debris to slow the cask even further. Although the tiedowns did not break loose during impact, posttest inspection of the debris indicated that the cask tiedowns had almost failed. The cask remained horizontal, as predicted, until impact with the crushed debris and wall. Forces to the cask were limited by crushing of the tractor-trailer structure and by the compressive strength of the balsa wood in the impact limiter. Following the main impact, the cask and trailer rotated to about 30° relative to horizontal and returned to the roadbed in front of the target.

Figure 9 shows the posttest condition of the cask and transport system. The cask remained intact and sustained only superficial damage to the external fins and piping. Instrumentation near the cask head indicated strains below the yield strength of the material. Rigid body accelerations on the cask were about 20 g's. The cask head was easily removed, and the fuel assembly was found to be intact and undamaged.

Overall response of the cask-transport system agreed well with pretest analytical and scale-model predictions. A quantitative comparison of the results is shown in Figure 10 (11), which illustrates both calculated and measured velocity-time histories.

Truck-Cask Impact Test at 130 km/h

For the second test, the same lumped-parameter SHOCK model was used to calculate the transport system response to a higher initial velocity (130 km/h). Again, the tiedown parameters in the model were varied to obtain information for a range of system response. Figure 11 shows the favorable and unfavorable system response calculated by the SHOCK model (11). Note that the curves for the two responses are not as widely separated as in the first case. This indicates that the system completely expends its capability to absorb kinetic energy during crushup, even in the favorable case. The influence of the tiedown structure would, therefore, have less effect in this test; the predicted impact velocity of the cask into the wall varied from 105 to 122 km/h. Since the structure of the trailer was identical to that of the trailer used in the 100-km/h test, it was assumed that the tiedown response would be similar; that is, the tiedowns would follow the favorable response curve and the impact velocity of the cask would be approximately 105 km/h.

To further analyze the damage to the cask, a finite-element computer code, HONDO, was used to calculate deformations to the cask with the SHOCK impact velocity as the input parameter. Figure 12a shows a finite-element model of the test cask before impact into an unyielding surface (11). Both the outer and inner steel shells are modeled with small elements. The lead, shown between the steel shells, has coarser elements. Figure 12b shows the test cask after a 105-km/h impact. Although bulging of the impacted end is significant, static analysis of the cask-head closure bolts indicated that the bolts would not fail. It was also predicted that the deformations might be severe enough to the head to cause minor seepage of fluid from within the container.

Scale-Model Tests

In the scale-model system tests, a test at the exact impact velocity of the second full-scale truck-cask impact test was not performed. Therefore, test results cannot be readily compared. Other scale-model tests of casks without their associated transport systems produced results that agreed with the HONDO predictions.

Full-Scale Test

Since the cask sustained little damage in the first test, it was cleaned, repainted, and remounted on an identical trailer. A similar cabover tractor was obtained for the second test. The cask was again loaded with a Savannah Core II fuel assembly, filled with water, and heated to 66°C.

The second truck-cask impact test was conducted on March 16, 1977, at a velocity of 135 km/h. As predicted by pretest analyses, the tractor and trailer were demolished. The fifth wheel failed, and the trailer moved forward through the cab and buckled. As predicted, portions of the impact limiter in contact with the cask were completely crushed, even though the tiedowns held until the final stages of impact. The cask again remained horizontal through the initial impact and rose with the trailer much as in the first test. Both cask and trailer came to rest in the upright position in front of the target.

Figure 13 shows the condition of the cask and transport system after the second test. After removal of the cask from the trailer, seepage at a rate of about 2 drops/min was detected from the cask head. The seepage later stopped after release of about 100 cc of fluid. Inspection of the cask revealed that the head was peened onto the cask and that the front of the cask had bulged. Several dents found on the surface of the cask head (Figure 14) were caused by the impact of the trailer fifth-wheel pin, which was forced in front of the cask by buckling of the trailer. Slight bending of the front portion of the cask occurred due to nonsymmetric impact conditions. As predicted, the front portion of the cask was permanently deformed (bulged). Rigid body accelerations measured on the cask were about 70 *g*'s (11). The cask head was removed with great difficulty. Inspection of the fuel assembly revealed deformation of the impact end. Some fuel-pin buckling occurred; however, no clad failure was detected.

The overall response of the cask transport system agreed well with pretest analytical predictions. A quantitative comparison of the results is shown in Figure 15 (11), which illustrates both the calculated and measured velocity time histories. Posttest measurement of model- and full-scale cask diameters and lengths revealed close agreement between measured deformations.

Grade-Crossing Test at 130 km/h

An analytical investigation of a grade-crossing accident involving the 130-km/h impact of a 186 Mg locomotive into a 22.7-Mg spent-fuel cask at a grade crossing was performed as the first step in this portion of the program (12). In this analysis, various configurations were evaluated. The first involved a superstructure impact in which the frame of the locomotive passes beneath the cask. Results of this analysis indicated that cask damage would be limited to minor deformations from impact with the engine-alternator unit of the locomotive. The second configuration involved a full-frame centerline impact between the cask and locomotive. This impact condition would occur only if the cask is placed on a lowboy transport trailer that is not used to transport current commercial spent-fuel casks. This analysis indicated that the cask would be moderately deformed after a centerline impact with the locomotive frame.

Later investigation of current shipping-cask configurations indicated that either a glancing frame or superstructure impact would occur in a two-track rural grade-crossing collision. The glancing frame impact, the more severe case, was selected for the full-scale test.

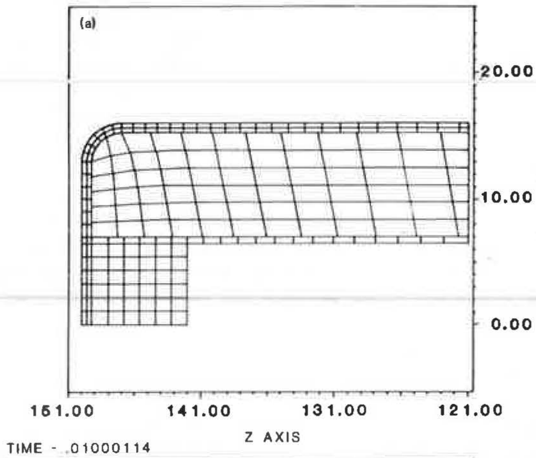
The major thrust of the remainder of the analysis involved using the finite-element HONDO code. The frame and cask impact condition is depicted in Figure 16. The HONDO model indicated that the twin I-beams of the frame would be crippled and form a ramp, causing the cask to be lifted into the superstructure. Once into the superstructure, the forces acting on the cask would be limited by crush up of the thin structural shell of the locomotive. Since the impact forces generated by the frame would be limited by crippling of the I-beam members, the increasing locomotive or train mass would cause a negligible increase in damage to the cask.

Scale-Model Test

One-eighth scale models of the test locomotive and cask-trailer system were constructed. The major structural elements and masses of the locomotive were modeled to adequately simulate the dynamic response of the structure (Figure 17). The front end of the frame of the model locomotive was accurately modeled to duplicate the full-scale locomotive.

The model locomotive was accelerated by a small rocket to an impact velocity of 126 km/h. In this scaled impact, the frame of the locomotive struck the cask a glancing blow. As predicted by the analyses, the I-beam section of the frame failed by buckling to form a ramp that lifted the cask into the superstructure (Figure 18). Posttest inspection of cask damage showed that the fins were scraped away by the frame and that two 2.5-mm depressions were formed at the point of impact with the

Figure 12. HONDO model: (a) preimpact and (b) postimpact.



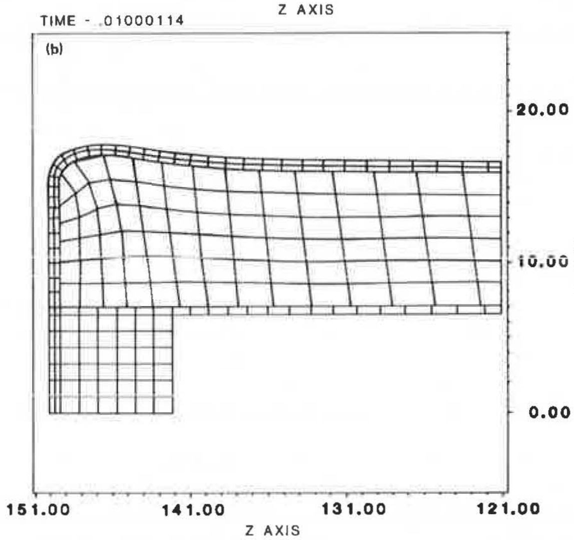


Figure 13. Posttest view—130-km/h truck test.

I-beams, but the cask shell was not ruptured.

Full-Scale Test

The locomotive grade-crossing test was conducted on April 24, 1977. The test cask was loaded with a fresh Savannah Core II fuel assembly. Rockets accelerated

Figure 14. Cask head—130-km/h truck test.

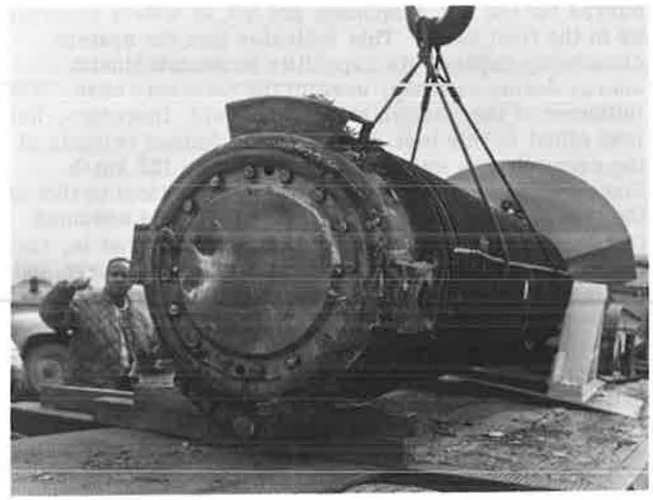
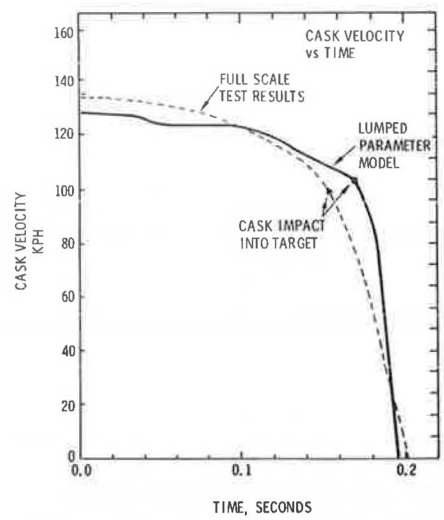


Figure 15. Comparison of analytical and full-scale results.



the 109-Mg locomotive to test speed (Figure 19), after which it coasted to an impact at 131 km/h. As predicted by pretest analysis and scale-model test results, the frame of the locomotive was crippled and formed a ramp, which allowed the cask to rise into the superstructure (Figure 20). As shown in Figure 21, failure of the locomotive frame closely resembled that in the model test. After superstructure crush up, the cask rolled to the right side of the locomotive, tumbled in the dirt, and came to rest between the rails. Posttest inspection of the cask indicated that the deformation behavior of the cask was very similar to that of the scale model. Two 26-mm depressions, which were caused by the impact with the I-beam members of the frame, were left on the surface of the cask. Leak testing of the cask after impact indicated a small leak in the head seal when the cask was pressurized. This leakage, had the cask contained water, would have caused essentially no risk to the public. The cask head was removed without difficulty and the fuel assembly was found to be intact. There was some bowing of the fuel pins; however, no clad failure was detected.

Comparison of the damage to the cask and locomo-

Figure 16. HONDO model.

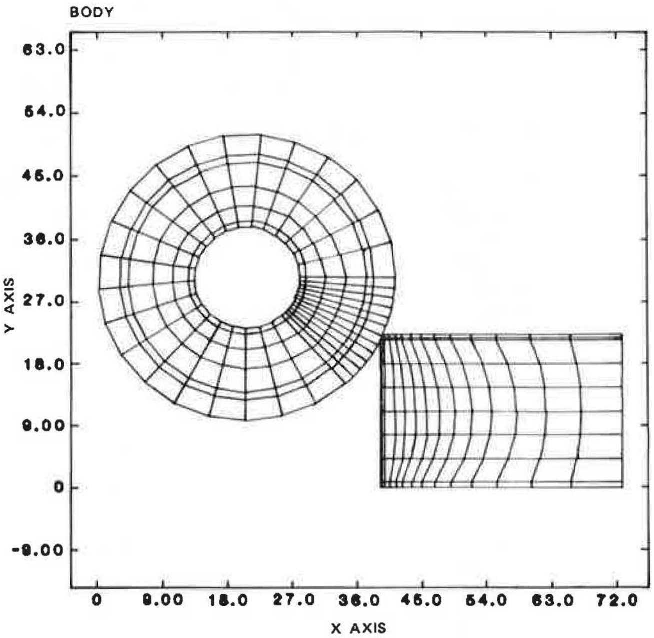


Figure 17. Scale locomotive model—scale test of grade-crossing crash.

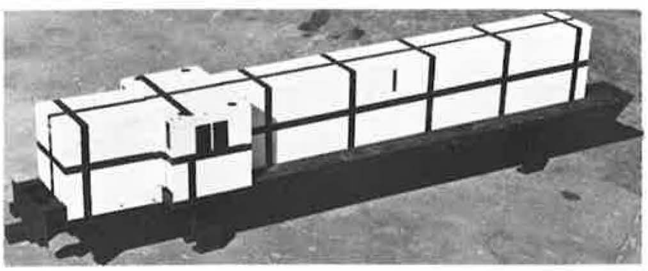
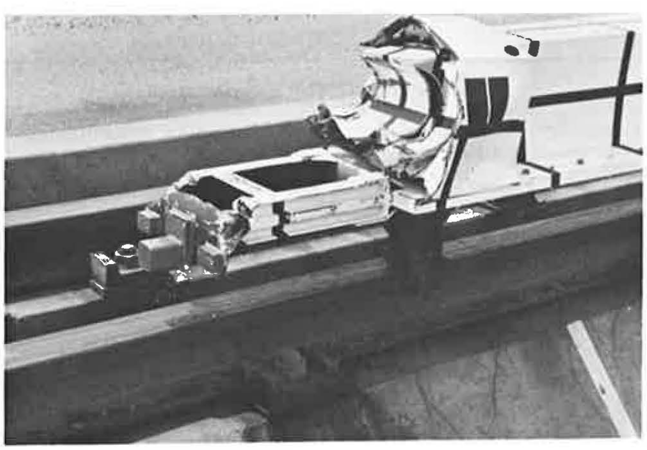


Figure 18. Posttest view of locomotive model—scale test of grade-crossing crash.



tive indicated that the overall response of the full-scale test agreed with pretest analytical and scale-model predictions.

ACCIDENT SEVERITIES AND PROBABILITIES

The test scenarios selected generally fall within the

Figure 19. Rocket-powered locomotive—full-scale grade-crossing test.

Figure 20. Full-scale impact—full-scale grade-crossing test.

Figure 21. Frame buckling damage—full-scale grade-crossing test.

extra severe or extreme categories described in the 1972 Atomic Energy Commission report (13). These conditions have been estimated in risk assessment studies of transportation accidents to be events of very low probabilities; no such accidents involving spent-fuel casks have ever occurred.

With the data from the studies on transportation accident severities, one can conservatively calculate the probabilities of occurrence for the various accident scenarios considered. Assuming that 3500 truck shipments (3200 km each, year 1990 estimates) are made per year, the probability of occurrence for the 100 km/h truck impact into a massive barrier is once every 70 years; and for a velocity of 130 km/h, approximately once every 1000 years, or no more than once every 1.13 $\times 10^7$ km traveled.

Using the same shipment conditions for the grade-crossing accident, the probability calculations indicate that for a velocity of 130 km/h, the predicted frequency of occurrence is somewhat less than once every 4500 years.

In the final planned test, which involves the impact of a special rail car and cask into a massive concrete barrier followed by a fire, the probability calculations for total shipment distance of 11.3 million km indicate that, for a velocity of 115 km/h, the probability of occurrence for impact is expected to be approximately once every 5900 years, and for a velocity of 130 km/h, no more than once every 18 000 years. These values do not include the combined impact and fire environment, which are at least 1000 times less likely to happen.

In the three full-scale impact tests conducted to date, the accidents of the severities described have not breached the container; therefore, had these casks been involved in such severe accidents during the transport of spent fuel, the public would not have been exposed to irradiated fuel elements.

CONCLUSION

The program objectives have been met successfully thus far. It has been shown that current analytical and scale-modeling techniques can predict vehicular and cask damage in extremely severe accident environments. In addition, much data have been collected on the response of transport systems in accident environments. These tests have shown that the spent-fuel casks tested are extremely rugged containers capable of surviving very severe accidents. The strong implication is that modern casks, designed and constructed to more rigid requirements, will survive equally well. Moreover, the capability to predict their survivability without full-scale testing has been shown to be feasible through mathematical analysis and scale-model testing.

ACKNOWLEDGMENT

This work was supported by the Division of Environmental Control Technology of the U.S. Energy Research and Development Administration.

REFERENCES

1. C. A. Davidson and J. T. Foley. Transportation Environment Data Bank Index. Sandia Laboratories, Albuquerque, SAND 75-0248C (updated), April 1977.
2. Final Environmental Statement on the Transportation of Radioactive Materials by Air and Other Modes. Office of Standards Development, U.S. Nuclear Regulatory Commission, NUREG-0170, Dec. 1977.
3. I. G. Waddoups. Air Drop Test of Shielded Radioactive Material Containers. Sandia Laboratories, Albuquerque, SAND 75-0276, Sept. 1975.
4. L. B. Shappert, N. C. Bradley, T. H. Evans, and M. C. Turgensen. The Obsolete Cask Test Program: Test Number 2. Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-TM-1312, April 1975.
5. V. K. Gabrielson and R. T. Reese. SHOCK Code User's Manual, A Computer Code to Solve the Dynamic Response of Lumped-Mass Systems. Sandia Laboratories, Livermore, CA, SCL-DR-69-98, 1969.
6. M. Huerta, H. R. Yoshimura, and A. W. Dennis. Impact Analysis of Spent Nuclear Fuel Shipping Systems. Sandia Laboratories, Albuquerque, SAND 77-0466, July 1978.
7. S. W. Key. HONDO, A Finite Element Computer Program for the Large Deformation Dynamic Response of Axisymmetric Solids. Sandia Laboratories, Albuquerque, SLA 74-0039, Jan. 1974.
8. D. E. McGovern and S. Thunborg. On the Use of Modeling in a Structural Response Problem. Sandia Laboratories, Albuquerque, SC-RR-70-880, 1971.
9. T. A. Duffey. Scaling Laws for Fuel Capsules Subjected to Blast, Impact, and Thermal Loading. Sandia Laboratories, Albuquerque, SC-RR-70-134, 1970.
10. H. R. Yoshimura and M. Huerta. Full Scale Tests of Spent Nuclear Fuel Shipping Systems. Transport Packaging for Radioactive Materials. Vienna, Austria, IAEA-SR-10/17, 1976.
11. M. Huerta. Analysis, Scale Modeling, and Full Scale Tests of a Truck Spent-Nuclear-Fuel Shipping System in High Velocity Impacts Against a Rigid Barrier. Sandia Laboratories, Albuquerque, SAND 77-0270, 1977.
12. A. W. Dennis. Analytical Investigation of a Grade Crossing Accident Between a Rail Train and a Spent Nuclear Fuel Cask. Sandia Laboratories, Albuquerque, SAND 74-0317, Jan. 1975.
13. Environmental Survey of Transportation of Radioactive Materials to and From Nuclear Power Plants. U.S. Atomic Energy Commission, WASH 1238, 1972.

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

Safe Transport of Munitions

Burton M. Rudy, Anthony M. Ragunas, and Terrence K. H. Wong, Military Traffic Management Command, Transportation Engineering Agency

The U.S. Department of Defense is conducting a study to determine procedures and methods that are technically and operationally feasible and economically acceptable to prevent, or limit, the effects of explosives incidents in rail cars and mass detonation of containerized munitions in port areas and aboard ships. Selected U.S. Department of Defense components, whose inherent mission, expertise, and physical assets are appropriate to developing solutions, will conduct technical and operational feasibility studies. Each performing agency will coordinate its areas of study with other governmental and industrial organizations. The 13 tasks have been categorized into six major areas of consideration. These include background information, traffic patterns, equipment, fire protection, buffering, and sea containers. The study, including a final report, is programmed to be completed within 33 months, ending in September 1980. The total cost is estimated to be approximately $3 million, which will be funded by both the Army and the Navy.

The importance of the safe transport of munitions (STROM) has been magnified tremendously in the past few years. There are countless technical and legal aspects of this subject, but we will be mainly concerned with four areas:

1. The magnitude of the problems involved,
2. What the U.S. Department of Defense (DOD) is doing,
3. Its basic considerations and involvements, and
4. What it hopes to achieve.

History books document reports of accidental explosions from the time that gunpowder was first developed. But now, due to the introduction of more sophisticated weapons along with more powerful explosives, as well as population increases near shipping routes, the problems have magnified. The days of relatively confined incidents and limited personal injury have been replaced by horrendous explosions and, in some instances, considerable loss of life.

A review of incidents that occurred in Roseville, California (Figure 1), and Benson, Arizona (Figure 2), will help to understand the magnitude of the problems.

A Southern Pacific train arrived in the Roseville, California, rail yard at approximately 6:00 a.m., on April 28, 1973. Included in the train were rail cars loaded with high-explosive bombs destined for Vietnam. At approximately 8:00 a.m., an explosion occurred in one of the bomb-laden cars. By propagation, 18 of the cars were destroyed by explosions over a period of 2.5 h. Bombs strewn throughout the remaining burning debris continued to explode until 4:00 p.m. the following day.

One hypothesis as to the cause of the incident was that heavy braking on mountain grades caused heat buildup in the car wheels. Oil and grease on the car underside subsequently ignited and created a floor char, which smouldered for hours and eventually broke into flames that caused the explosions. This is only one hypothesis. A complete report of the incident is not yet available due to ongoing litigation involving both the Southern Pacific Railroad and the United States government. .

Figure 1. Roseville, California.

Figure 2. Benson, Arizona.

A little less than a month later, on May 24 at approximately 7:00 p.m., another Southern Pacific train, this one with 12 cars, loaded again with high-explosive bombs destined for Vietnam, was near Benson, Arizona, when it was racked by a series of explosions, which continued for 6.5 h, destroying all 12 bomb-laden cars. Fortunately, the train was 8 km (5 miles) from the nearest home.

The National Transportation Safety Board hypothesized, in its report of the Benson incident, that the initial explosions were caused by a fire, which most likely originated when sparks were thrown from the car brake shoes and ignited the floor boards, which were impregnated with sodium nitrate from a previous lading. Again, this is only a hypothesis.

Although property damage was quite extensive, totaling well over $3 million, the Roseville and Benson incidents caused only few personal injuries and no fatalities.

However, a recent explosives incident occurred in Iri, South Korea (Figure 3), where nearly 60 people were killed and hundreds injured by the explosion of one carload of dynamite. We can imagine what would have happened had the Roseville and Benson incidents occurred as the trains were passing through heavily populated urban areas. This potential for disaster has long been recognized and a special note of it was made by the National Transportation Safety Board in its Benson report. One point must be stressed—this potential for disaster is of the greatest concern to all involved in the STROM program.

The Benson incident, occurring so soon after Roseville, brought an old problem to the surface: How to prevent or limit the effects of explosives incidents in rail cars and mass detonation of containerized munitions in port areas and aboard ships. Our task is to learn everything we can about the problem and determine what corrective actions can be taken.

DOD started to attack the problem soon after the Benson incident and developed the STROM study plan. The plan stemmed from recommendations made by their Explosives Safety Board in the fall of 1974. The safety board recommended that technical and operational feasibility studies be conducted in six areas:

1. Limited use of spacer cars,
2. Heat sensors with alarm systems,
3. Use of fire experience and test data previously acquired,
4. Use of installed fire protection systems,
5. Use of buffer systems other than spacer cars, and
6. The use of all-steel cars.

The safety board also recommended that a project manager be named by the Military Traffic Management

Figure 3. Iri, South Korea.

A woman cries and a man buries his head in sorrow over the damage. (AP) A man stands near the crater made by the bomb. (AP)

Command (MTMC), with the safety board and other DOD components to be on call as required. MTMC prepared the study plan, which outlined the various actions that comprise the STROM program and served as program coordinator.

The study plan is flexible so that other areas can be considered as the program progresses. Two additional areas of study have already been incorporated into the plan. The first encompasses rail car stability, as well as shock and vibration control. The second is concerned with containerized munitions.

The study does have one specific constraint. There are several classes of explosives, but in order to confine the scope of the study to an acceptable limit, only Class A, or detonating explosives, are under consideration.

Our study objective is to determine procedures and methods that are technically and operationally feasible and economically acceptable to prevent or limit the effects of explosives incidents in rail cars and mass detonation of containerized munitions in port areas and aboard ships.

In order to meet this objective, certain tasks were assigned to study participants according to the availability of special expertise and physical assets. The four primary DOD participants are the Army Ballistic Research Laboratory, the Army Ammunition Center, the Navy Weapons Center, and MTMC. Other organizations, both within and outside the government, will be approached for information and consultation as required.

There are 13 tasks to be completed by the participants. So as to logically develop all aspects of our objective, the tasks have been categorized as follows.

Background

1. Identify the regulations that govern the shipment of munitions by rail and estimate carrier compliance.
2. Identify the hazard characteristics of DOD munitions during transportation.
3. Determine, on a statistical basis, accident cause and scope of damage to personnel and property, in reference to munitions transported by rail.

Traffic Pattern

4. Analyze the distribution of munitions and determine whether cargo flow patterns minimize in-transit exposure, in regard to population density.

Equipment Considerations

5. Study the consequences of restricting future munition shipments to rail cars of all steel, or otherwise noncombustible construction.
6. Determine if rail car stability, as well as shock and vibration control, can aid in the prevention of explosives incidents in the rail movement of munitions.

Fire Protection Systems

7. Determine if sensors in a car carrying munitions, coupled to an appropriate alarm system, will provide adequate detection of dangerous heat buildup in the car.
8. Study the use of fire protection systems, within or on rail cars transporting munitions, with the objective of preventing or controlling fires.
9. Examine the application of test data and fire experience acquired by the Naval Weapons Center to the reduction of the risk of fire in railroad rolling stock.

Buffer Systems

10. Investigate the use of buffer systems, other than spacer cars, to reduce the risk of explosives propagation from car to car.
11. Study the use of spacer cars to prevent the propagation of an explosion between rail cars.
12. Study the use of containers on flat cars and trailers on flat cars for transporting munitions, as a means to prevent or minimize explosives incidents.

Port Areas and Ships

13. Analyze methods for preventing, or limiting the effects of, mass detonation of containerized munitions in port areas and aboard ships.

Each of the tasks, as well as subtasks, has a time schedule and all are projected to be completed within a 27-month time frame. The plan calls for a report, with recommendations, to be submitted for each task. These reports are to be analyzed by MTMC, which will then develop and publish a final report.

The total cost of the program is almost $3 million. Both the Army and the Navy have allocated funds in support of the STROM effort.

The first coordination meeting for the program was held in Washington, D.C., on November 16, 1977, and the first working meeting was on March 29, 1978, in Newport News, Virginia. Program plans have been finalized and a number of tasks begun in January 1978. The remainder of the tasks are scheduled to start sometime prior to October 1978. Quarterly progress reports are being submitted, and general review meetings are held semi-annually. The final report is scheduled to be published in September 1980, 6 months after all tasks are completed.

ACKNOWLEDGMENTS

We wish to acknowledge the work and efforts of D. F. Eichhorn and J. F. Ingman who were responsible for the initial preparation and coordination of the Safe Transport of Munitions Study.

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

Tort Liability: Special Problems Encountered by Highway Agencies and Contractors in Designing Work Zone Layouts

David C. Oliver, Federal Highway Administration

The principles of tort liability apply generally, whether the case is one of design, maintenance, or construction. All case principles are, therefore, applicable and lessons may be learned from nonconstruction zone cases. In another sense, however, construction zones present special problems in that they are at variance with the motorist's normal expectations. Thus, adequate warning devices and barrier safeguards are required. The question of adequacy in tort law discussion usually takes place in the negative, which further complicates the subject. That is to say, most of the cases discuss what is not adequate; what is adequate remains a vague item in terms of legal discussion. In light of this, this paper discusses some general principles, some considerations involving federal regulations or programs, and some recent cases that provide first-hand knowledge of judicial treatment of the topic at hand.

Lawsuits arising out of accidents as a result of alleged defects in a highway generally have four principle issues:

1. Did a potentially dangerous defect exist?
2. Was that defect the proximate cause of the accident?
3. Did the defendant have actual or constructive knowledge of the hazardous condition?
4. Was there any contributory negligence on the part of the plaintiff?

In seeking to answer these questions, the courts have established some guidelines, which are helpful in indicating general responsibilities.

1. The state is not an insurer of the roads or a guarantor of absolute safety.
2. The motorist has a right to presume and to act on the presumption that a highway is safe for usual and ordinary traffic, both in the daytime and at night. He or she is not required to anticipate extraordinary dangers, impediments, or obstructions to which attention has not been directed or of which he or she has not been warned.
3. Public highways must be maintained in a way that is reasonably safe for travel. What is reasonable? An acceptable definition is, "That is reasonable which is expected in a given circumstance." A road reasonably safe for travel is one that is maintained within accepted and understood criteria, under generally promulgated engineering standards, or subjected to generally promulgated engineering attitudes.
4. Maintenance of the highways in a manner that is reasonably safe for travel leaves wide latitude for the exercise of administrative discretion, but continual supervision and inspection are axiomatic. It is in the area of this general principle that a noticeable connection exists between positive administrative attitudes and negligence cases.
5. The courts recognize modifying factors in establishing what is reasonably safe, among them the terrain encountered and traffic conditions.
6. Recovery is predicated on more than the presence of hazardous conditions.
7. The authorities must provide proper safeguards or adequate warnings of such conditions; these warnings must be commensurate with danger. For example, an oil film on a highway has been held to be more than a slippery condition and warning signs or speed advisory signs are necessary to alert motorists.
8. Negligence is predicated on knowledge or information of the existence of a dangerous or defective condition and a subsequent failure to safeguard such condition.

These are only general principles because there is no legal rule by which to measure conditions and determine precisely whether a condition in a highway constitutes a defect.

FEDERAL SAFETY PROGRAMS AND REQUIREMENTS

The federal-aid highway program is a state program, federally assisted. The courts have interpreted this historical development to mean that the primary role of the federal government is to safeguard the expenditure of federal funds. This interpretation has successfully protected the federal government from judgment in most liability actions.

The passage of the Highway Safety Act of 1966 indicated that the congress desired that the federal government play a stronger role in the creation of a safe highway environment. This act was followed by the Highway Safety Acts of 1973 and 1976.

One interesting development was highlighted in a press release on March 3, 1977, which publicized the limitation on timber barricades on federal-aid projects. The policy resulted from a testing program that confirmed that timber barricades fail to retain and redirect colliding vehicles traveling in excess of 56 km/h (35 mph). The new instructions require that where positive barriers are needed to control traffic in construction zones, concrete safety-shape barriers or metal-beam systems should be used. Further, for purposes of marking traffic lanes or channeling traffic, a variety of temporary devices are listed in the Manual on Uniform Traffic Control Devices (MUTCD).

This new policy is of interest because the common law has established that where there is a question of barriers, as a general rule, they should be erected where necessary to provide a reasonably safe road for travel. Generally speaking, the character and strength of the barriers are usually left to the judgment of engineers. The only judicial rule of sufficiency is that barriers must make the road reasonably safe for travel. Barriers must be proved to meet the tests of (a) strength to carry out their purpose and (b) strength to withstand ordinary weights and forces to which they may be subjected.

In light of supportive research that indicates that timber barricades fail to retain and redirect colliding vehicles traveling in excess of 56 km/h, the states appear to have been less than diligent in protecting themselves from liability. It is to be hoped that the new federal policy will improve the defensibility of the states in barrier collision cases in the future.

In a recent case in Kansas, the plaintiff placed heavy reliance on the federally inspired program to upgrade safety. In this case, Martin v. State Highway Commission [518 P.2d 582 (Kan. 1970)], the court affirmed the positive intent of the federal program in such a manner as to alleviate states' fears of litigation originating in the federal requirements.

The court discussed the availability of federal money for federally approved projects, which require as a first step the submission of a statewide inventory of hazardous locations. Of course, Kansas was just as reluctant as any other state to concede that it had any such locations in its highway system. Kansas was using the tried and true technique of ducking anytime something new and strange appears on the horizon. In order to ensure its share of federal funds, however, the highway commission did prepare and submit an inventory for the state.

The federal project called for such items as removal of roadside signs; replacement of break-away supports, edging, striping, and wrong-way signs; and the installation of guardrails. It was a 3-year project, expected to be completed in 1969. As part of its participation, in June 1968, the commission let a contract to place guardrails at 59 locations on I-70, including the intersection involved in this accident. Work on the project began in fall 1968, and the guardrails at this intersection were completed the following spring, some months after the accident.

The plaintiff introduced this evidence on the theory that it showed the required notice of the defect. In fact, the court held that it had no probative value. There was no question of notice as the commission had known all along that there were no guardrails at this intersection. The real thrust of the evidence showed that the absence of the guardrails was recognized by the commission as hazardous, and thus defective. The court said, "But... changing standards and wholly laudable efforts to improve the safety of our highways does not make 'defective' that which has long been considered adequate."

The court also referred to the problem of upgrading and modernizing older designs, as well as the financial burden that would result from upgrading simply because newer and better designs are used in construction today. The most important point in the case is that a decision to upgrade a highway system does not render defective those portions that the program has not yet reached.

The message is that there are certain duties to be met. The choice is whether to victimize a state's program through fear of change or to identify the problem areas and begin a remedial action program. Nothing short of a perfect system will prevent legal suits; therefore, the state should opt for the most defensible posture. The avoidance alternative can be very expensive.

RECENT CASES

The case of Brock v. State [396 N.Y.S. 2d 282(N.Y. 1977)] involved a wrongful death action arising out of collisions that occurred after a truck driver crossed a bridge in the rain. Three accidents occurred at the same place under the same conditions. The bridge is located at the bottom of two steep grades, 7 percent on the west side and 5 percent on the east side, with curves on the east side of the bridge.

The vehicles skidded and jackknifed at approximately the same speeds, weather, and highway conditions; each trailer was empty and the accidents occurred within 18 m (60 ft) of each other. No signs warned of slippery-when-wet conditions at the site. The construction of the highway called for an 80-km/h (50-mph) limit, which had just been raised to 97 km/h (60 mph) and then to 105 km/h (65 mph), ostensibly because of police inability to enforce the lower limit. Prior to these accidents, over a period of 34 months, there were 34 accidents within several hundred meters of each other and under similar circumstances.

The state was aware of this situation. Citizens had complained and there had been at least one on-site safety inspection. The state had conducted numerous tests, such as the ball-bank indicator and coefficient friction tests, but the friction tests were made during dry weather. Other tests made during wet weather were disregarded since no readings were obtainable.

The trial court found that the curve was not built to permit reasonably safe travel at high speeds and that the increase in the speed limit without warning or regulatory devices was only an accommodation for speeders that evidenced an indifference to the available indicia bearing on the causes of the accidents.

The appellate court agreed with the trial court. In the words of the court, "The unusual rate of accidents, the worn riding surface of the bridge and roadway, the complaining letters, the community meetings and the mountainous terrain all combine to charge the state with actual knowledge of the dangerous condition." Even state witnesses conceded that there should have been warning signs.

The lesson of this case is that it is necessary to post signs affording timely warning to motorists that they are approaching a segment of the road where uncommon dangers exist. Further, the posted speed was far in excess of the safe speed under certain conditions and led drivers to believe that their speed was reasonably safe when evidence indicated it was only marginally safe at best under the conditions then existing.

Beardsley v. State [395 N.Y.S. 2d 848(N.Y. 1977)] arose out of a two-automobile head-on collision at a construction site where a culvert pipe was being installed under the road. The duty of the state to construct and maintain its highways in a reasonably safe condition includes giving adequate warning, by sign or otherwise, of dangerous conditions on the highway. The evidence in this case indicated that the portion of the highway involved was unpaved, on a lower grade than the paved roadway north and south of it, and of insufficient width to accommodate the simultaneous passage of two automobiles traveling in opposite directions. The state had erected only two signs for warning purposes, both far removed from the reconstruction area. No signs directed a reduction in speed or warned of a narrowed road. The road was inadequately lit at night and also inadequately guarded and barricaded. The award was for $100 000 to the motorist and $20 000 to his wife for loss of services.

The case of Smith v. Cook [361 N.E. 2d 197 (Ind. 1977)] is an interesting case involving the MUTCD and a construction site. In this case, the accident involved a vehicle proceeding along a road under construction and a vehicle crossing that road. The road in question was US-31, a north-south highway, which was in the process of conversion to a four-lane, divided highway. The western southbound lanes were being used to conduct traffic in both directions until the other lanes were completed. The defendant approached on a crossroad and, at the intersection, observed approaching traffic from the south but was unaware of the closed lanes. As he attempted to cross the lanes to reach the median, he was struck by a northbound automobile in the western lane.

The contention was that the state had negligently failed to mark the intersection and approaches thereto in a manner sufficient to warn of the construction and that the southbound lanes were being used for two-way traffic. It was alleged that this was in violation of the Indiana MUTCD. The specific alleged omissions were a type A barricade, no ROAD CLOSED sign, no TWO-WAY TRAFFIC signs at the intersection, and no signs warning of possible obstructions or restrictions due to highway construction.

This case is interesting because it was not tried on the basis of reasonable care but on the basis of statutory negligence—a violation of a specific requirement of the law. Thus, the court analyzed the MUTCD extensively, and the court held that the manual is not sufficiently specific to impose an absolute duty.

The court treated the manual as a whole and because this was a statutory negligence case did not dissect and individually determine whether the placement of each kind of traffic-control device is or is not governed by a specific and absolute duty. The manual, for example, makes the decision to use many devices a discretionary decision. Also, the use of most, if not all, traffic-control devices involves some measure of independent judgment. The court referred to the manual language, referencing the manual as a guide with flexible qualities. Thus, the court did not find the requisite specificity or absoluteness to meet the statutory negligence test. The court said that the manual is only evidence bearing on the general duty to exercise reasonable care.

In any event, the court's opinion was that the signs and illustrations in the manual, such as ROAD CLOSED, TWO-WAY TRAFFIC, and ROAD CONSTRUCTION AHEAD, and type A barricades are intended to warn oncoming drivers of hazards. The court found no indication that the devices are intended to warn laterally approaching drivers of hazards on an intersecting road. The court said, "Indeed, to warn motorists of hazards that do not exist on their route would likely be confusing and engender disregard for all traffic control devices."

Another interesting case occurred in Ohio. The case of Knickel v. DOT [361 N.E. 2d 486 (Ohio 1976)] involved a $4000 award for damage suffered as a result of injury caused by a blow-up of the pavement. It is interesting because it indicates the catch-22 nature of maintenance in the courts. The vehicle involved was proceeding over a four-lane, reinforced cement, straight section of divided highway at between 75 and 90 km/h (47 to 55 mph) on a bright, clear, dry day. The pavement was in a state of deterioration. Repairs were constantly being made and a rehabilitation project, involving resurfacing with blacktop at a cost of $3.5 million, had been bid at the time of this accident.

The problem of blow-ups was recognized by the state, which had issued a design policy memorandum on the subject. Much research has been done and the court recognized Ohio as a leader in this research. But much is still unknown, for example, when or where a blow-up will occur and of what magnitude it will be. Blow-ups occur in concrete, at the joints of concrete squares, and are more frequent in the summer. They generally do not occur in newly built stretches of concrete. They can be minimized but at high economic cost.

The court had all this information before it—the technology and research, the awareness of economic factors, and the knowledge that generally few accidents of minor severity result from this condition. But the court asked a question of great significance: Who will bear the loss from sudden blow-ups—the state, which has the duty to maintain reasonable safety, or the general public, who uses the highway? The court decided that the state should bear the loss.

The court considered whether the state had done all that a reasonable person could have done. The absolute elimination of this condition would require the destruction of concrete highway and the substitution of asphalt or macadam roads, and this would be too costly to be borne by the state. The installation of pressure relief joints on all concrete highways would be equally costly. The court expressed awareness of the dilemma that it might be less expensive to pay the cost of damages caused by the hazard than to pay the cost of eliminating the hazard. But the court felt that this was a policy and an economic question to be solved by the legislative and administrative bodies of the state.

The case points to the dilemma of the 1980s—an aging road system shows stress, and less money is available to provide for all highway needs. The real question is, can the money be better spent for repair of the highways on a systematic basis, or will it be parceled out to injured individuals? If the latter choice is made, there is not any possible social return. The choice is judicial action, which is leading the way. The roadmap the judiciary is setting out should be obvious to all by now.

Another case involving a manual, the Iowa highway maintenance manual, resulted in a $501 750 judgment against the state. In that case, Hunt v. State [252 N.W. 2d 715 (Iowa 1977)] the plaintiff was injured when his automobile skidded on a frost-covered bridge in the early morning during clear and calm weather. The question was one of the constructive knowledge of the state of the frost condition on the bridge and compliance with manual procedures. It is another case of economic judgments and manual directions.

The court discussed the obligation of maintenance personnel to make reasonable use of weather information. In this case, the maintenance manual, if followed, would have disclosed a probability of frost on the bridge. The manual was explicit in describing policy and procedure regarding bridge deck frosting. The court found that the availability of the procedure coupled with the weather conditions favorable to frost gave constructive notice of the hazard in time to guard against or eliminate it. The court found that the existence of the maintenance procedure in itself was evidence that the state knew that frost conditions are predictable.

The procedure in question requires the maintenance supervisor to contact a weather station and obtain a dew point and forecast. If the dew point is 0°C (32°F) or lower, if the forecast temperature less 6 degrees is lower than the dew point [i.e., colder than -3°C (26°F)], and if there is little wind and no low clouds, frost on bridge floors is likely. Here, there was a weather station less than 1.6 km (1 mile) from the bridge and the other conditions were met. The state, however, contended that it is wasteful and sometimes hazardous to apply sand or salt to a dry roadway as a preventive measure. But expert testimony and a state maintenance directive on the use of salt to prevent icing contradict this approach.

The procedures actually followed did not include the use of weather forecasts. Random frost checks were the only method of ascertainment and such visual checks were not made until after 6:00 a.m. during the frost season. Earlier information was to be provided by law officers on an informal basis, and this apparently was not reliable. The court felt that this method, random observation, did not permit anticipatory remedial action, and that the failure to follow the manual procedure was actionable negligence.

A Louisiana case, Graham v. Rudison [348 So. 2d

711 (La. 1977)], resulted in a judgment totaling $170 000. A collision occurred as a result of a decedent's efforts to avoid a large hole, which covered practically the entire northbound lane of a narrow, two-lane road. There was prior notice to the state, but no attempt at repair had been made except an earlier placement of shells in the hole. There was no attempt to mark the road to warn motorists of the hazard.

The case of Woolie v. City of Baton Rouge [348 So. 2d 747 (La. 1977)] involved a breach of duty to adequately warn oncoming traffic of a construction site. The plaintiff drove through a barricade and into a large hole. Witnesses for the city testified that the hole had been dug about 2 h before the accident, and that five barricades, three smudge pots, and a sign warning that the lane was closed 152 m (500 ft) ahead had been put out. The trial court, however, found that the warning sign was much closer than contended, the witnesses saw no smudge pots, and the only barricade was 23 to 31 m (75 to 100 ft) from the hole. The trial court decided that in view of the nature of the road, its heavy traffic, and speed limit of 80 km/h (50 mph), there was no adequate warning. In this case, as is often the situation, the issues are factual in nature and often involve credibility of witnesses. Thus it is important to document actions that have been taken in order to support them at a later time.

An award of $150 000 was given in the case of Warning Safety Lights, Inc. v. Gallor [346 So. 2d 92 (Fla. 1977)], which involved an action against a contractor and subcontractor. The plaintiff crashed into a median wall while attempting to avoid hitting traffic cones, which were in her lane of traffic. The contract between the state and the contractor and the subcontractor imposed a duty to maintain proper traffic control for the safety of the public during construction work. The minimum traffic-control safety standards provided by the Florida safety manual were to be observed. This manual provided for placement of cones 0.6 m (2 ft) from the edge of the traveled way and that the cones should be weighted or fastened down so as not to tip or move. The evidence indicated that lane closure was by placement of single cones, weighing about 4.5 kg (10 lbs) each, on the stripline, which divided the closed lane from the adjacent lane of moving traffic. Cones were blown and knocked over. The defendant contended that there was no evidence as to how misplacement occurred and that automobiles may have hit and misplaced them. But the testimony indicated misplacement to begin with, not in conformity to the manual. The jury finding of negligence was supportable.

In Mora v. State [369 N.W. 2d 868 (Ill. 1977)], suit was brought to recover damages for injuries sustained in an automobile collision on a dark and rainy morning. One of the automobiles was a passing vehicle. At the scene of the accident the road makes a double-S blind curve as it goes up a small hill. Liability in this case would have to be predicated on the lack of signs or markings on the highways, which would have advised that passing at that point would be hazardous. The accident site was a construction area, just recently repaved.

The state and one contractor were dismissed as parties. Eaton Asphalt Company had done the repaving and its responsibility was at issue. Prior to the repaving, this section of the highway was not a no-passing zone nor were there any advisory signs warning of the curve and hill. The Illinois Manual of Uniform Traffic Control Devices for Streets and Highways was introduced. It provides for a no-passing zone to be established in any area where a motorist's ability to see ahead falls below a specified minimum. Surveys were taken after the accident and it was contended that the roadway in question would qualify for posting as a no-passing zone under the manual standards.

Eaton had placed strips of reflecting tape to indicate the center line after the repaving. This was required by the contract. But the repainting of the permanent lines was a function of the state. It could not be done until the asphalt had cured, and at the time of the accident neither the center line nor the edge lines had been repainted.

The rule is that a contractor has a duty to give warnings of dangers created by it. Here, the danger of the curve was not a consequence of the contractor's conduct—the contractor did not create the topography of the land, nor did repaving change the configuration of the roadway or remove any warnings indicating the presence of a danger zone.

In all cases of contractor liability, the contractor has created the hazard. In this case, the danger arose out of the very nature of the roadway as it had existed long before the contractor came on the scene. Hence, he or she could not be saddled with what was the duty of the state.

With respect to the individual state highway department employees, none were in the traffic division, which is in charge of line painting. One was the head of the district in which the accident occurred and it was contended that he should have established a no-passing zone at the site. The hill and the curve were gentle and the sight distance deficiency was not visible to the naked eye.

The claim was that defendant should have directed that a survey be made—there are 1930 km (1200 miles) of state roads in his district. A description of the activity involved must be characterized as discretionary not ministerial, and so he could not be personally liable.

Duties of contractors take many forms and shapes. They must (a) adequately mark highway detours they have constructed; (b) warn of excavations they have created or exposed; (c) warn of obstructions, uneven surfaces, and other dangers they place in road surfaces; (d) warn drivers of an abrupt narrowing of the road at a bridge; and (e) warn of lane changes required by their work on the highway. Contractors have a duty to warn where there is unequal knowledge, actual or constructive, of a dangerous condition and the contractor knows or should know that harm may occur if no warnings are given.

The case of Cummins v. Rachner [257 N.W. 2d 808 (Minn. 1977)] was unusual in that the negligence of the state was in question even though the state was not a party. A $225 000 judgment was returned against a contractor and driver for the death of a passenger. The accident occurred at nighttime in the snow. In a bypass area the driver became confused by lane markings painted on a road surface in an area of construction and drove her vehicle over a median into oncoming traffic, where a collision occurred.

The highway was being upgraded to Interstate standards. The work was being done in stages, using bypasses, so that a four-lane divided highway would remain open to the public while the new freeway was under construction. This segment was 2.9 km (1.8 miles) in length. To delineate the driving surface, the state painted new white lines on the highway and the newly constructed portions of the bypass and at the same time applied a coat of black paint to obliterate the old markings, which if not completely obliterated would direct an unsuspecting motorist directly into the oncoming lane of traffic. The state had also placed a barricade, which consisted of three crossmembers painted alternately with white and orange diagonal stripes, adjacent to the position where the old highway lane markings and the newly painted markings intersected. There were no overhead lights or flashing warning signals in the immediate area.

A state highway patrolman retraced the route of the accident and found the original pavement markings as bright and as white as the new lane markings. These markings led directly into the oncoming lane. Thus, despite the attempted obliteration of the old lane markings through the application of a coat of black paint, they remained visible.

The contractor sought to avoid liability by contending that the primary responsibility was on the state to provide traffic-control devices and markings on its highways. But the court found this was not so under the provisions of the state manual for construction. Not only are there manual provisions, but case law as well, to establish that when a contractor enters into a road construction contract, he or she assumes a general duty to protect the public from hazards or traps within the construction zone.

In this case, the construction site supervisor admitted that while he did not feel the state's painting job was inadequate, he could still plainly see the old lane lines, even after the attempted obliteration. He did not inform the state of this condition. A safety engineer, whose job was to ensure that the segments of the highway within the construction site would be completely safe for the general public, did not testify. However, there was testimony that he did not notify the state of its failure to completely obliterate the old lane lines.

The court held that the contractor shared a mutual duty with the state and failed to notify the state of the obvious danger created by the inadequate obliteration. The contractor also did not erect any signs to warn motorists of the condition when he had a duty to do so under the contract. This was a breach of its mutual duty. The judgment was affirmed.

Publication of this paper sponsored by Committee on Traffic Safety in Maintenance and Construction Operations.