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IDEA *Innovations Deserving Exploratory Analysis Project*

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Report of Investigation

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ROAD CREW PORTABLE LASER WARNING SYSTEM CONCEPT DEVELOPMENT AND DEMONSTRATION

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MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Loral Advanced Projects, Manassas, Virginia, working with Loral Electro-Optical Systems Divisions, Pasadena, California; Loral AeroSys, Seabrook Maryland; and Loral Librascope, Glendale, California, has developed and demonstrated a road crew portable laser warning system. Loral developed the system under the auspices of the Innovations Deserving Exploratory Analysis (IDEA) programs for the National Cooperative Highway Research Program (NCHRP). The system employs laser technology as the basis for a state-of-the-art device to improve highway worker safety. The system warns workers performing highway maintenance along a roadside or in a traffic lane that has been temporarily closed to traffic of cars or trucks approaching on a path that would put these workers at risk. The road crew warning system developed and tested under this IDEA initiative would help reduce the hundreds of needless deaths and injuries to road crew workers that occur each year in the United States.

In developing the warning system, investigators took advantage of extensive government research in state-of-the-art laser technology. For example, the Department of Defense (DOD) has developed small, eye-safe lasers and associated detectors as part of the Multiple Integrated Laser Engagement System (MILES) for training soldiers. MILES uses laser "bullets" to simulate the lethality and realism of the modern battlefield. Gallium arsenide laser transmitters capable of shooting pulses of coded infrared energy simulate the effects of live ammunition in military training exercises. DOD implemented MILES 14 years ago, and their investment has exceeded $400 million. This substantial investment provided the technology base for application of the existing equipment to the development of a road crew warning system at an affordable price.

The road crew warning system consists of a laser transmitter, one or more laser receiver-transmitters, and a worker notification system. These components together provide a laser barrier along the border of the work zone, as illustrated in Figure 1. The laser beam from the transmitter is detected by the receiver-transmitter at the beginning of the work zone. Beam detection at the receiver-transmitter initiates a second laser beam that is directed to the receiver at the end of the work zone. If either beam is broken, the final detector activates warning devices that alert the workers that a vehicle is heading toward them. Additional receiver-transmitter sets can be employed to extend the barrier or change the beam direction to accommodate other warning-zone geometries. The warning system provides additional time for the workers to take evasive action, which they cannot do when they have no advance warning.

Testing and analysis of the prototype system have been conducted at the Loral Electro-Optical Systems Division in Pomona, California, and the feasibility of the concept has been verified.

IDEA PRODUCT

The road crew portable laser warning system fills the need for a system to provide warning for workers performing maintenance tasks in temporary work-zone areas. This need exists because New Jersey barriers, which normally provide substantial physical protection, are not usually set up at temporary work zones. However, the warning system that was designed and developed for this project is appropriate for providing a warning of approaching vehicles that would put highway workers at risk.

The benefits of a warning system, if proven practical, can be substantial. Of primary importance is the increased safety of workers engaged in highway construction and maintenance activities through the reduction in deaths and injuries caused by traffic accidents. Additional benefits include reduction in job time lost as a result of injuries, reduced medical costs, reduced insurance premiums, and increased worker productivity due to an increased feeling of safety. Road crew injuries and deaths are a significant problem in the United States; many fatalities occur each year. Figure 2 shows data collected by the Federal Highway Administration on recent work-zone fatalities *(1)*. There is no standard definition of "work-zone fatality" for states, and there is no breakdown of the data according to whether fatalities are caused by vehicles intruding into work zones or by other types of accidents. Thus, these data should be used only to indicate trends and not as absolute numbers. The system being developed under this IDEA initiative can help to reduce fatalities due to work-zone intrusions by vehicles.

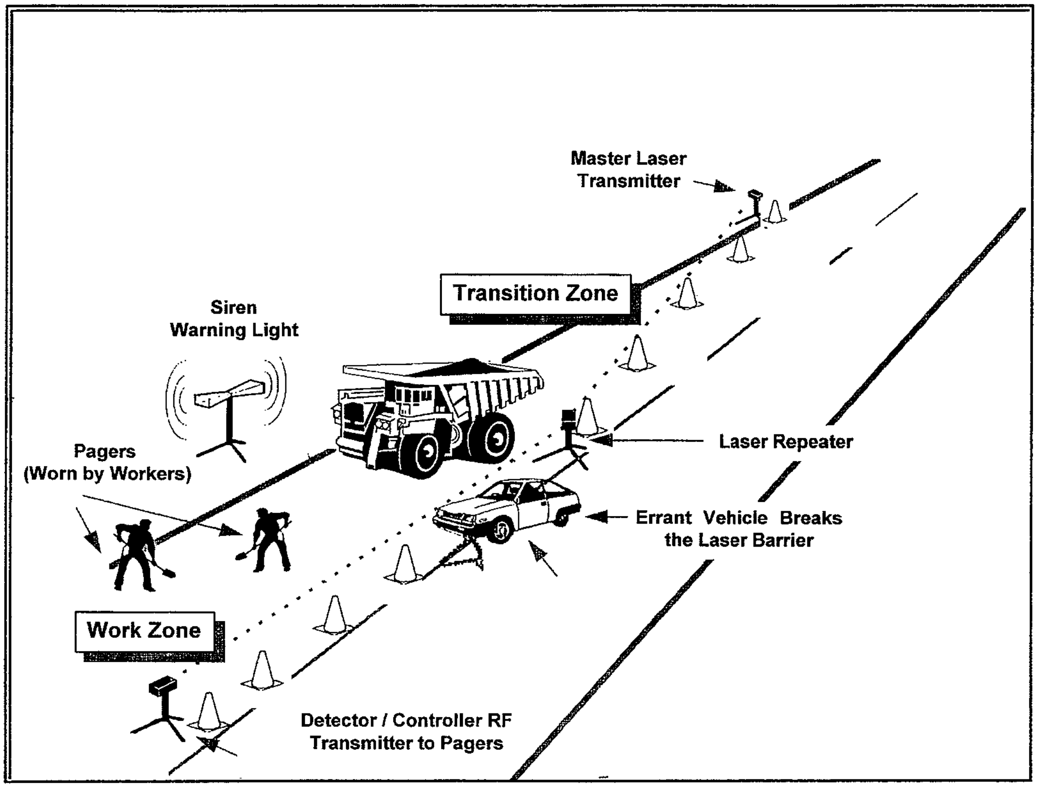


FIGURE 1 Road crew portable laser warning system.

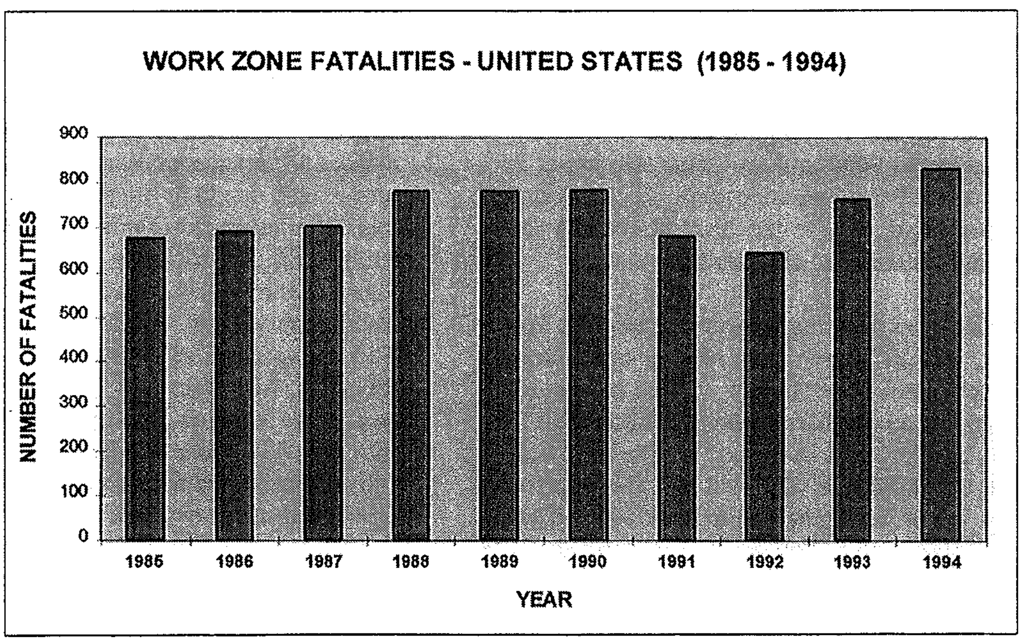


FIGURE 2 Recent history of fatalities in traffic work zones in the United States.

WORK-ZONE CONFIGURATIONS

Typical work zones in temporary construction or maintenance areas are shown in Figures 3 and 4. Drivers approaching a work zone are alerted to a forthcoming traffic flow change by appropriate warning signs and the closing of a traffic lane. The lane closing is accomplished by gradually shutting down the lane with traffic cones that create an exclusion barrier called a *taper*. Figure 3 shows a typical traffic control system for closing half of a multilane conventional highway. Figure 4 shows a more complex configuration for roadway closure on a multilane conventional highway. Additional variations of these lane-closing schemes are employed for traffic control at on- and off-ramps.

OVERVIEW OF THE WARNING SYSTEM

The road crew warning system that resulted from the analysis, design, and development efforts of this program consists of several components: a battery-powered master laser transmitter mounted on a traffic cone, one or more laser receiver-transmitters mounted on traffic cones, and a worker notification system. Figure 1 illustrates the operational concept.

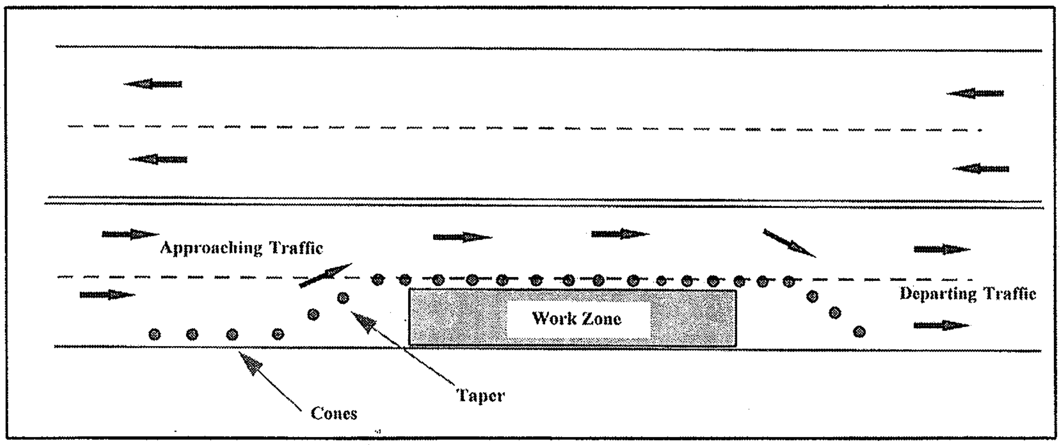


FIGURE 3 Traffic control system for half roadway closure on a multilane conventional highway.

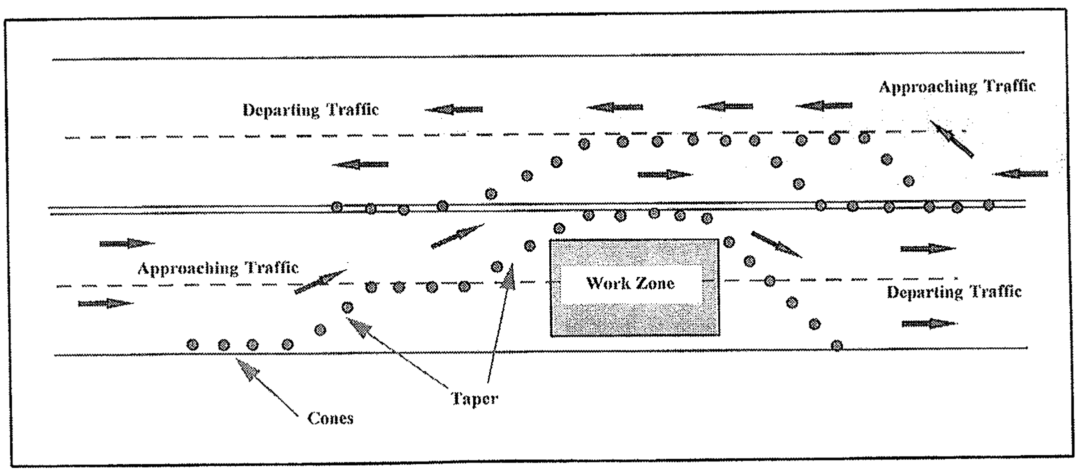


FIGURE 4 Traffic control system for lane closure on a multilane conventional highway.

A pulsed laser beam from the master laser transmitter is directed toward the laser receiver-transmitter located at the end of the taper. The beam is detected by the receiver located at that point. The detection event triggers the laser that is co-located with the receiver, and the laser transmits pulses toward a second receiver located at the end of the work zone. The retransmitted laser beam is received by the final detector at the end of the work zone. If either the first beam or the retransmitted beam is interrupted at any point by an errant vehicle, the lack of a laser signal at the final receiver causes an electrical signal to be generated that activates an alarm system. The alarm system notifies workers to take evasive action. In this way, the laser beam acts as an electrooptical barrier along the taper and the work zone.

The alarm system that is sounded when the barrier laser beam is broken provides warning redundancy, which consists of an audio alarm backed up by warning lights and pager-beepers worn by the workers. (The pager-beepers can also be set to give the workers a vibratory signal. This vibration would be felt when the pager is worn so that it is in contact with the worker's body.) The alarms alert workers that a threatening vehicle is approaching so that they can get out of the way. The warning lights are designed to have the dual purpose of warning workers and attracting the attention of the driver of the intruding vehicle so that he or she can change direction and avoid the work zone.

The road crew protection system is envisioned to be very small, capable of operating in all weather conditions, portable, battery-operated, low-cost, highly reliable, and user-friendly. The system characteristics are described in greater detail in following sections.

CONCEPT AND INNOVATION

MULTIPLE INTEGRATED LASER ENGAGEMENT SYSTEM

The warning system using MILES is unique in that it takes advantage of the substantial investment in research that the Department of Defense (DOD) made to develop small, eye-safe lasers and associated laser detector-receivers as part a soldier-training system. MILES uses laser "bullets" to simulate the lethality and realism of the modern tactical battlefield. Gallium arsenide (GaAs) laser transmitters capable of shooting pulses of coded infrared energy simulate the effects of live ammunition. The transmitters are attached to all hand-carried and vehicle-mounted direct-fire weapons. Laser detectors located on opposing troops and vehicles receive coded laser pulses from the weapons when they are fired. The coded infrared energy is received by silicon detectors located on the target. The detectors are installed on a webbing harness (the MILES "vest"), which is worn by the soldiers. Additional detectors are attached to a web band that fits on helmets. The combination of detectors on the MILES vests and on the headbands provides 360-degree coverage in azimuth.

MILES decoders determine whether laser bullets are accurate. The target vehicles or troops are made instantly aware of the accuracy of laser shots by means of audio alarms and visual displays. MILES decoders then determine whether the target was hit by a weapon that could cause damage and whether the laser bullet was accurate enough to produce a casualty.

DOD implemented MILES 14 years ago, and their investment has exceeded $400 million. Over 50,000 rifles and machine gun systems and 10,000 tank and antitank missile systems have been produced.

The MILES laser transmitter is rugged, small, and lightweight. With miniaturized optics and electronics, the laser

- Is low in power consumption,
- Operates on all commercial 9-volt batteries,
- Indicates when the battery is low,
- Uses a built-in functional test indicator,
- Meets stringent MIL-STD 810D environmental requirements,
- Uses an eye-safe GaAs (0.904-μm wavelength) laser beam,
- Is completely operable with other MILES training devices, and
- Has a range capability of up to 5,577 meters (1,700 feet).

Figures 5 and 6 show the main components of MILES, including the MILES laser transmitter and the MILES vest and headband with laser detectors.

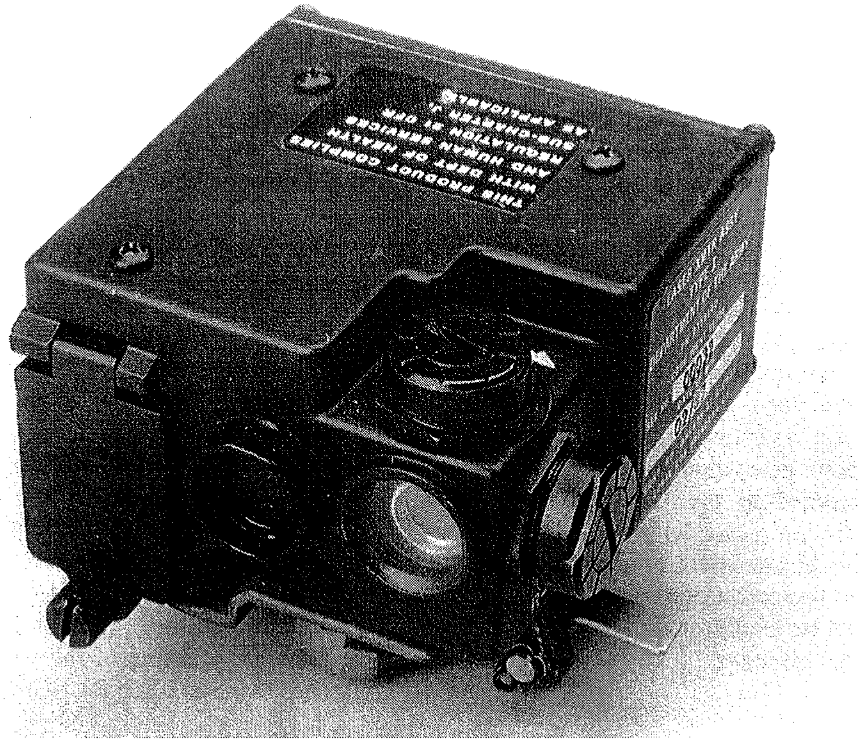


FIGURE 5 MILES laser transmitter.

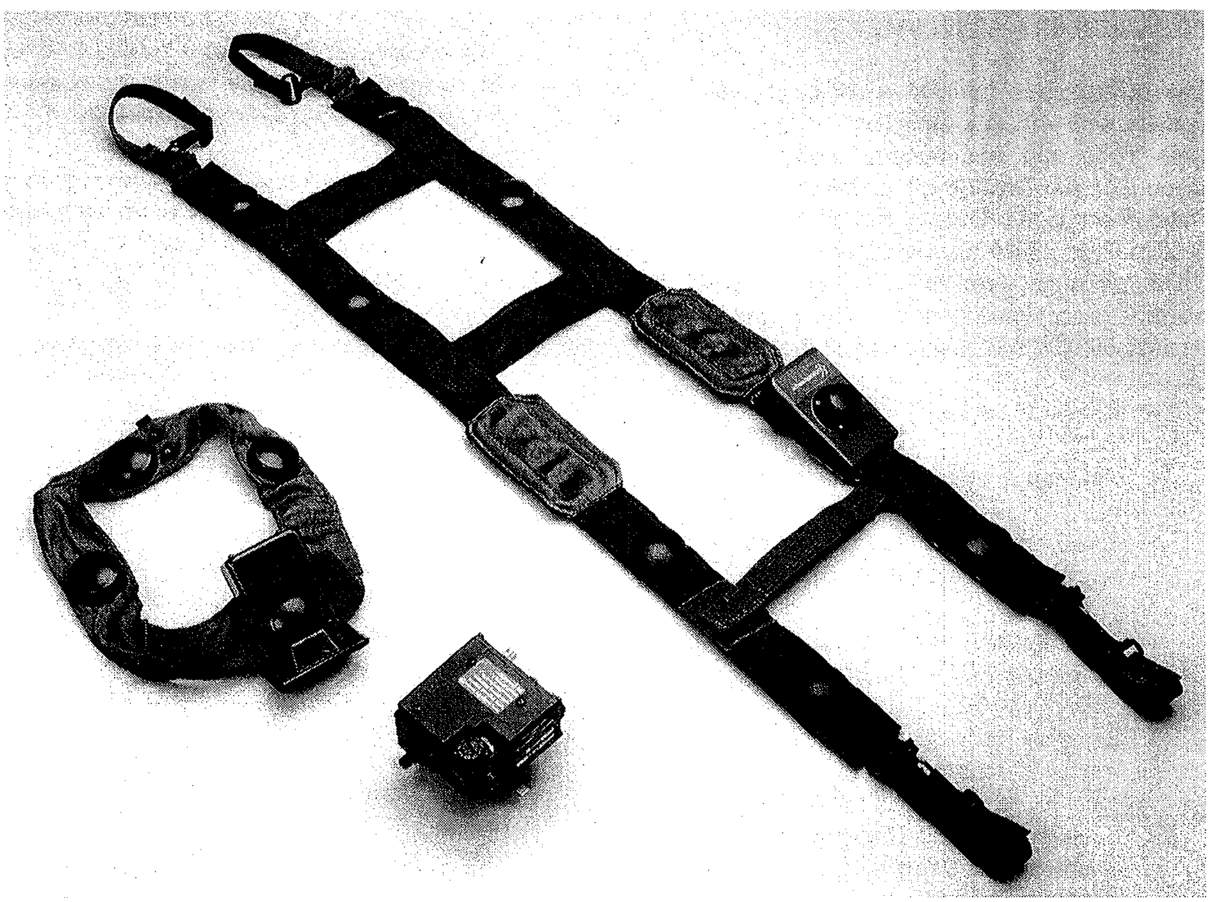


FIGURE 6 MILES vest and headband, with attached laser detectors, and MILES laser transmitter.

APPLICATION OF MILES TECHNOLOGY TO A TRAFFIC WARNING SYSTEM

The substantial MILES development effort provides the technology base for application of existing equipment to the problem of warning road crews at an affordable price. For the purposes of the road crew portable laser warning system, the investigators considered the use of the MILES laser transmitter and receiver, the MILES vest and headband, and a MILES radio frequency (RF) transmitter (operating in the 300-MHz frequency range) and RF receivers. All items were readily available from military inventory. MILES has been upgraded to a second-generation system, which is currently being supplied to the U.S. military. First-generation MILES lasers and detectors are now surplus and are available at a nominal refurbishment cost for use in road crew protection systems. First-generation equipment would be totally qualified to meet the requirements for such systems.

INVESTIGATION

PRELIMINARY ASSESSMENT

The investigators initiated a series of meetings nationally with officials from the California, Maryland, New York, and Pennsylvania transportation departments and the Department of Public Works-Highway Department in the District of Columbia to better understand the issues associated with road crew safety. These meetings were useful in reviewing the traffic warning concept and providing suggestions to enhance its usefulness. It was suggested that the system

- Be easy to set up,
- Not require extensive training for operation,
- Entail minimum risk during setup — it should be capable of being set up from a vehicle,
- Not interfere with workers' performance of their tasks,
- Suppress the warning alarms if workers inadvertently break the beam,
- Consist of several configurations so as to accommodate the needs of a variety of maintenance site configurations, and
- Be low in cost.

The investigators evaluated the utility of road crew portable laser warning system concepts in light of the recommendations received at the review meetings. Analytical verification and bench-scale experimentation were performed to gain insight into the strengths and weaknesses of the various concepts. The results of the validation demonstrated the feasibility and desirability of the concepts and led to subsequent prototyping for operational testing. This analysis and experimentation permitted the investigators to look at critical design issues.

The objective of the investigation was to conduct a laboratory and analytical study of the feasibility of a laser-based warning system to provide effective warning to maintenance and construction crews. An analytical study was performed on the laser system to assess technical and cost issues for fielding such a system in highway use. The initial study was followed by laboratory testing of the system candidates and a limited demonstration for NCHRP representatives.

DESIGN ISSUES

The primary technical issues related to the evaluation of the road crew portable laser warning system concept for highway worker safety were as follows:

- *Effectiveness:* Can the system provide a measurable increase in the amount of warning time of potential danger to road crew personnel?
- *Reliability:* For what period of time is the system capable of operating without failure? For what period of time is a 9-volt battery power supply capable of operating before having to be recharged or replaced?
- *False Alarm Rate:* Is the false alarm rate sufficiently low so as to prevent user personnel from being conditioned and thus ignoring the system's intended function?
- *Portability:* Can the system be set up and operated in a reasonable amount of time by untrained personnel? Can the system be relocated within acceptable user time limits?
- *Operational Ranges:* Are the laser power and detector sensitivity sufficient to effectively operate at ranges to 3,280 meters (1,000 feet)?

[A master laser transmitter operating with a laser receiver-transmitter located at the end of the taper would have a total operating range of 6,562 meters (2,000 feet).]

- *Environment:* Will the system function at the maximum intended operating range of 3,280 meters (1,000 feet) for each laser under a variety of weather conditions? Is the system capable of operating effectively on a variety of road conditions, including roads with curves?

- *Visibility:* Will the system function in dusty conditions?

- *Maintainability:* Is the system easy to maintain by user personnel? (For example, can user personnel replace the 9-volt battery and swap-out the laser transmitter?)

- *Affordability:* Are the three system concepts within the production cost budgets of the state transportation departments?

Work Plan

This project was accomplished by (a) establishing realistic requirements against which to evaluate the effectiveness of the warning system; (b) developing a set of viable candidate system configurations that meet the requirements; (c) evaluating the candidate system configurations by testing them to determine the strengths and weaknesses of each; (d) demonstrating, on a limited scale, the feasibility of the candidate systems for NCHRP representatives; and (e) recommending the system configuration that best satisfies the requirements. The work on implementation issues supported the design viability and generation of technical requirements identified and resolved critical design and performance issues.

Steps taken to evaluate the feasibility of the road crew portable laser warning system concept and its application to highway practice were

- Performing an engineering analysis of the MILES laser concepts to calculate power, size, geometric, and other technical requirements;

- Performing an engineering analysis of the MILES laser concepts to determine the audible incident warning device requirements;

- Performing operational trade analyses to determine system utility, feasibility, identification of system deficiencies, and critical design issues;

- Performing a high-level system design of the MILES laser system concepts;

- Performing bench-scale experimentation and an analytical study to validate the MILES system concepts in the laboratory; and

- Conducting a limited proof-of-principle demonstration of MILES laser system concepts at the Loral Electro-Optical Systems facility in Pomona, California.

Warning Time Analyses

The warning time available for road crew workers depends on the geometry of the road closure scheme and the location of the work zone with respect to the closure boundaries. The geometry of the closure is a function of several factors, including number of lanes to be closed, the availability of existing barriers between incoming and outgoing traffic lanes, the size of the work zone, the placement of the work zone with respect to traffic barriers, and the posted speed limit of the highway. This report does not provide precise calculations for the warning times for all possible cases because of the large number of variables that would need to be considered. The discussion that follows provides several examples illustrating how the warning times can be calculated once the geometric factors have been defined.

In general, construction work zones can be categorized as long- and short-term. The characteristics and levels of protection are different for each category.

Long-term work zones are usually associated with the construction and rehabilitation of roadways and bridges. Traffic control plans for lane closures and traffic detours are usually prepared because of the long duration of such projects, and work zones are well protected with traffic safety devices. The safety devices include New Jersey barriers, which are typically placed along the closed lane to separate the traffic flow and the construction zone. Attenuators are installed at the

beginning of the work zone, and other traffic control devices including traffic drums, cones, and barricades are typically used.

Short-term work zones are typically set up for roadway resurfacing or utility work and involve closure of a lane or shoulder. These work zones are not as well protected and are usually demarcated only with traffic cones and truck-mounted attenuators placed at the beginning of the work area. Despite the use of truck attenuators, the work-zone crews still remain susceptible to accidents from vehicles breaking into the construction area from the side; therefore, the warning system that is the subject of this study can be of particular benefit to road crews in short-term work areas.

A typical work zone is illustrated in Figure 7. A taper precedes the work zone to smooth the effect of lane closure. The length, L, of the taper depends on the highway speed and the width of the closure.

The *Manual on Uniform Traffic Control Devices (2)* provides the following formula for calculating the length of the taper for a lane closure:

For speeds of 72 km/hr (45 mph) or more:

$$L = 0.62 * S * W \quad (1)$$

For speeds of less than 72 km/hr (45 mph):

$$L = 0.006 * W * S^2 \quad (2)$$

where

L = minimum horizontal length of taper, in meters (feet),

S = numerical value of posted speed limit prior to work, or 85th-percentile speed, and

W = width of the closure offset.

According to these formulas, for a typical freeway section with an 89-km/hr (55-mph) speed limit and a standard 3.6-meter (12-foot) lane, the minimum taper length for one lane closure would be

$$L = 0.62 * 89 * 3.6 = 199 \text{ meters}$$

For a speed of 48 km/hr (30 mph) and a lane width of 3.6 meters (12 feet),

$$L = 0.006 * 3.6 * 48^2 = 50 \text{ meters}$$

<u>Case I: Speed S is 72 km/hr (45 mph) or higher</u>

From Equation 1,

$$t = \frac{0.62 * S * W * 3600}{S * 1000} \text{ seconds}$$

$$t = 2.23 * W \quad \text{seconds}$$

For the closure of a 3.6-meter (12-foot lane), t = 8.2 seconds (for all speeds).

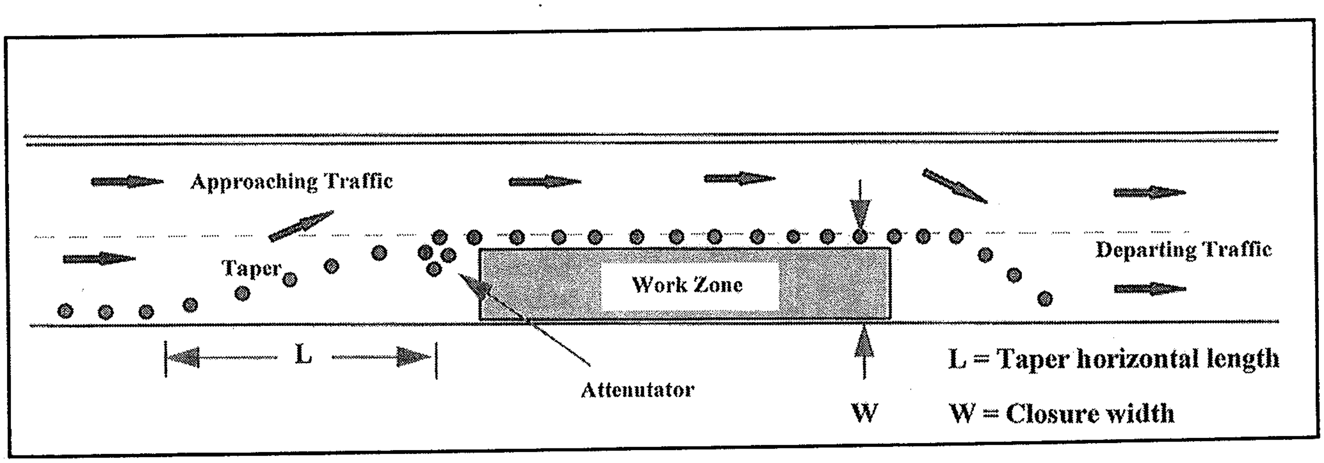


FIGURE 7 Typical work zone.

Case II: Speed S is less than 72 km/hr (45 mph)

If a vehicle running at a speed of S breaks into the designated work zone at the beginning of the taper, the time t for the vehicle to reach the actual work area, as given by Equation 2, is

$$t = \frac{0.006 * S^2 * 3600}{S * 1000} \quad \text{seconds}$$

$$t = 0.022 * W * S \quad \text{seconds}$$

The time t varies proportionally with the speed in this case. For a 3.6-meter (12-foot) lane closure and speed of 48 km/hr (30 mph), $t = 4$ seconds.

Therefore, a maximum of 8 seconds is theoretically available to the road crews after the work-zone break-in. It could be less than 8 seconds for a low-speed roadway or if the errant vehicle drives enters the work zone from the side.

Reaction time is defined as the interval between the instant that the alarm goes off and the instant that the person starts reacting to it. A similar concept of reaction time is used by transportation engineers to calculate the stopping distance of a vehicle. A number of studies *(3–5)* have been conducted to determine driver reaction time, which have shown that minimum reaction times could be at least 1.64 seconds for alerted drivers. An important difference between drivers and road crews is that drivers are usually alert to traffic conditions, whereas work crews are not always aware of approaching vehicles. Thus, the reaction times for road crew workers are expected to be higher.

Reaction time and relocation time (the time it takes a worker to move to a safe place) together constitute the time necessary for workers after the warning alarm goes off. The upper limit on the time available for workers to get out of harm's way, t_u, is given by

$$t_u = 2.23 * W - 1.64 \ \text{seconds} \ (\text{speed} \geq 72 \text{ km/hr})$$

$$t_u = 0.022 * W * S - 1.64 \ \text{seconds} \ (\text{speed} < 72 \text{ km/hr})$$

The purpose of the road crew warning system is to increase the time available for workers to get out of the way of errant vehicles. At best, workers may only have several seconds. The warning system can extend what would be a very short time by perhaps several seconds, depending on the speed of the vehicle.

Basic System

The basic system employs lightweight, low-cost MILES components: a MILES laser transmitter, one or more laser receiver-transmitters, MILES optical detector electronics, and a horn-and-flashing-light warning system. The laser transmitter, shown in Figure 5, is contained in a 8 x 8 x 5 cm enclosure mounted on top of a traffic cone. The laser itself is eye-safe, operates in the near-infrared region of 0.904 μm, and has a pulsed peak power output of 0.5 watt. The maximum range of the laser is about 366 meters (1,200 feet). The MILES detector, shown in Figure 8, is a 3 x 3 x 8 cm device that contains the amplifier, electronics, and 9-volt battery. Each has a field-of-view of approximately 170 degrees. When a car or truck interrupts the beam of the laser barrier, a signal is generated at the detector that trips a relay and sets off the warning system.

The receiver-transmitter unit redirects the laser beam so as to accommodate the change of direction needed at the end of the taper or to accommodate direction of a beam along a curved roadway. Curves in a road pose an additional danger to road crew personnel because they can limit the driver's field-of-view. The road crew portable laser warning system uses one or more additional receiver-transmitters to "straighten" the road and eliminate this hazard. The warning system can be especially effective in providing protection in this situation. One or more laser reflectors can be used to solve the road curvature problem. The number of receiver-transmitters needed depends on the degree of curvature of the road and the distance to be covered.

The receiver-transmitter consists of a small arms transmitter (SAT) modified by adding a hybrid detector on the side at an angle of 45 degrees to the housing. The hybrid detector module includes a photodetection device and an amplifier-comparator circuit. When this repeater picks up the boresight code of 600 pulses per second (pps), it retransmits the code at 600 pps. The unit is shown in Figure 8. The retransmitted boresight code is transmitted to the final detector (also shown in Figure 8), or in the case of a curved roadway, to the next receiver-transmitter. The final receiver, which is similar to that used in the basic system, is used to turn on the warning system when the incoming laser beam is broken.

Worker Alert Options

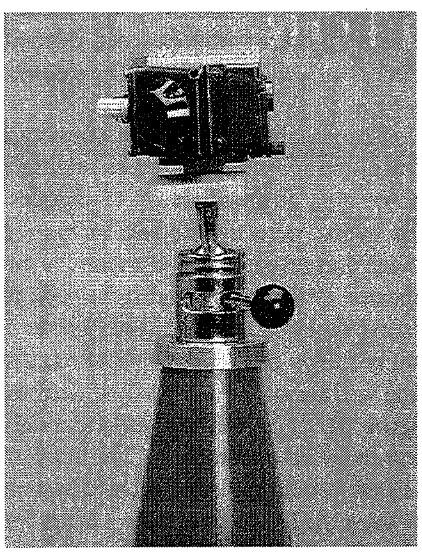
Three options were proposed for alerting workers once the laser barrier beam is broken. The options are (a) the MILES vest, (b) the MILES RF transmitter, and (c)

a pager-transmitter system. The warning alert options would be operated in conjunction with the basic system.

MILES Vest Worker Alert Option. In this option individualized warning is provided to the road crew workers in addition to the warning they receive from the horn and flashing light. The individualized warning is based on the use of a telescopic laser transmitter and MILES laser detectors. The second laser (telescopic) transmitter is triggered by any break in the laser barrier beam along the taper and work zone and floods the area in which the crew is working. The transmitted signals are received by MILES detectors attached to vests worn by the workers. As shown in Figure 6, the MILES vest detectors, weighing less than 12 ounces, are worn over the outer clothing and provide the means to activate a miniature audio alarm on each worker. In addition to the vest detectors, three detectors would be mounted on the workers' hard hats. (Each of the MILES detectors covers an approximately 170-degree field-of-view.) The individual warning detectors worn by the road crew would pick up the signal and broadcast an audio response into an earphone worn by the road crew worker. This type of warning has the added benefit over the basic system of alerting workers operating jackhammers or noisy equipment or whose view of the flashing warning light is blocked so that they would not have to depend on the horn or light devices.

The telescopic laser transmitter that sends the warning signal to the detectors worn by the workers uses an identical laser as that used in the laser transmitter and detector unit.

MILES RF Transmitter Worker Alert Option. The second option for alerting workers consists of a telescopic MILES RF-CW transmitter (miniature RF receivers and earphones operating in the 300-MHz range). The telescopic RF-CW transmitter, triggered by the barrier laser transmitter-detector unit, provides maximum false alarm reduction by flooding the work area with CW illumination when the laser barrier is broken. A miniature RF receiver on each worker's hard hat detects the CW emission and causes the audio alarm to sound. The RF signal is coded to eliminate false alarms. The RF transmitter with its antenna horn approximates the size of a MILES laser transmitter. This alternative is similar to the MILES option, with the RF transmitter taking the place of the MILES warning laser transmitter that signals the workers.



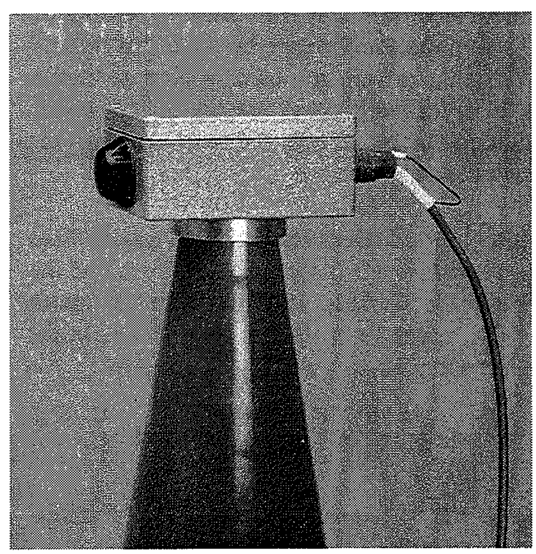


FIGURE 8 Laser receiver-transmitter (left) and laser detector (right).

Pager-Transmitter System Alert Option. This approach utilizes an RF pager-transmitter to activate the individual pagers worn by the workers. The concept is similar to the MILES RF warning option except that the RF pager-transmitter and pagers would be less expensive than the MILES RF equipment. In addition, the pager could be set to the vibration mode. A worker could clip the pager so that it was close to his body and the vibration could be felt when the pager went off. When the laser barrier beam was broken, the final laser beam receiver electronics unit would transmit a signal to the pager-transmitter, which would, in turn, transmit a coded RF signal that would be picked up by the pagers. Upon receipt of a correctly coded signal, the pagers would provide an audio alarm and a vibration alarm. The pager-transmitter and pagers are shown in Figure 9.

SYSTEM EVALUATION

The work program in this project consisted of planning, building, and testing the basic system and the warning options. Once the basic system and the warning options had been defined, components for the configurations were acquired and assembled and the equipment was set up for experimentation and testing. Limited testing was carried out to demonstrate the effectiveness of each of the candidate configurations. Specifically, the evaluation included the following tasks:

- Definition of the objectives of the road crew warning system.

- Definition of the critical issues to be addressed in the program:

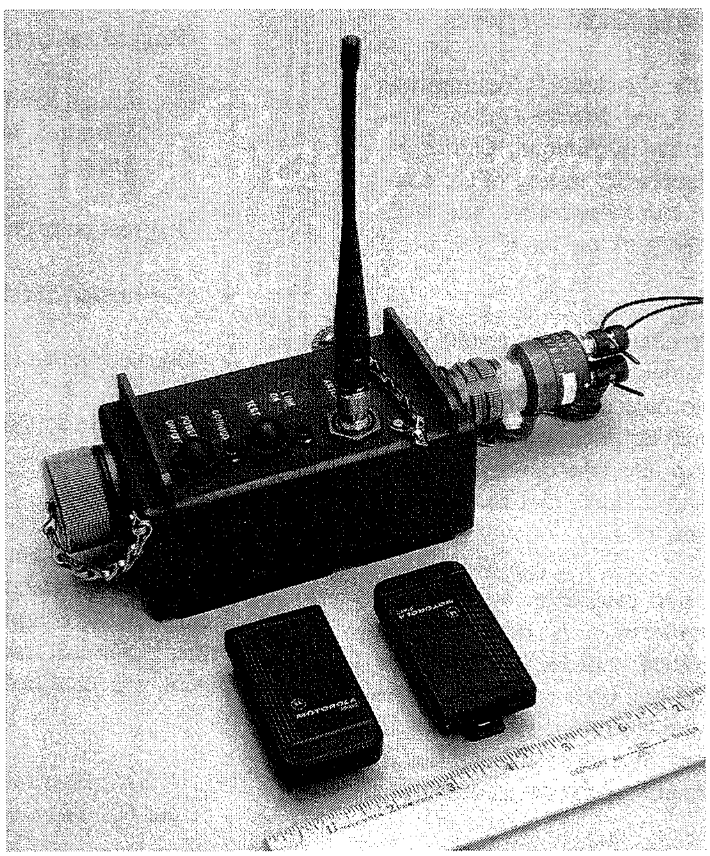


FIGURE 9 Pager-transmitter and individual pagers worn by workers.

- What is the contribution of the road crew warning system to the protection of the road crew?

- To what extent is the basic road crew warning system effectiveness improved when it is supplemented by the warning options studied in this project?

- Definition of the candidate warning options. Engineering judgments were made as to the expected effectiveness of each of the alternatives in meeting the objectives of the road crew warning system. This process served as a filter to delete alternatives that did not appear to exceed the expected utility of other alternatives.

- Acquisition of test components. The lasers, detectors, reflectors, and other equipment were supplied by Loral Electro-Optical Systems Division and Loral Librascope Division in preparation for testing candidate systems.

- Testing of candidate systems. Testing was conducted at the Loral Electro-Optical Systems Division facility in Pomona, California, and consisted of laboratory testing of the components to ensure correct operation and technical testing in the parking lot of the Loral facility.

- Analysis of test results. The test results were analyzed to determine how well the alternatives achieved the objectives of the warning system. The analyses included false alarm rates, ease of setup and take-down, clarity of the warning signal provided, and convenience of system operation.

- Demonstion of the candidate systems for NCHRP representatives. A demonstration session was scheduled with NCHRP after the preliminary testing had been completed. The objective of the demonstration session was to show through actual operation the abilities of each system to provide road crew warning.

Basic System

Laboratory experiments and analytical studies were conducted to determine the feasibility of the proposed concepts and to suggest new or modified approaches. This was followed by an engineering analysis. Design concepts were rated by determination or calculation of the following factors:

- Power requirements and expected battery life;

- Equipment size and weight (including batteries or other power sources);

- Maximum range of protection and effective range of protection taking into account environmental factors;

- Protected region geometry and limiting factors;

- Environmental sensitivities, including the effects of

  - Temperature and humidity,
  - Sand and dust,
  - Rain, snow and sleet, and
  - Fog and mist;

- Ruggedization of equipment, including

  - Rough handling,
  - Vibration, and
  - Shock;

- Estimation of equipment reliability;

- Estimation of false alarm rate;

- Recurring and equipment costs;

- Ease of installation; and

- Ease of use.

A high-level system design was developed for the alternatives. Each design was documented by a system block diagram, an equipment list, and a listing of risks and critical technical issues. Specifically, the following equipment was modified or developed, analyzed, and tested.

- A SAT laser modified to operate in a continuous 600-pps mode;

- A second SAT outfitted with detector(s) and modified to operate as a laser pulse repeater;

- A laser detection system modified to trigger a warning system upon loss of continuous laser transmissions; and

- An electric horn device (audio alarm), personnel alarm/pager, and a warning light procured as commercial-off-the-shelf equipment.

The warning system concepts evaluated for the basic system and the options are discussed below.

Testing and analysis were conducted to determine the feasibility of the basic system and to suggest new or modified approaches. It was found that it was difficult to line up the laser beam on the receiver-transmitter. The standard MILES laser has optics that create a narrow beam so as to simulate bullets. A narrow beam is difficult to line up on a desired point. In the case of the warning system, the desired point is the next receiver-transmitter or the final detector. To overcome the beam orientation problem, a holographic diffuser with a shorter-focal-length lens than the lens system used for MILES was employed for the basic system. The effect of the shorter-focal-length lens was to generate a wider beam than that of the standard MILES SAT. The wider beam was easier to line up on the next reflector and aided in reducing the effects of transmitter movement due to roadway vibrations from traffic or equipment. The vibrations cause the beam to jitter and move off the final receiver, causing a false alarm.

The beam measurements for the replacement lens are shown in Table 1. With beam size as large as that measured, any difficulty in lining up the beam on a detector at the next receiver-transmitter or final receiver should be minimized, since the beam does not have to be centered on the detector. As long as the detector is in any part of the beam, the system will operate correctly.

TABLE 1 Beam Size for the Laser Transmitter (all dimensions in meters)

Range	Horizontal	Vertical
32	1.0	1.2
50	0.9	1.1
100	1.3	1.2
210	2.7	3.6
340	3.6	3.0

The response of the detector on the final receiver was measured as shown in Table 2 for a laser peak power of 0.74 watt and a pulse duration of 135 nanoseconds. The pulse repetition rate was 600 pps. The incident energy level available at a detector placed 300 meters from the laser exceeds the sensitivity level of the detector and thus will be detected unless the beam is broken by an intruding vehicle, person, or equipment. The MILES laser used in the repeater-transmitter also had a shorter-focal-length lens attached, as in the case of the primary laser. The diffused beam makes beam aiming easier and reduces false alarms due to laser or receiver-transmitter vibrations.

TABLE 2 Detector Sensitivity

Unit	Threshold (microwatts/cm^2)
Detector	3.2

Operating characteristics in terms of the protection region and the environmental sensitivity of the basic system and size and weight data are provided in Tables 3 and 4. As can be seen, the length of coverage should be sufficient for most taper work-zone configurations. The setup time, battery life, and physical conditions under which the system can operate should not limit the usefulness of the system either.

TABLE 3 Operating Characteristics of the Basic Warning System

Item	Characteristic	Item	Characteristic
Taper	> 300 meters	Sand / dust	Light blowing
Worker zone	> 300 meters	Wavelength	0.904 µm
Environmental	-20° C to 62° C	Shock	4.2 g's at 5 Hz to 500 Hz
Humidity	100 %	Vibration	20 g's sawtooth
Reliability	> 2,000 hours	False alarms	< 1 per 100 hours
Setup time	< 30 minutes	Battery life	> 150 hours

TABLE 4 Size and Weight of the System Components

Equipment	Size (cm)	Weight (kg)
SAT	8 x 8 x 5	0.7
Repeater	8 x 8 x 5	0.8
Horn	15 x 10 x 10	2.3
Pagers	8 x 5 x 1	0.2
Pager Transmitter	30 x 30 x 30	3.6

Warning Options

MILES Vest Worker Alert. The detectors used with the MILES vests and on the headbands have the same sensitivity as the detectors used in laser barrier beam detection. This option was judged to be less than satisfactory when compared with the pager-transmitter option for several reasons. The laser signal from the laser telescopic transmitter could be blocked as the workers moved around the work zone and as equipment moved in and out of the work zone. Blockage occurred because an unobstructed line of sight was needed between the telescopic laser transmitter and the workers. The incidence of inadvertent blocking caused false alarms. A high rate of false alarms could reduce the workers' confidence in the warning system and cause them to disregard it over time, thus reducing its effectiveness in the case of an actual emergency. Also, the equipment the workers would need to carry is more bulky and weighs more than the simple pager associated with the pager option.

MILES RF Transmitter Worker Alert. This type of warning has similar capabilities as the MILES vest warning option, with the added capability of being able to provide warning coverage over a much larger work area. The major improvement over the MILES vest option is that the laser signal to the MILES vest can be blocked so that it does not reach the vest detectors; the RF signals are not subject to shielding.

This option does require a more costly transmitter and receivers than the equipment associated with the pager option.

Pager-Transmitter System Worker Alert. No major drawbacks were noted with this option when compared with the other warning options. The equipment is relatively inexpensive and easy to setup and operate. The volume control of the pager would have to be turned up high enough for the pager to be heard in a noisy roadside environment.

PLANS FOR IMPLEMENTATION

RECOMMENDED SYSTEM

Considering the analysis work accomplished, the recommended configuration is the basic system plus the pager warning system option to supplement the flashing light and horn. The components of this system are shown in Figure 10.

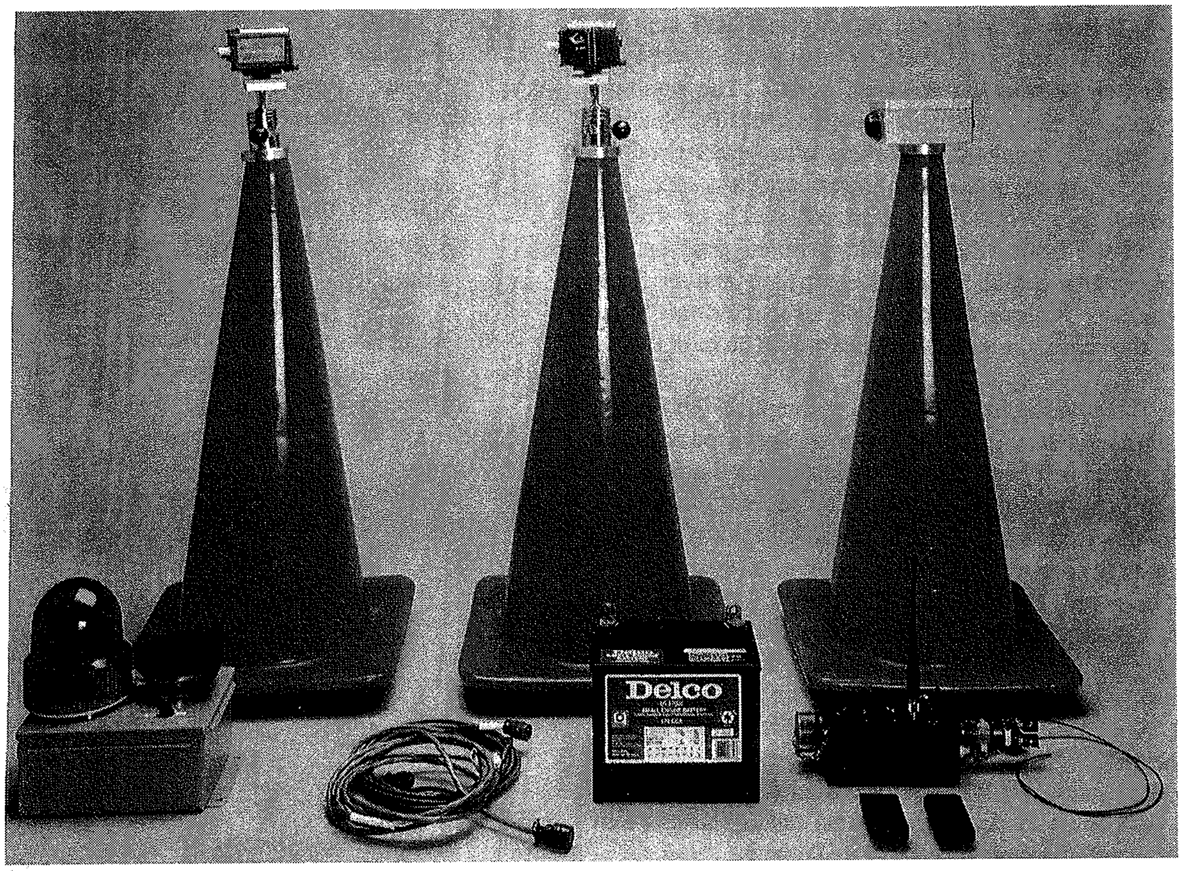


FIGURE 10 The system components. From left, light-horn warning system, laser transmitter, laser receiver-transmitter, and final laser receiver all mounted on traffic cones; battery to power the warning system; and RF transmitter with its associated pagers.

SYSTEM COST

The cost of the MILES equipment that makes up the recommended system as presently constituted would be high for use in an operational system. For example, the cost of each military SAT is approximately $400 when purchased in quantities of several hundred units.

Much less expensive laser transmitters could be built that are based on the proven existing MILES technology and meet the road crew warning system requirements, but they do not have all of the military SAT features. Production transmitters employing plastic housing, a lower parts count, and simplified circuit cards could achieve significant cost savings in the approximately $50 to $100 range (in volumes of 1,000 units). Receivers currently cost approximately $100. This cost could be reduced for high-volume production units. The cost for a pager-transmitter would be around $200 and pagers would cost approximately $25 each. Cables, connectors, and batteries would add another $200 to the cost. The cost of the horn and flashing light, as used in the demonstration, is about $75.

All of these component prices would drop with quantity purchases. For a system for six workers, with one receiver-transmitter, the cost would be around $1,500 for low-volume purchases. The cost could drop $200 to $300 for volume production.

FUTURE PLANS

The investigators plan to demonstrate the prototype systems to highway departments in California, the District of Columbia, Maryland, New York, Pennsylvania, and Virginia. The investigators will then make the system available for trials to interested highway departments so that further assessment can be made and feedback provided to the investigators to aid in developing operational systems.

In follow-up work, the investigators will address the design issue of workers or maintenance vehicles inadvertently breaking the laser beam. The preliminary assessment is that this problem could be handled by equipping trucks and workers who could possibly cross the laser beam with laser detectors and RF transmitters. When the authorized vehicle or worker entered the beam, the transmitter would send an RF message that would inhibit the warning system from operating. As long as the vehicle or worker was in or near the beam, the warning notice would be inhibited.

The investigators will also accomplish the design of various system configurations so that a package of equipment will be readily identifiable with the needs of a particular maintenance job. The investigators envision three configurations for use by highway departments: (a) a basic system consisting of a laser, a detector, a pager-transmitter, and pagers for protection at small maintenance sites; (b) an expanded system consisting of a laser, laser receiver-transmitter, a final receiver, a horn-light, and a pager warning system; and (c) all of the second system plus additional receiver-transmitters as needed for use in large construction or reconstruction work zones. Detailed design work will be performed to determine system configurations that will match the typical needs of road crews.

CONCLUSIONS

The investigators have designed and evaluated a number of road crew portable laser warning systems and have shown the feasibility of the systems through testing. Considering the design and demonstration work accomplished, the investigators feel that the prototype system that has been developed shows the future usefulness of the system in providing an increased level of safety for road crew workers.

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