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16. Abstract

This report presents the results of research to develop recommendations to (1) improve the vehicle and equipment warning light policy for the Texas Department of Transportation, and (2) improve the safety of the department's pavement data collection activities. Research efforts included a nationwide survey of vehicle warning lights and pavement data collection procedures, a motorist survey of their perceptions and interpretations of vehicle warning light color configurations, field studies of the effect of different warning light color configurations upon traffic operations, and a critique of current pavement data collection equipment and traffic control procedures. Researchers recommend that current policy to allow blue lights to be used with yellow lights on selected vehicles and equipment should be retained. However, researchers do suggest other changes to the policy, and provide recommendations to improve the safety of pavement data collection operations.

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HIGHWAY CONSTRUCTION, MAINTENANCE, AND SERVICE EQUIPMENT WARNING LIGHTS AND PAVEMENT DATA COLLECTION SYSTEM SAFETY

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and Safety Evaluation of Pavement Data Collection Systems

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DISCLAIMER

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1. INTRODUCTION

The Texas Department of Transportation (TxDOT) places significant emphasis on maintaining and improving worker and motorist safety, especially when work activities require that personnel be next to and within roadway traffic. Through the years, the Department has sponsored numerous studies to develop improved traffic control and safety procedures for various types of construction and maintenance work zones and other situations requiring temporary traffic control (see references *1-6,* as examples). This emphasis on safety has led to significant improvements in temporary traffic control standards and operational guidelines at both the state and national level (*7, 8*).

SPECIAL VEHICLE FLASHING WARNING LIGHTS

Although much has been done to improve many aspects of worker and motorist safety during various work activities, the potential for more improvement exists in other areas. Questions have existed for some time about how to best use vehicle warning lights to delineate highway maintenance, construction, and service equipment. Although the need for vehicle warning lights is well understood and mandated by law, the large number of options available to TxDOT and other transportation agencies (rotating beacons, flashing incandescent or strobe lights, lens color, mounting positions, etc.) places considerable pressure on policy makers to incorporate more and more lighting technologies on maintenance, construction, and service vehicles that are similar visually to those implemented on police and emergency vehicles (e.g., light bars, blue flashers, etc.).

Past studies have demonstrated the potential benefit of these warning light technologies with regards to conspicuity and/or information transmission (*9-11*). However, it is also apparent that overuse of any technology (including those employed for vehicle warning lights) can reduce their effectiveness. The question thus becomes how to decide if such devices should be used, on which vehicles they should be used, and under what conditions. In addition, questions exist as to whether it is beneficial to use more than just amber (yellow) lights on certain types of service vehicles and equipment. (For purposes of simplicity, researchers will refer to the amber lights as yellow lights throughout this report. This is the term utilized by motorists when surveying them about alternative warning light colors).

PAVEMENT DATA COLLECTION ACTIVITIES

Past research has also not focused extensively on worker and motorist safety during pavement data collection activities. The Department maintains over 70 different pieces of equipment used to collect pavement data statewide. Most pavement data collection activities fall into either stop-and-go or mobile operations. TTI has conducted research on both types of operations for basic maintenance activities under limited roadway conditions (moderate-volume freeway facilities) (*1, 2, 5*). This research has led to improved traffic control procedures for these conditions. However, pavement data collection activities have somewhat unique characteristics, which may necessitate special considerations when developing appropriate traffic control and operating procedures. These characteristics include the following:

- They sometimes utilize much smaller vehicles (and fewer numbers of vehicles in a caravan) than are used in typical maintenance activities, and so may be much less conspicuous to approaching motorists;
- They may utilize special equipment that hamper motorist efforts to pass the data collection vehicle (such as the ground penetrating radar which extends in front of the data collection vehicle);
- Although some activities may be classified as stop-and-go operations (such as the falling weight deflectometer), the actual time spent stopped at each location may be as short as a few minutes (making it difficult to provide static warning signs, cone tapers or other indications to warn approaching motorists);
- Some data collection activities can be accomplished at near normal highway speeds and so do not generate the same speed differentials as those activities conducted at lower operating speeds but which still must be adequately protected through safe but effective vehicle warning lighting and traffic control procedures; and
- Some test procedures apply water to the pavement which can surprise an unsuspecting driver following behind and result in erratic behaviors.

Previously, very little research had been conducted to address these special traffic control needs and characteristics of pavement data collection systems. Little research also has been done to investigate how the major modifications made to "stock" pavement data collection vehicles might affect the safety of the workers operating that equipment.

RESEARCH OBJECTIVES AND TASKS

This report describes the results of a 17-month research effort for TxDOT by the Texas Transportation Institute to address some of the issues in both special vehicle flashing warning lights and pavement data collection systems. The specific research objectives were as follows:

1. Develop recommendations for improving TxDOT's warning light policy and practices for highway maintenance, construction, and service equipment; and
2. Evaluate pavement data collection equipment and operations, and develop recommendations for potential safety improvements.

To accomplish these objectives, researchers performed the following tasks:

- A nationwide survey of current DOT warning light and pavement data collection practices;
- A review and critique of current modifications to TxDOT pavement data collection vehicles;
- An assessment of motorist perceptions and interpretations of alternative warning light color configurations;
- An evaluation of the effect of alternative vehicle warning light color configurations upon traffic operations;
- Identification of safety problems being experienced by pavement data collectors in the field; and
- Evaluation and improvement of current pavement data collection equipment, procedures, and traffic control used during these procedures.

Researchers met periodically with the TxDOT project advisor and with several other TxDOT personnel who served on the project advisory committee (PAC). This group was responsible for guiding the overall direction of the research. Early on in the project, for example, the group decided that the research needed to focus on whether the use of blue lights in conjunction with yellow lights on selected equipment had a beneficial impact in getting motorists to be more cautious and to slow down. Consequently, researchers accomplished this through a motorist survey and field studies of alternative warning light color configurations as listed above.

ORGANIZATION OF THE REPORT

This report consists of six chapters. Following this introduction, Chapter 2 presents the overall background for this research, and describes the results of the nationwide telephone survey of vehicle warning light and pavement data collection system traffic control practices. Then, Chapter 3 provides a description and results of the survey conducted to assess motorist perceptions of alternative warning light color configurations. Chapter 4 describes the field studies conducted in three cities statewide to evaluate the effect of the alternative warning light color configurations upon traffic operations. Chapter 5 is devoted to the evaluation and critique of the pavement data collection equipment, procedures, and traffic control. Finally, the researchers present a summary of the findings from the research and recommendations for improvements in TxDOT warning light policy and in pavement data collections system activities in Chapter 6.

2. BACKGROUND

SPECIAL VEHICLE FLASHING WARNING LIGHTS

Previous Research

Special vehicle flashing warning lights have two primary functions. The first function is to attract the attention of nearby drivers and pedestrians so as to alert them to the situation they are approaching or that is approaching them. The second function is to provide those drivers and pedestrians with information about the situation so that they can take whatever appropriate action is needed. With respect to the first function, a significant amount of research has explored the understanding of human visual perception and detection of flashing warning lights. This research has shown that the detection (or conspicuity) of a light is predominantly dependent upon the effective intensity of its flash, with generally higher flash intensities associated with increased conspicuity (*12*). However, a flash too intense can have a deleterious effect by temporarily "blinding" an individual, particularly at night.

Other characteristics of a light such as the flash rate, on-off cycle, flash pulse shape, and flash duration also have some influence upon human detection capabilities (*12*). With respect to flash pulse shape and duration, a significant distinction exists between rotating or flashed incandescent lights which have a rather long duty cycle, and gaseous-discharge lamps (strobe) lights which emit an extremely intense light over a very small time duration (generally around 0.001 s). Whereas strobe lights tend to be more efficient at converting electricity into light than incandescent lights (*13*), evidence suggests that the extremely short duration of the flash hinders some driver's ability to estimate distance and movement to the light. To counter this effect, strobe manufacturers have developed multiple-flash units, spreading the total flash intensity out over two or more closely-spaced flashes. Originally used in roadway applications beginning in 1968, strobe lights have become an integral part of many emergency warning and highway construction/maintenance vehicle warning light systems. Combinations of incandescent and strobe lights are also commonly used to capture the benefits of both types of lighting technologies.

Likewise, the color of the light also has some effect on its conspicuity. Other researchers have shown that in daylight conditions, red lights are more conspicuous than blue lights, whereas the opposite is true under nighttime conditions. Interestingly, the conspicuity of yellow lights generally falls in between the blue and red lights in both daytime and nighttime viewing conditions (*10*).

In addition to the above characteristics, the number of flashing lights on a vehicle also affects the likelihood of detection and perception of that vehicle by a driver. Theoretically, each light added to a vehicle increases the probability that it will be seen under a given viewing condition. Of course, there is a space limit to the number of lights that can be added to a given vehicle. Perhaps more importantly, the additional conspicuity (detection potential) gained through the addition of more lights, different lighting types or mounting configurations, etc. may also reach a practical maximum. For example, does the ability to detect a vehicle from 1.6 kilometer (1 mile) away offer any substantial safety benefit than being able to detect it from 0.5 kilometer (0.5 mile) away? Similarly, does a reduction in detection time from 0.25 to 0.23 seconds (these are purely hypothetical values) help improve safety in a real sense? The real question that is of interest is whether an improvement in safety justifies the additional expense and complexity associated with installing and operating a more complex lighting system.

Studies conducted in the late 1980s lend some insight into the practical differences that can be expected from certain alternative warning light systems for maintenance (service) and construction vehicles (*9*). Researchers conducted some experiments to determine motorists' ability to estimate speeds of maintenance vehicles outfitted with each of the alternative systems, as well as their ability to judge the rate at which they were closing on that vehicle. Other experiments examined the effect of the lighting systems on driver lane changing behavior relative to the location of the maintenance vehicle. The study examined several factors related to light design (flash rate, intensity, mounting location, and type) but limited the evaluation of light color to yellow (or amber) because yellow is used almost exclusively for maintenance vehicle applications throughout the U.S. Also, many states restrict the use of other colors to authorized emergency vehicles only.

Although those researchers examined only a limited number of alternatives, the results did show that factors such as flash rates (between 60 and 100 cycles per min), intensities, and mounting location did not have a measurable effect on the performance measures examined in the study. Interestingly, combining different types of flashing technologies (i.e., four-way flashers with a flashing warning light, or combinations of rotating and flashing warning lights together on a single vehicle) did result in slightly improved responses. Strobe lights, although superior for conspicuity purposes, did not yield good judgements about vehicle speed or closure rates in comparison to those achieved with incandescent flashing lights. This was true for both the single and the double-flash strobes tested.

Another interesting finding was that the most effective vehicle warning light system differed depending on whether the study was performed at a short-term stationary lane closure or a continuously moving operation. For moving operations, an all-yellow light bar system (with rotating elements) was effective. However, this system did not work as well in a stationary lane closure environment. The researchers hypothesized that some motorists incorrectly associated the light bar with a moving operation (such as tow truck), and so did not change lanes until they were almost on top of the work zone. The rotating beacons/flashing strobe light combination system worked well in both the stationary and the moving work zones.

These last set of findings illustrate some of the issues associated with the other function of vehicle flashing warning lights, proper information transfer to motorists and pedestrians. Whereas detection/perception of a warning light is primarily physiological, information transfer is primarily cognitive. Here, the sensory information received through the visual system is converted to something meaningful through a pattern recognition process. Among other things, this process is highly dependent upon driver expectations developed through past experiences, how those experiences are coded in memory, and the context in which the information is received (*14*).

Color plays an important role in the memory coding and pattern recognition process. This fact is well accepted in the traffic engineering community, and is the main reason why traffic signs utilize standard colors to indicate different types of information (regulatory, warning, guide, etc.). A similar rationale exists for assigning warning light colors to certain applications (hence the restriction of certain light colors to emergency vehicles and yellow to maintenance and construction vehicles). However, the assignment of a single color (yellow) to all maintenance vehicle applications implies to motorists that all types of situations in which these vehicles are used are equal in terms of their severity, hazard potential, expected response, etc. Whereas it may be perfectly appropriate to convey a single message for emergency vehicles (i.e., high-hazard emergency situation approaching), service vehicles are used to perform many different activities, some much more hazardous to both motorists and workers than others. At the very least, it seems logical that some distinction is appropriate between those situations and activities which pose lower risk to workers and motorists, and those which pose higher risk (such as where workers are out next to traffic and little or no advance traffic control signing is present).

TxDOT's Equipment Warning Light Policy

Summary of Current Requirements

Section 547.105 of the *Texas Transportation Code* requires TxDOT to adopt standards and specifications relative to the application of warning lamps to highway maintenance and service equipment in Texas (*15*). The topic of equipment warning lights for TxDOT is covered in detail in the Department's *Equipment and Procurement Manual*, Section 3, Chapter 10, Sections 1 (General Equipment Lighting Policies) and 3 (Equipment Lighting Requirements, Warning Lights) (*16*). The Department states in that policy that the goal is for the public to be able to distinguish between its equipment and authorized emergency vehicles (police, fire, and ambulance vehicles) as defined in the Texas *Transportation Code*. At the same time, the intent is to assist the public in identifying highway maintenance (and construction and service) vehicles, presumably so that they use caution and safely approach and proceed past the equipment.

The policy calls for warning lights to be used on equipment whenever it is being used to perform its specific function on the roadway, the shoulder, or adjacent roadside outside of a traffic control barricade setup. Warning lights are recommended (but not required) on equipment being used within a barricade setup. In addition, special mobile equipment that is not intended for transporting persons or property but which occasionally travels on or are moved over the roadway (e.g., asphalt spreaders, ditch-diggers, bucket loaders, etc.) should display warning lights whenever they are on the roadway and require caution from approaching motorists.

Special instructions are provided for courtesy patrols. Courtesy patrols respond to a variety of crash and incident situations at all types of locations. Because incidents cannot be preplanned the same way that construction or maintenance-type activities can, these locations and conditions often present special difficulties and hazards to both workers and motorists. Presently, the policy is rather restrictive in how these patrols can operate their lights:

> "The [courtesy patrol] warning lights should be used while the vehicle is parked or stopped on the shoulder adjacent to the roadway to aid in the control of traffic at the scene of an accident or other road hazard"(*16*).

Discussions with courtesy patrol operators in Dallas and San Antonio indicate that they are often the first response vehicle on scene and the last to leave. In certain jurisdictions, the local law enforcement agency will leave the site when their official duties are completed and leave TxDOT to complete the clean up on its own.

There are three important configuration restrictions specified in the current warning light policy. The first is that no warning lights are allowed to display a red indication toward the front of the vehicle or a white light to the back of the vehicle. The second is that multiple warning lights are not allowed to wig-wag rhythmically. The third restriction is that warning lights cannot be installed inside the vehicle cab, behind a grill, or into the OEM standard light lenses on a vehicle. These restrictions are all included in order to keep the warning light system from appearing too similar to those of authorized emergency vehicles. The policy also provides specific restrictions regarding the warning light colors allowed for use. A special caution is included in the policy regarding the use of blue lights:

> "To maintain the effectiveness of the blue warning lights, vehicles so equipped must use them only when performing the approved functions; at other times blue lights should not be used."

The policy states that all types of equipment have at least one omnidirectional flashing amber (yellow) warning light mounted as high as possible and clearly visible from all directions. The policy also allows (but does not require) additional warning lights to be installed if desired according to the following requirements:

- One pair of front-facing simultaneously flashing white or amber warning lamps, mounted on the exterior of the vehicle as high (but identical) and as far apart as possible; and

- One pair of rear-facing simultaneously flashing red or amber warning lamps, rear-mounted as high as practical on the exterior of the vehicle, at the same height and spaced as far apart as possible. If these are used on off-roadway or special mobile equipment such as mowing equipment or tractors, the lenses are to be at least 178 mm (7 in) in diameter.

The policy also requires incident response vehicles to have at least one omnidirectional flashing amber light but also allows a low-profile warning light bar to replace or supplement this single warning light. If the vehicle will be used for directing or channelizing traffic at an incident site, it is to also have an arrow panel that complies with the *Texas Manual on Uniform Traffic Control Devices* (MUTCD) attached to the vehicle as well (*7*).

Above these general requirements, current TxDOT policy also specifies that certain types of vehicles and equipment may utilize blue lights in conjunction with the amber warning lights. Traditionally, the equipment for which the policy approves blue lights include those which perform functions that require additional safety of work crews (who may be out of the vehicle from time to time or traveling at much slower speeds than normal and so more vulnerable to traffic). The equipment list approved for blue light use includes the following:

- Snow plows and ice-control equipment,
- Street sweepers,
- Signal-light maintenance trucks,
- Advanced-warning (shadow) trucks with truck-mounted attenuators (TMAs) for center-stripe machines,
- Herbicide spray vehicles,
- Skid-testing vehicles,
- High-speed profilometers,
- Dynaflect and falling-weight vehicles,
- Pavement-evaluator-rator vehicles,
- Motorist assistance (courtesy patrol) vehicles,
- Trash trucks, and
- Vehicles used by maintenance foremen or assistant maintenance foremen.

The policy also provides specifics about the layout of warning light colors allowed on light bars for incident response vehicles (vehicles for courtesy or motorist assistance patrols or for maintenance and assistant maintenance foremen). The policy calls for amber, blue, and white lights to be visible to the front of the vehicle. Colors to be visible to the rear of the vehicle on the light bar are amber, blue, and red.

Critique of Current Policy

Early on in this study, researchers met with the TxDOT Project Advisory Committee as a group and with select members individually to discuss problems with the current warning light policy. The controversial aspects of this policy within the Department tend to hinge on the blue light usage and lighting configurations for the courtesy patrol vehicles. The opinion of TxDOT field personnel is that motorists disregard amber lights and only respond (i.e., slow down) when a vehicle also has blue lights attached. Conversely, law enforcement (Department of Public Safety) officials are concerned that the increased use of blue and other colored warning lights will dilute their effectiveness for all applications (including emergency vehicle response) and lead to a reduced level of safety for both work personnel and the motoring public. Key questions exist as to how drivers perceive differences warning light color configurations and whether they alter their driving behavior in response to those perceptions.

Related to blue light use policy, concern has also been expressed about how to best specify which equipment can utilize blue lights. Requests to add more equipment to the approved list come in regularly to the Department. Many of the jobs being performed with non-approved equipment subject work crews to conditions believed to be as hazardous as those which the equipment approved for blue light use are used. As an example, crews responsible for collecting Global Positioning System (GPS) roadway data operate in a manner very similar to some of the pavement data collection activities, but vehicles which they use have not been approved for blue light use at this time. Specification of a more functional-based policy (i.e., a statement that a certain type of work activity on a given type of roadway can use blue and yellow lights on vehicles used for that activity) has been suggested. However, this approach has potential problems as well in assuring that the number of blue lights in use is controlled so as to not reduce their overall effectiveness.

Warning Light Colors Used in Other States

As part of study efforts for this project, researchers performed a telephone survey of each of the state departments of transportation to determine (a) whether they used any other colors besides yellow or amber for their fleet vehicle flashing warning lights, (b) whether they utilized any of the newer warning light technologies (i.e., light sticks, light bars) on their equipment, and (c) whether they perceived a need or were interested in supporting a national standard for service vehicle warning light systems.

As expected, all states indicated that yellow was the primary warning light color utilized on its vehicle fleet. However, 12 states (24 percent) utilize at least one other color besides yellow. Those questioned mentioned the following colors during this survey:

- Blue (mentioned by seven states),
- Red (mentioned by five states), and
- White (mentioned by five states).

Although seven states indicated that they did utilize blue lights, four of them noted that this color was limited to use on their snow removal equipment. Others indicated that the color was included in the light bar assembly mounted on top of their courtesy patrol vehicles (as was generally the case for the use of the red and the white lights also).

In general, most departments indicated that they did not use a single type of warning light technology on their equipment, but instead used a variety of rotating beacons, strobes (single or multiple flash), and light bars (full or mini). Four of the state departments of transportation indicated they were also using light "sticks" on a few of their vehicles (courtesy patrols and research vans were specifically mentioned). These sticks have several lights arranged in a row that can be operated in one of several sequencing, simultaneous, or wig-wag patterns. At least one state utilizes these sticks in combination with a light bar (the sticks are mounted below the light bar and face to the rear). A number of departments also indicated that they had gone to an integrated vehicle warning light system that incorporates the special flashing warning lights on the top of the vehicle with the regular four-way flashers on the front and back of the vehicle

Researchers also asked whether the state agency had developed an official state policy regarding special vehicle warning lights for its fleet. Only 14 states (28 percent) responded positively to this question. Of course, since most states utilize yellow lights exclusively, little need may exist for them to establish a formal warning light policy. Nonetheless, the survey results do suggest that most state transportation agencies do not view their current vehicle warning light practices with a great deal of concern at this time.

PAVEMENT DATA COLLECTION SYSTEMS

TxDOT Traffic Control Guidelines

With respect to traffic control guidelines and procedures established by TxDOT and FHWA (*7,8*), pavement data collection generally falls in the mobile work activities category or in the short duration category in special instances (such as testing at a single location on the roadway). It is recognized that these activities are difficult to treat from a traffic control perspective because standard traffic control setups for work in the roadway (advance signing, channelizing devices, etc.) take much longer to install and remove than the actual work being done and so may create a greater total risk to motorists and workers than a quicker, simplified traffic control setup. It is generally held that simplified control procedures may be warranted for short duration and mobile work, and that these simplified procedures "...may be offset by the use of other more dominant devices such as special lighting units on work vehicles" (*7*).

TxDOT traffic control plans for mobile operations calls for the use of protection (shadow) vehicles following the service equipment/vehicle at a distance that ensures adequate visibility of the protection vehicle by approaching motorists as well as sufficient protection of the service vehicle. On multilane divided roadways, arrow panels and lane blocked signs (FCW20-6) or lane closed signs (CW20-5) are required. Generally speaking, TxDOT designed these plans to accommodate, as best possible, the many day-to-day mobile operations required for highway maintenance (i.e., pothole patching, crack sealing, paint striping, marker replacement, etc.) under the many different operating conditions present within the state.

Unfortunately, it is sometimes difficult to justify the use of a shadow vehicle for some pavement data collection activities, particularly those that occur on low-volume roadways that involve only a few minutes at a given location or two. To investigate how data collection activities were addressed in other states, researchers also used the nationwide telephone survey described above to query other states about their traffic control practices for pavement data collection.

Pavement Data Collection in Other States

Many of the other states contacted concerning traffic control for their pavement data collection also identified the plans incorporated in their state MUTCD for mobile or short duration work activities as what they follow for pavement data collection work. A few states, however, have developed more specialized plans and procedures for one or more of the types of data collection equipment used and activities performed. In Missouri, for example, workers mount the advance signing called for in a typical moving operation on the back of three vehicles spaced up to 150 m (500 ft) apart and parked on the shoulder of the roadway upstream of the pavement test equipment. Also, the typical first sign, ROAD WORK AHEAD, is replaced with a ROAD TESTING AHEAD sign. This provides the advance signing as required by state and national standards, and allows the data collection crew to move as desired without delays in picking up and setting out the signs at each data collection location.

Another state that has developed more extensive traffic control plans and procedures for pavement data collection is Colorado. The DOT has established a traffic control plan specific for mobile deflection testing of its pavements (using a falling weight deflectometer [FWD]) that includes the following elements:

- Strobe emergency warning lights mounted on both the vehicles and the equipment trailer;
- 457 mm (18 in) square orange flags mounted on each corner of the truck that tows the equipment;
- Telescoping flag trees that hold three of the square orange flags and are attached to the rear bumper of the FWD trailer. These extend to a height of 3.8 meters (12.5 feet);
- Special folding black on orange signs (61 mm x 76 mm [24 in x 30 in]) displaying the words "SUDDEN STOPS." These signs are displayed on the front of the truck towing the FWD and on the rear of the FWD trailer;
- An arrow panel is required, flashing in either a caution or arrow mode depending on the roadway being tested;
- ROAD TESTING NEXT X MILES signs are positioned on each end of the road segment being tested (the maximum length of testing allowed at one time is 8 km [5 mi]); and
- On two-lane, two-way highways where flaggers are needed to control alternating one-way traffic around the FWD, a sign is placed on the tailgate of the shadow vehicle that states DO NOT PASS/WAIT FOR SIGNAL.

3. MOTORIST INTERPRETATIONS OF VEHICLE WARNING LIGHT COLORS

One of the reasons for considering the use of additional colors and color combinations (other than just yellow) for special flashing warning lights on certain types of maintenance and construction vehicles is the assumption that these other colors imply a greater sense of danger or hazard to motorists. Traditionally, yellow flashing lights have been employed on vehicle warning lights, intersection beacons, and flashers mounted on signs and barricades in work zones. The level of hazard associated with these uses varies dramatically. Conversely, most states restrict certain colors of flashing lights to authorized emergency vehicles. Intuitively, one expects that these restrictions in effect teach motorists a flashing light color hierarchy over time as they encounter the different types of emergency vehicles and their associated warning light combinations. However, these assumptions have never been investigated in an objective manner. This chapter presents the results of surveys conducted in Dallas-Fort Worth, Houston, and San Antonio to assess motorist interpretations of special vehicle warning light colors.

SURVEY DESIGN

The survey consisted of two parts. In the first part, motorists answered the following questions for each of several warning light colors and color combinations:

1. "If you saw flashing (color or color combination) warning lights mounted on top of a vehicle, how hazardous would you consider the situation you were approaching?"

2. "What driving action, if any, would you take?"

Possible responses to the first question were as follows:

- Not hazardous at all,
- Somewhat hazardous,
- Moderately hazardous,
- Very hazardous, or
- Extremely hazardous.

Possible responses to the second questions were as follows:

- No action,
- Take foot off accelerator,
- Tap brake,
- Apply brake gently, or
- Apply brake firmly.

Researchers queried motorists on each of the following colors/color combinations:

- Yellow,
- Blue,
- Red,
- Yellow/blue,
- Yellow/red,
- Blue/red, and
- Yellow/blue/red.

Researchers counterbalanced the presentation order of the various colors/color combinations to eliminate potential biases or the implication of increasing or decreasing hazard associated with a given order of presentation.

The second part of the survey asked subjects what colors of lights they expected to see on top of different types of vehicles. Vehicle types included the following:

- Police vehicle;
- Ambulance;
- Fire truck;
- School bus;
- Highway construction, maintenance, or service vehicle;
- Tow truck; and
- Motorist assistance or courtesy patrol vehicle.

An example of the survey form (showing one of the seven presentation orders) is provided in Appendix A.

SURVEY ADMINISTRATION

TTI researchers traveled to Dallas-Fort Worth, Houston, and San Antonio during the spring and summer 1998 to administer the survey at Department of Public Safety (DPS) driver licensing stations. Researchers approached potential subjects as they stood in line to renew their licenses, and asked them to participate in the short survey. In general, subjects were able to complete the survey in 10 minutes or less. In the interest of timeliness, researchers did not ask subject any questions regarding age or education. However, researchers did attempt to obtain responses from both younger and older subjects, and so the results reported in this chapter are believed to be fairly representative of the overall driving population in Texas.

At each driver licensing station, researchers attempted to obtain a total of 100 responses. This target goal was met in Dallas-Fort Worth and in Houston. However, only 56 surveys were obtained in San Antonio because subjects generally did not have to wait in line (adequate service capacity was available for license renewal) and were reluctant to remain around afterwards to complete the survey.

SURVEY RESULTS

Motorist Perception of Warning Light Colors

Table 3-1 summarizes the responses to the question about the level of hazard associated with each light color/color combination. Overall, the results do indicate that Texas drivers have learned a definite color hierarchy with respect to special flashing vehicle warning lights. Researchers conducted chi-square tests of independence between the various warning light color combinations and response categories. These tests identified several significant differences between warning light colors and color combinations. Test results for the data presented in Table 3-1 are summarized in Appendix B.

Individually, yellow lights appear to convey the least degree of hazard to motorists, followed by blue, and then red. However, it is interesting to note that blue lights alone also received a significant number of "not hazardous" ratings (even slightly more than for yellow), indicating that its use alone does not convey a consistent level of urgency to all motorists. A few more of these "not hazardous" ratings came from the San Antonio location than from the other two locations. However, the differences in response by location for that color are not statistically significant at an 0.05 level of significance.

When two or more colors are combined in one display, the yellow/blue combination represents a slightly more hazardous situation to motorists than the yellow lights considered alone. However, statistical tests also indicate that the yellow/blue combination is perceived to represent a lesser degree of hazard than does the yellow/red combination. The red/blue combination yielded higher hazardous ratings than either the yellow/blue or the yellow/red combinations. Although the red/blue color combination received a large number of higher hazard rating by subjects, it was not as high as was obtained by just the red lights alone. Similarly, the red/blue/yellow combination yielded ratings that were not significantly different than the red/blue combination, but tended to be slightly less hazardous than those received for the red lights alone.

Table 1. Level of Hazard Associated with Various Light Colors/Color Combinations

Flashing Warning Light Color/Color Combination	Percent of Motorists Responding															
	"Not Hazardous"				"Somewhat Hazardous"				"Moderately Hazardous"				"Very Hazardous" or "Extremely Hazardous"			
	H	D-FW	SA.	Avg.	H	D-FW	SA	Avg.	H	D-FW	SA	Avg.	H	D-FW	SA	Avg.
Yellow	13	11	18	13	40	52	49	47	39	30	27	33	8	7	7	7
Blue	17	18	30	20	33	29	23	29	35	33	34	34	15	20	14	17
Red	3	0	0	1	12	10	9	10	20	21	18	20	65	70	73	68
Yellow/Blue	15	8	11	11	29	38	32	33	39	34	48	39	17	20	9	17
Yellow/Red	9	8	3	7	22	27	17	23	38	33	42	36	32	32	39	33
Red/Blue	3	6	0	4	10	15	7	11	36	29	43	34	52	50	50	51
Red/Blue/ Yellow	5	1	5	3	14	10	0	13	31	27	23	28	49	62	59	56

H = Houston
D-FW = Dallas-Fort Worth
SA = San Antonio

Corresponding to the results shown in Table 1, Table 2 presents a summary of survey responses as to the appropriate driving actions to take when encountering each flashing vehicle warning light color/color combination. Appendix B also includes the results of statistical tests of independence between these various colors/color combinations and driving action response categories. Although responses differed between all but two of the color combinations in Table 1 (the red/blue and red/blue/yellow combinations were not significantly different), only a few color combinations generated significantly different driving action responses considered to be appropriate when approaching the lights. For example, responses shown in Table 2 were not found to differ significantly between the yellow, blue, and yellow/blue color combinations. In particular, subject choices about the appropriate driving action to take were not significantly different between the yellow light only, blue light only, or yellow and blue lights together. Overall, 40 to 45 percent of the subjects believed they should take no action or simply take their foot off the accelerator in response to seeing these colors on a vehicle. However, the yellow/red combination did result in different responses than did the yellow or the blue lights alone. Red lights alone yielded responses that differed significantly from the yellow, blue, yellow/blue, and yellow/red light combinations, but were similar to those obtained for the red/blue and red/blue/yellow light combinations.

In terms of location-by-location differences in the responses, San Antonio subjects generally selected a greater percentage of less-dramatic actions (e.g., no action or take foot off accelerator) for the yellow, blue, and (surprisingly) yellow/blue combination than did subjects in the other cities. Researchers do not know whether the ongoing extensive roadway construction activity in the region or other unknown factors have reduced driver sensitivity to these lights in this city.

In summary, it does appear that motorists associate less hazard or danger with yellow flashing warning lights relative to some of the other colors and color combinations they may see. As a result, they also seem to perceive less of a need to slow down when approaching vehicles with flashing yellow lights than when approaching vehicles with yellow combined with red lights. Whereas it does appear that the presence of a blue light with the yellow light implies a greater sense of hazard to motorists, it does not appear that they associate a need to alter their driving behavior because of the presence of blue and yellow lights. This has important implications with regards to TxDOT's vehicle warning light policy. Recommendations regarding policy changes are provided in Chapter 6.

Table 2. Appropriate Driving Action Associated with Various Light Colors/Color Combinations

Flashing Warning Light Color/Color Combination	Percent of Motorists Responding															
	"No Action"				"Take Foot Off Accelerator"				"Tap Brake"				"Apply Brake Gently" or "Apply Brake Firmly"			
	H	D-FW	SA	Avg	H	D-FW	SA	Avg	H	D-FW	SA	Avg	H	D-FW	SA	Avg
Yellow	6	13	16	11	37	33	44	37	14	13	11	13	43	40	29	39
Blue	14	15	18	15	30	26	36	29	18	12	14	15	38	47	32	41
Red	2	0	0	1	11	14	7	12	9	8	7	8	79	78	86	80
Yellow/Blue	10	8	9	9	24	27	45	29	17	19	14	17	50	47	32	45
Yellow/Red	7	6	0	5	21	20	22	21	17	16	14	16	55	58	64	58
Red/Blue	2	4	0	2	14	13	16	14	16	11	18	14	69	72	66	70
Red/Blue/ Yellow	6	2	2	4	12	13	20	14	14	9	16	12	69	76	61	71

H=Houston
D-FW = Dallas-Fort Worth
SA = San Antonio

Motorist Association of Warning Light Colors to Specific Vehicle Types

Researchers designed the second phase of the survey to investigate the types of warning light colors and color combinations motorists tend to associate with different types of emergency and other official vehicles. In this phase, they asked motorists to write down the special vehicle warning light colors they associated with each type of vehicle. Responses were completely open-ended. Subjects were not provided any type of list of appropriate colors or any other guidance (other than the colors investigated in part 1 of the survey). A summary of the major colors/color combinations that motorists associated with each vehicle type is provided in Table 3. Only those colors which received at least 10 percent of the responses are shown in the table. Consequently, the values in the various cells do not necessarily total 100 percent.

Table 3. Warning Light Colors Associated with Various Vehicle Types

Vehicle Type	Flashing Warning Light Color/Color Combination	Percentage Responding			
		Houston	Dallas-Ft. Worth	San Antonio	Average
Construction, Maintenance, or Service Vehicle	Yellow	69	75	58	70
	Blue	-	-	11	-
Motorist Assistance Vehicle	Yellow	20*	56	58	42
	Blue	17	12	14	14
	Blue/Yellow	-	-	14	10
	Blue/Red	18*	-	-	-
Tow Truck	Yellow	74	65	76	70
	Red/Yellow	-	12	-	-
Police	Blue/Red	56	42	56	50
	Yellow/Red/Blue	-	17	12	13
	Red/White/Blue	12	10	-	-
	Blue	-	-	10	-
Ambulance	Red	43	30	46	38
	Red/Blue	10	13	-	10
	Red/White	26	19	12	21
	Red/Yellow	10	16	-	12
Fire Truck	Red	63	46*	78	58
	Red/White	18	15	11	16
	Red/Yellow	10	11	-	-

\- less than 10 percent of the respondents
* percentage is significantly different ($\alpha = 0.05$) than the other two locations

For the most part, the results in Table 3 are consistent with current Texas special vehicle warning light policies regarding color. Specifically, most motorists associate the color yellow with basic service vehicles (construction and maintenance vehicles, motorist assistance vehicles, and tow trucks). However, 11 percent of those surveyed in San Antonio identified the color blue with use in construction and maintenance vehicles. Responses from the other cities did not yield similar results with respect to blue lights. This result may help explain the association of blue lights with less dramatic driving actions by San Antonio subjects as shown previously in Table 2.

Responses for the motorist assistance vehicles also included other light color configurations besides yellow. Researchers expected this, as the patrols in each of the three locations surveyed do typically utilize more than just the yellow lights only. Also, the distribution of responses did vary considerably from location to location. Again, this was expected, as there is some variance in how the different agencies outfit their motorist assistance vehicles. For example, the motorist assistance patrol in Houston is a consortium of several agencies and the private sector and is manned by uniformed law enforcement officers from the Harris County sheriff's office. Consequently, these vehicles are outfitted with a blue/red light combination that is typical for law enforcement vehicles in many jurisdictions statewide. In addition, TxDOT operates a service patrol in Houston after hours that is equipped with both yellow and blue lights. This may also help explain why the responses from the Houston subjects did not identify any one color or color combination as being predominant for that location.

The responses subjects provided regarding light colors on emergency vehicles also generated some interesting results. In particular, motorists do appear to recognize differences in warning light color combinations used by police vehicles and those used by other types of emergency vehicles. For example, motorists cited a red/blue light combination most often for police vehicles (by 50 percent of those surveyed), whereas the single color red was more often cited for ambulances and fire trucks. In fact, only 10 percent of motorists associated the red/blue light combination with an ambulance, and less than 10 percent did so for fire trucks. However, substantial differences in these responses are evident from location to location. In Dallas-Fort Worth and in San Antonio, for example, a red/blue/yellow light combination for police vehicles was the second-most frequently identified combination (behind the red/blue combination). In comparison, Houston subjects cited the red/blue/white combination for police vehicles second-most frequently. With respect to fire trucks, Dallas-Fort Worth subjects reported a wider variety of colors and color combinations and generated responses that were not consistent with those from Houston and San Antonio.

IMPLICATIONS OF RESULTS TO TXDOT VEHICLE WARNING LIGHT POLICY

Current TxDOT policy calls for the use of yellow (amber) warning lights to be used on appropriate fleet vehicles and equipment. A blue light supplements the yellow light on certain types of equipment that present higher risk to workers and the motoring public because of the nature of the work where these vehicles and equipment are used. For courtesy patrol and other vehicles used for incident response, the colors red and white (with appropriate viewing restrictions) are allowed to be installed on the vehicle as well.

The purpose of allowing blue and yellow lights on selected vehicles and equipment is the assumption that the use of the blue light added a greater sense of urgency and need to be cautious by motorists as they approach the vehicle. The results of this survey does suggest that the combination of blue and yellow lights implies a slightly greater sense of hazard to motorists than does the yellow light alone. However, this greater sense of hazard does not necessarily translate into differences in how motorists believe they need to respond to the different color lights. In fact, when asked what action they should take in response to a yellow light in comparison to a yellow and blue light combination, no statistically significant differences in responses were found. Somewhat surprisingly, it is a yellow and red light combination on top of the vehicle which motorists say is indicative of a higher hazard condition and which implies to them a greater need to respond by applying their brakes. Although this configuration is not judged as hazardous as the red/blue/yellow configuration allowed for use on courtesy patrols, it does represent a more significant shift in subject perceptions from the yellow light only configuration.

It is important to recognize the limitations of a pencil and paper survey when attempting to assess perceptions such as these. For instance, whereas many subjects may indicate on paper that they believe they should apply their brake in some manner as they approach a vehicle with only a yellow light flashing on top (such as is implied in Table 2), these same subjects may or may not actually behave in this manner while driving. Consequently, the results of the survey described in this chapter are more likely to reflect motorist perceptions of correct interpretations and behavior, rather than actual behavior. Nonetheless, the results indicate a limited potential for blue lights to actually affect driving behavior more than the use of yellow lights only.

4. FIELD STUDIES OF ALTERNATIVE VEHICLE WARNING LIGHT COLOR CONFIGURATIONS

The survey results described in chapter 3 suggest that motorists do indeed perceive differences in vehicle warning light color configurations, and believe they should respond differently to them. To determine whether these perceptions actually translate into differences in driver behavior, researchers conducted a series of field studies on five urban freeway sections in Houston and San Antonio, Texas. In each study, TxDOT maintenance or courtesy patrol vehicles were outfitted with different vehicle warning light color combinations and placed, one at a time, on a shoulder next to moving traffic with the lights activated. Consistent with current TxDOT policy, the warning light color combinations examined in this phase of the study were as follows:

- Yellow lights only,
- Yellow/blue lights,
- Yellow/blue/red lights (San Antonio courtesy patrol), and
- Blue/red lights (Houston motorist assistance patrol).

Researchers did not test the yellow/red light configuration in the field. The basic question to be answered in these studies was whether the use of different lighting configuration had an effect on operational behavior at all. The study encompassed both ends of the spectrum with respect to driver perceptions of hazard (the yellow light at the lesser end and the yellow/blue/red or blue/red light at the greater end), and so researchers expected it to provide an answer to that question. Furthermore, researchers believed that the results from these configurations would allow some inferences to be drawn about whether a yellow/red lighting configuration could be beneficial.

A fourth combination, consisting of yellow and blue strobes mounted in the back window of a TxDOT sport utility vehicle and strobes mounted in the rear-tail light assemblies (operating in a simultaneous double-flash mode), were also tested at two of the sites. To evaluate the effect that vehicle type itself has upon driving behavior, TTI was assisted in the research by officers with the Texas Department of Public Safety (DPS). These officers brought out their police cruisers (and their yellow/blue/red warning light) and allowed researchers to obtain data at the same locations as where the alternative warning light configurations on TxDOT vehicles were evaluated.

STUDY METHODOLOGY

At each of five study sites, researchers videotaped traffic approaching the vehicle from 150 to 450 m (500 to 1500 ft) upstream (depending on viewing conditions) to determine vehicle speeds, traffic distribution by lane, lane-changing activity, and brake activations under each of the flashing vehicle warning light configurations. Researchers collected approximately 1 hour of data at each site for each warning light configuration tested. They tested vehicles on either the left or the right shoulder in either daytime or nighttime conditions (both daytime and nighttime conditions were evaluated at Site 1). Brake applications could only be determined during the nighttime studies, however. Furthermore, camera difficulties and other temporary problems did not allow all of the different types of data to be obtained from each of the five sites. Nonetheless, the data were sufficient to allow a fairly extensive evaluation to be completed in most cases.

TTI researchers during this study benefited greatly from the use of the freeway traffic management systems in both San Antonio (i.e., Transguide) and Houston (i.e., TranStar). Personnel at each center assisted the researcher with camera and videotaping access and with field communications, and other agency personnel brought vehicles outfitted with the appropriate warning light configurations to the study sites.

SITE DESCRIPTIONS

Studies were conducted at a total of five different freeway locations in San Antonio and Houston. Data on some of the warning light configurations were also collected during a short-term maintenance activity in Dallas. Unfortunately, a less-than-ideal camera viewing perspective coupled with debris in the roadway upstream of the service patrol vehicles did not allow the data collected at that location to be used in the final analysis.

Table 4 presents a summary of the roadway characteristics at each site. Site 1 was located on Interstate 410 (I-410) westbound in northern San Antonio just prior to the interchange with Interstate 10 (I-10). The roadway in this direction of travel consists of three through travel lanes, a partial left shoulder, an exit-only lane to the right onto I-10, and a full right shoulder. The courtesy and police patrol vehicles used in the study were parked on the left side of the freeway beyond the left shoulder opposite the gore area for the right-hand exit lane. This location was approximately 150 m (500 ft) upstream of a left-hand exit from I-410 to I-10 eastbound, which may have had affected the responses of drivers in the left-hand lane as they passed the study vehicles. High-mast lighting illuminated the entire study area at night. Upstream of the test location, I-410 was undergoing major freeway reconstruction. However, no lane closures were present during the study to unduly influence vehicles speeds or driver lane choice. Significant (more than 300 m [1000 ft]) sight distance was available to the study vehicles. Both daytime and nighttime data were collected at this site.

Site 2 was also located in San Antonio on I-35 southbound south of downtown past Division Street. This site also consisted of three travel lanes southbound, plus full left and right shoulders except at overpasses where they are narrowed down. At this location, study vehicles were placed on the right shoulder just prior to where the shoulder narrows down across the overpass. The freeway raises to cross over the arterial at this location, such that the study vehicles were elevated and visible to approaching traffic from significant distance upstream. Because of camera problems, only daytime data were collected at this location.

Table 4. Summary of Study Site Characteristics

Site	Location	# Lanes	Shoulders?	Overhead Lighting?	Vehicle Location
1	I-410 EB @ I-10, San Antonio	3	partial left, full right	high-mast	beyond left shoulder
2	I-35 SB @ Division, San Antonio	3	full left, full right (narrowed at bridge)	N/A	right shoulder
3	I-610 EB @ Kirby, Houston	5	full left, partial right	high-mast	in exit ramp gore area
4	US-59 NB @ Hillcroft, Houston	5	full left, full right	high-mast	right shoulder
5	US-59 NB @ Shepard, Houston	5	full left, full right	high-mast	right shoulder

Site 3 was located in Houston on I-610 (South Loop) eastbound at the exit to Kirby. The roadway at this location is very wide, consisting of five travel lanes plus a full left shoulder. Agency personnel positioned the study vehicles in the gore area between the right travel lane and the exit ramp. This section of freeway provided good sight distance to the study vehicles, and high-mast lighting was present to provide good nighttime visibility at this location. Only nighttime data were collected at this location in order to limit demands upon TranStar personnel for this activity.

Site 4 was also located in Houston, on US-59 (Southwest Freeway) northbound at Hillcroft. Again, the freeway section at this location consisted of five travel lanes in this direction, plus full inside and outside shoulders. This section had also recently been reconstructed to higher design standards. Consequently, the roadway alignment was fairly level and straight, which afforded drivers good sight distance to the vehicles. Agency personnel positioned the study vehicles on the right shoulder. High-mast lighting was once again present at this location, and only nighttime data were collected.

The fifth and final site, also in Houston, was also located on US-59 northbound, but inside the I-610 loop at Shepard. The freeway consisted of five lanes in this direction plus a large left and right shoulder. The section was slightly elevated, which appeared to cause some problems for the camera used for data collection purposes. The alignment of oncoming traffic was such that headlights tended to aim into the camera, causing the iris to close and create a darker picture than was actually desirable. Furthermore, high-mast lighting was present at this location, but was not quite as bright as for the previous site. The vehicles were located on the right shoulder for this study as well. Data collection efforts were limited to nighttime hours only.

DATA REDUCTION AND ANALYSIS

Researchers brought the videotapes taken at each study site back to the office, and overlaid a running time stamp (to the nearest 1/100th second) on the image. This allowed researchers to estimate travel speeds of vehicle by measuring travel times over an approximate 61-m (200-ft) distance on the roadway. They measured speeds near the location of the study vehicle. In a few of the nighttime cases, the camera perspective and lighting conditions did not allow speeds to be measured.

Researchers also measured traffic volumes by lane in order to evaluate any changes in lane choice due to the different warning light color configurations. Actual lane changes occurring within the fields of view provided by each camera (generally 100 to 300 m [300 to 1000 ft]) were also counted from the video. Finally, brake light actuations occurring within the field of view were counted during the nighttime studies only.

STUDY RESULTS

Effect of Warning Lights on Vehicle Speeds

Table 5 presents a comparison of average speeds of vehicles passing the test locations when the different vehicle warning light configurations were being displayed. These data represent the average of approximately 120 vehicles during each time period. Camera problems did not allow speed data to be obtained from Site 4 (US-59 at Hillcroft) in Houston or during certain other portions of the study as illustrated in the table.

At two of the five sites tested, vehicle speeds when the yellow and blue light combination was displayed were significantly (8 to 10 kmph [5 to 6 mph]) lower than when only a yellow light was displayed. At the other three sites, speeds were not significantly different between these two warning light configurations. Interestingly, no statistically significant differences were found in average speeds at any of the sites when the yellow/blue/red (or blue/red) warning light configuration was compared to the yellow warning light only configuration. The yellow and blue strobes with red strobes in the vehicle tail lights did not yield a significantly lower speed at Site 1 relative to the yellow only configuration during either the daytime or the nighttime study period.

Table 5. Effect of Warning Light Colors on Average Speeds

Site		Average Speed, mph				
		Yellow Only	Yellow/Blue	Yellow/Blue/ Red	Yellow/Blue (Strobe)	Yellow/Blue/ Red (DPS)
1:	Day	68	71	71	66	N/A
	Night	60	58	58	60	61
2:	Day	61	56*	63	58	N/A
3:	Night	59	56	56[a]	N/A	58
4:	Night	N/A	N/A	N/A	N/A	N/A
5:	Night	60	54*	61[a]	N/A	59

* Significantly lower ($\alpha = 0.05$) than the yellow only light condition
[a] The motorist assistance patrol in Houston utilizes a red and blue warning light configuration
N/A data not available
note: 1 mph = 1.6 kmph

Perhaps equally surprising was the finding that the presence of the DPS vehicle parked on the shoulder with its lights flashing did not affect speeds any more than the TxDOT vehicles. No statistically significant differences were found between speeds observed when that vehicle was present and when the TxDOT vehicles with yellow flashing lights were present. Average speeds at four of the five sites were not particularly excessive, even for the yellow light configuration, and so may have been why the presence of the DPS vehicle with flashing light did not have more of a significant effect. Unfortunately, daytime speed data were not available for the DPS vehicle at Site 1, where average speeds for the other warning light configurations were higher.

Effect of Warning Lights on Driver Lane Choice and Lane Changing

Researchers also examined driver lane choices as a potential measure of performance regarding different vehicle warning light colors. They evaluated lane choice both in terms of the percentage of traffic in the lane closest to the vehicle warning lights, and in terms of lane-changing rates away from the lights (within the camera field-of-view). Table 6 presents the percentage of traffic in the lane closest to the flashing warning lights. Sample sizes for these percentages were between 100 and 1000 vehicles per hour per lane, depending on the time and location. Generally speaking, the different warning light color configurations had very little effect upon this performance measure. The only statistically significant differences detected occurred during the nighttime studies at Site 1, where lane percentages adjacent to the yellow/blue/red and yellow/blue strobe warning light configurations decreased slightly relative to the yellow light only configuration. As with the speed data, no significant differences were detected in the lane distribution when a DPS vehicle was used relative to the other warning light configurations tested.

Table 6. Effect of Warning Light Colors on Lane Distributions

Site		Percent of Traffic in Lane Next to Study Vehicle				
		Yellow Only	Yellow/Blue	Yellow/Blue/ Red	Yellow/Blue (Strobe)	Yellow/Blue/ Red (DPS)
1:	Day	33	34	36	39	34
	Night	39	35	33*	33*	36
2:	Day	33	35	39	33	39
3:	Night	16	19	19[a]	N/A	18
4:	Night	22	21	19[a]	N/A	N/A
5:	Night	11	11	12[a]	N/A	9

* Significantly lower ($\alpha = 0.05$) than the yellow only light condition
[a] The motorist assistance patrol in Houston utilizes a red and blue warning light configuration
N/A data not available

Table 7 shows the percent of traffic making a lane change away from the location of the study vehicle (i.e., to the left if the vehicle is on the right shoulder, towards the right if it is on the left shoulder). From these data, it is also apparent that the type of warning light configuration displayed had little, if any, effect on driver lane choice behavior. Site 3 did experience significantly higher lane changing rates away from the lights when blue and red colors were used in conjunction with yellow light (in comparison to the all yellow light configuration). However, this was not repeated at the other sites. At Site 5, the use of the DPS vehicle also yielded an increase in lane-changing away from the vehicle, but this again was not replicated at any of the other sites.

Table 7. Effect of Warning Light Colors on Lane Changing Frequency

Site	Percent of Traffic Changing Lanes Away From Study Vehicle				
	Yellow Only	Yellow/Blue	Yellow/Blue/ Red	Yellow/Blue (Strobe)	Yellow/Blue/ Red (DPS)
1: Day	2.6	2.2	1.7	2.5	5.4
Night	2.8	2.2	1.9	5.6	2.9
2: Day	6.3	3.9	2.1	1.1	N/A
3: Night	12.6	20.8*	20.7*[a]	N/A	15.7
4: Night	11.2	12.5	10.4[a]	N/A	N/A
5: Night	4.8	0.0	3.6[a]	N/A	18.5*

* Significantly higher ($\alpha = 0.05$) than the yellow only light condition

[a] The motorist assistance patrol in Houston utilizes a red and blue warning light configuration

N/A data not available

Effect of Warning Lights on Brake Activations

The final performance measure examined was the frequency of brake light activations for motorists approaching the various vehicle warning light color configurations. These comparisons could only be made for those studies conducted at night. Table 8 presents the percent of brake light applications under each configuration at each of the nighttime study sites. Unlike the lane choice data, these data trends did tend to be more consistent. At three of the four sites where nighttime data were collected, the yellow/blue/red warning light configuration resulted in a higher braking percentage than the yellow light only. The yellow/blue configuration also resulted in a significantly higher braking percentage (relative to the yellow only configuration) at one site. It is also important to note that at two of the three sites where data were available for the DPS vehicle, brake light activations were also significantly greater than they were when the yellow light only on the TxDOT vehicle was displayed.

Although researchers did not measure pavement illumination levels during these studies, it did appear that the overhead lighting was a little brighter at Sites 1 and 4, and less so at Sites 3 and 5. Furthermore, the study Site 5 was located just over a crest hill, which slightly limited sight distance to the test vehicle. Interestingly, these sites were where the more significant differences in performance were observed as a function of warning light color. Researchers hypothesize that the relatively lower overhead lighting levels (and limited sight distance at one site) made it more difficult for motorists to determine the type of vehicle that was associated with the different warning light color configurations, and so more of them tapped their brakes prior to reaching the vehicles. When overhead lighting was higher, motorists could see from farther away the type of vehicle and its location on the roadway ahead. In this situation, the warning light color configuration may have become a less critical information source for motorists, and resulted in little differences in braking applications.

Although significant differences by warning light color configuration were not always present at each site, the presence of warning lights in general did affect braking application relative to a normal (no warning light) condition. This is evident in the fact that brake application rates at three of the four sites were significantly greater than zero for all warning light color configurations, including yellow only. At Site 3, the braking percentage associated with the yellow light only was not significantly higher than zero, but were for the yellow/blue and yellow/blue/red configurations.

Table 8. Effect of Warning Light Colors on Brake Light Activations

Site	Percent of Traffic Activating Brake Lights				
	Yellow Only	Yellow/Blue	Yellow/Blue/ Red	Yellow/Blue (Strobe)	Yellow/Blue/ Red (DPS)
1: Day	N/A	N/A	N/A	N/A	N/A
Night	3.9	9.3*	9.5*	9.1*	4.5
2: Day	N/A	N/A	N/A	N/A	N/A
3: Night	1.6	5.4	7.9*[a]	N/A	15.8*
4: Night	14.9	14.0	20.4*[a]	N/A	N/A
5: Night	2.2	3.0	4.2[a]	N/A	11.3*

* Significantly higher ($\alpha = 0.05$) than the yellow only light condition
[a] The motorist assistance patrol in Houston utilizes a red and blue warning light configuration
N/A data not available

IMPLICATION OF RESULTS TO TXDOT VEHICLE WARNING LIGHT POLICY

It is often very difficult to detect small effects of certain traffic control devices upon traffic operations. This is because traffic operations in general are affected by a large number of other factors which cannot be controlled for in an experiment such as this (i.e., driver attitudes and thought processes while driving, environmental effects, individual vehicle interactions, etc.). The combined effect of these factors is the stochastic nature of traffic behavior, which can camouflage a subtle effect due to a specific traffic control or management technique. It appears that this may be the case with vehicle warning lights. The analysis of speeds found a few significant reductions in speeds at a few sites for a few warning light color combinations, but not all. Also, researchers observed a few more reductions for the yellow/blue light configuration than for the yellow/blue/red light configuration or for a DPS vehicle, which is a rather puzzling result. Consequently, it is difficult to draw any solid conclusions about the effect of vehicle warning lights upon vehicle speeds.

Lane choice performance measures examined in these studies (lane distributions and lane changes) were similarly inconclusive as to any consistent effects of warning light color configuration. However, analysis of brake light applications did indicate a trend towards increased brake usage for the red/yellow/blue light configuration relative to the yellow light only configuration. There was also evidence that the yellow/blue light configuration may also result in slightly greater frequency of brake applications, although not as dramatic as for the red/yellow/blue configuration. As would be expected, the presence of a law enforcement vehicle (DPS) generally resulted in significantly higher frequencies in brake light activations

The fact that speeds were lower at two sites when the yellow/blue light configuration was tested suggests that this combination can have the desired speed-reducing effect in some instances. This would indicate a need to maintain current TxDOT policy to allow blue and yellow lights to be used together on those vehicles used for activities that place workers or the public in particularly hazardous situation. However, since this speed reduction did not continue to be seen when the more elaborate yellow/blue/red light configuration was displayed or even when a law enforcement vehicle was used, one has to question whether those reductions were truly influenced by the presence of the warning lights or by some other factor which could not be controlled.

Researchers believe that the brake light activations may actually be a more pure measure of the potential impact of warning light color configurations upon driving behavior. These results from these studies are more consistent with findings from the survey discussed in Chapter 3. Here, a definite trend towards increased motorist response frequency is evident as colors are added to the basic yellow light used on most service (construction, maintenance, utility, etc.) vehicles. Furthermore, the presence of other enforcement cues (i.e., the law enforcement vehicle) further increases this response by motorists. According to these data, the combination of yellow and blue lights may have some incremental benefit above and beyond that of a yellow light only.

5. SAFETY OF PAVEMENT DATA COLLECTION ACTIVITIES

INTRODUCTION

The pavement data collection process usually involves vehicles traveling at normal/near-normal speeds or operating under stop-and-go slow speed conditions. In addition to these planned vehicle operations, other safety hazards might require erratic maneuvers (i.e., sudden acceleration or panic stops). This warrants extreme care in retrofitting and operating data collection vehicles to ensure the safety of motoring public, vehicle occupants, and data collection equipment. The focus of this part of the research project was to assess concerns voiced by operators and to develop recommendations for improving safety of the data collection systems.

The first step in the process was to study data collection equipment and to understand the concerns of TxDOT personnel operating the data collection equipment. In order to accomplish this objective, TTI research staff discussed operational requirements of the different types of equipment with TxDOT engineers and operators either by phone or in person. Also, researchers made some observations during pavement data collection operations. A small number of maintenance personnel were also queried to discuss how the current traffic control procedures for maintenance activities apply to data collection system concerns.

CONCERNS OF DATA COLLECTION PERSONNEL

Through the interview process, TTI requested the following information from data collection personnel:

- Equipment operations,
- Weather conditions in which the equipment may be operated,
- Types of traffic control used,
- Procedures used to enter and leave a travel lane,
- Speed of operation,
- Personnel required to perform the tasks,
- Ideas for improvements, and
- Safety concerns.

These interviews yielded a number of user concerns related to pavement data collection operations. These are listed below:

- The visibility and reliability of rotating beacons,
- The need to provide timely information to motorists about the activity,
- The safety of equipment mounted inside the vehicles,
- Rear visibility for certain vehicles and types of equipment,

- Externally mounted equipment that sticks out of the vehicle,
- Equipment added at districts that is not positively secured,
- Need for better guidelines for starting and stopping a data collection convoy,
- The training of new drivers or operators,
- Personal safety at horizontal and vertical curves, and
- Accidents caused by inattentive or DWI drivers

The sections that follow critique the various pavement data collection systems and in-vehicle equipment layouts with respect to these concerns.

ASSESSMENT OF PAVEMENT DATA COLLECTION SYSTEM OPERATIONS

The pavement data collection schemes can be broken into three types of systems. The first type is pavement data collections systems traveling at normal or near normal speeds. This equipment includes the siometer, profiler, profilometer, multi-functional vehicle (MFV), skid system, and the ground penetrating radar (GPR). The second type is stop and go operations which includes the Dynaflect and falling weight deflectometer (FWD). The third type is the mobile load simulator (MLS). This data collection device involves major setup time, testing time, and several pieces of external equipment.

Category 1: Near Normal Travel Speed Activities

The first category of pavement data collection systems is the equipment that moves at normal or near normal traffic speeds. This includes the Profiler, Profilometer, and Multi-Functional Vehicle (MFV).

The Profilers and the Profilometer are essentially the same systems which include laser sensors for measuring longitudinal profile which can be used as summary ride data for network level data collection or raw profile data for project level data collection. They also have acoustical sensors that measure transverse profile at 5 points across the lane to give summary or raw rut depth measurements. On the profilers the laser sensors and the acoustical sensors are located in an aluminum box shaped bar mounted on the front of the vehicle. This bar extends across the entire width of the van and has wings on each side that extend an additional 30 centimeters (12 inches) outside the van's width while collecting data. On the Profilometer the laser sensors are mounted between the front and rear axles, however the acoustical sensors are located in a bar on the front of the vehicle as mentioned above. Both of these systems require a driver and an operator and can test at near posted road speeds. The setup for operation is performed in a parking lot or similar location. Between runs the operator can reset the system while the driver is traveling to the next section to be tested or the while pulled off the edge of the road. Often the driver and the operator switch positions.

Figure 1. Profile/ Rut Bar on the Front of the Test Vehicle

Generally speaking, this category of equipment does not appear to suffer from many of the safety concerns expressed above by data collection personnel. Basic guidelines indicate that this equipment can only be used in daytime conditions (30 min after sunrise to 30 min before sunset) on dry roads with good overall visibility. Since these vehicles travel near normal traffic speeds, traffic control needs are minimal above normal vehicle lighting (such as rotating beacons or flashing strobes) and signals. Maneuvers into and out of traffic lanes are accomplished with caution turn signals.

One possible difficulty does exist with the profiler equipment positioned in the front of the research van. Specifically, the width of the device and its slight extension of the front of the vehicle does have the potential for being bumped by passing vehicles, particularly if they begin to move back into the travel lane too soon after passing. Researchers believe that a small reflector should be added to each side of the two sensors that extend past the vehicle during data collection activities. This small addition would add extra visibility to the corners of the equipment and assist motorists in maneuvering around the research vehicle.

The Multi-Functional Vehicle (MFV) is a data collection vehicle that has been developed in-house to meet TxDOT's specific requirements for high volume roads in urban areas. It has the same profile and rut collection capabilities as the Profiler and Profilometer, but utilizes cameras to collect a right-of-way view and a pavement view for manual and automated pavement distress surveys. The MFV can collect network level or project specific data. The onboard Mission Manager system uses a relational database that provides historical data analysis, the ability to filter logged distresses or instrument measurements, one step data reduction efforts with the Pavement Management Information System (PMIS) sectioning and automatically writing data to those sections, customized report generation, and audit capabilities for pavement distress survey contractors and TxDOT-conducted surveys.

Figure 2. Illustration of the MFV

Similar to the profiler, the primary concern for the MFV is the equipment mounted on the front of the vehicle that stretches the entire width of the vehicle. As noted above, researchers suggest that a small reflector be added to each side of the sensors that extend outside the vehicle during data collection.

The Skid System (Figure 3), consisting of a pickup truck tow vehicle and trailer, is used to collect highway surface friction data. It travels at 64 kmph (40 mph) while testing, which is significantly slower than traffic on highways where the average speed is 113+ kmph (70+ mph) and is normally served by a driver and an operator. The automatic data collection process involves spraying water on the pavement, locking up the drivers side trailer tire while the water is spraying, and measuring the resulting friction. Friction is measured through the tire by a torque sensor. The wet drag force and the downward force are used to calculate a skid number.

Figure 3. Example of a Skid Truck

With respect to traffic control and operational safety, a small concern does exist about the water spray placed on the pavement during the friction test. In particular, the sudden presence of water may surprise a motorist following closely behind. It is conceivable (although the risk appears to be rather slight) that he or she could react with an abrupt braking or steering maneuver and lose control of their vehicle. An informational sign to warn following motorists of the potential for water (i.e., "CAUTION--WATER SPRAY" or similar message) is attached to the back of some of the skid trucks in the state. Researchers believe this should be required on all skid trucks being used.

The GPR system is used to collect pavement layer and condition information. The GPR vehicle requires both an operator and a driver. The equipment used to store and analyze the incoming data is mounted in a full size van. Preparation for data collection is done either in a parking lot or on the shoulder. Preparation includes mounting a 1.8 m (6 ft) boom on the front of the vehicle and attaching the radar antenna to it (see Figure 4). Cables run from the van to the antenna. The setup process, calibration, and stow away process all require the operator to be out of the vehicle.

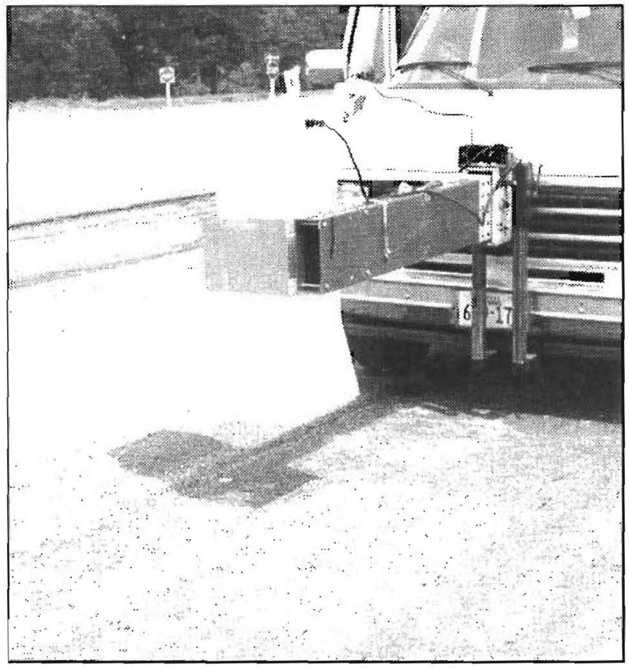

Figure 4. Front of GPR Van

The biggest concern while collecting data with this van is with the radar antenna and mounting boom. These items protrude 1.8 m (6 ft) in front of the van. Equipment operators have noted problems with motorist changing lanes extremely close to the front of the radar van and the protruding equipment. Currently, the boom for the antenna is red but the radar antenna is white. Unfortunately, the radar equipment itself is extremely sensitive and any item fabricated from metal or wood or that produces electromagnetic noise will degrade the quality of the radar data. Consequently, any potential additions to the antenna to increase visibility would have to first be evaluated by radar design experts. Researchers think that attaching a flag to the front corners of the vehicle (possibly attached to the bumper) would call attention to the front of the vehicle and the protruding antenna. The height of the flags would have to be kept low so as to not interfere with driver visibility.

Another alternative is to utilize signing on the back of the vehicle. In Florida, data collection personnel use the magnetic sign shown Figure 5 ("CAUTION TESTING") on the back of their GPR van. Researchers believe a sign such as this could be used in Texas as well, but should be modified to provide more concise information to motorists. For instance, two magnetic sign panels, one on each rear door of the van, could display the following:

CAUTION TEST VEHICLE		EQUIPMENT IN FRONT

Another alternative would be to develop a simple diagram for the second panel similar to the "THIS TRUCK MAKES WIDE TURNS" message placed on the back of many large trucks. However, it is difficult to properly convey complex information through symbol signs that will be understood by a large number of motorists. Therefore, the researchers recommend the use of the word messages at this time.

Figure 5. Example of a Magnetic Sign

Category 2: Stop-and-Go Data Collection Activities

The second type of data collection equipment includes the Dynaflect and the FWD devices. Both of these are used for collecting pavement stiffness data. The Dynaflect is shown in Figure 6. The Dynaflect is operated by the driver. Preparations for a data collection run are done in a parking lot or at the side of the road. To collect data, the vehicle stops and then the trailer puts a low frequency continual vibration into the road. The vibration is then received by geophones and recorded by the electronic equipment. Rubber-coated metal wheels placed on the pavement from the bottom of the trailer, and pulled along the roadway at about 32 kmph (20 mph) create the vibration.

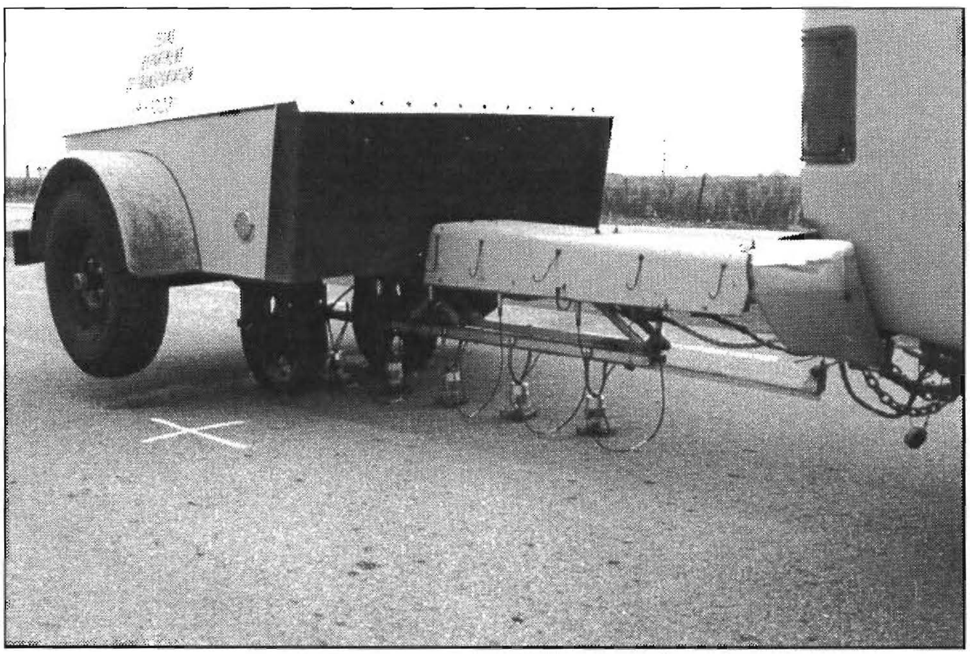

Figure 6. Dynaflect in Data Collection Mode

The FWD shown in Figure 7 is also used to collect pavement stiffness data. The Dynaflect equipment is gradually being phased out in favor of the FWD. Normally, data collection preparations for the FWD are completed before leaving the TxDOT parking lot. Data collection requires a driver and an equipment operator. To collect data, the vehicle stops and the FWD lowers a 0.3 m (1 ft) circular plate to the pavement surface. Data is collected by dropping weight on the loading plate and measuring the force at the load plate and the resulting pavement deflection. Generally, once stopped, the data collection process takes 3 to 5 min to complete. This process is continued at 6 to 150 m (20 to 500 ft) intervals over a section of roadway up to 32 km (20 mi) long.

Figure 7. Illustration of the FWD

These types of activities are the most difficult to treat from a traffic control perspective. As noted in Chapter 2, they fall in the mobile work category of traffic control plan requirements (*7*). These requirements vary depending on the type of roadway on which data is being collected, but generally involve the use of shadow vehicles, truck-mounted impact attenuation devices, and arrow panels (in either directional or caution mode as dictated by the type of roadway). On multilane divided highways, a vehicle on which a LANE BLOCKED sign (FCW20-6) is mounted is driven on the shoulder approximately 450 m (1500 ft) upstream of the first shadow vehicle.

However, the fact that these devices stop intermittently or travel at fairly low speeds creates special problems on urban freeways because these roadways involve both high traffic volumes and high speeds. Oftentimes, headways (spacings) between vehicles is so short that a following motorist cannot see an adequate distance ahead. If the vehicle in front waits to move out of the lane until it is rather close to the shadow vehicle, the motorist following may surprised and have to make a quick decision and maneuver to avoid the shadow vehicle. This can be especially problematic for passenger vehicles following immediately behind a large truck.

In the interest of safety, many districts put out a lane closure for a mobile operation on an urban freeway, coning off as long a section as can be worked on in an hour or so. They then move the beginning of the closure downstream and continue working in this manner until the work activity is completed. Research has shown the importance of the channelizing devices, which create the lane closure taper in obtaining proper motorist response to vacate the closed lane (*5*). In addition, many urban areas (San Antonio and Fort Worth, in particular) have installed lane control signals over the travel lanes. These signals, controlled at the traffic management center (TMC), can be changed to indicate that a lane is closed downstream. Pavement data collection personnel should coordinate their work activities not only with the local District maintenance office but with these local TMCs as well.

Category 3: Stationary Data Collection Activities

The last data collection device discussed is the MLS, shown in Figure 8. The time required for an accelerated pavement test under optimal conditions is currently 3 months. Installation of the MLS is a major undertaking requiring oversize permits, long-term lane closures protected by concrete median barriers (CMB) and full advance signing, and more. Consequently, the traffic control plan at this type of data collection location is as safe as any other long-term construction project. However, in the interviews of the MLS operators, one concern that was noted involved public curiosity about the device. Specifically, when the MLS is first installed on a section of road, the public has a tendency to stop on the road to ask personnel present about the purpose and operation of the device. In fact, this type of event occurred during one time researchers were present observing the operation of the device. The motorist actually stopped in the travel lane and asked for an explanation of the device. Such behavior is clearly undesirable from a safety standpoint.

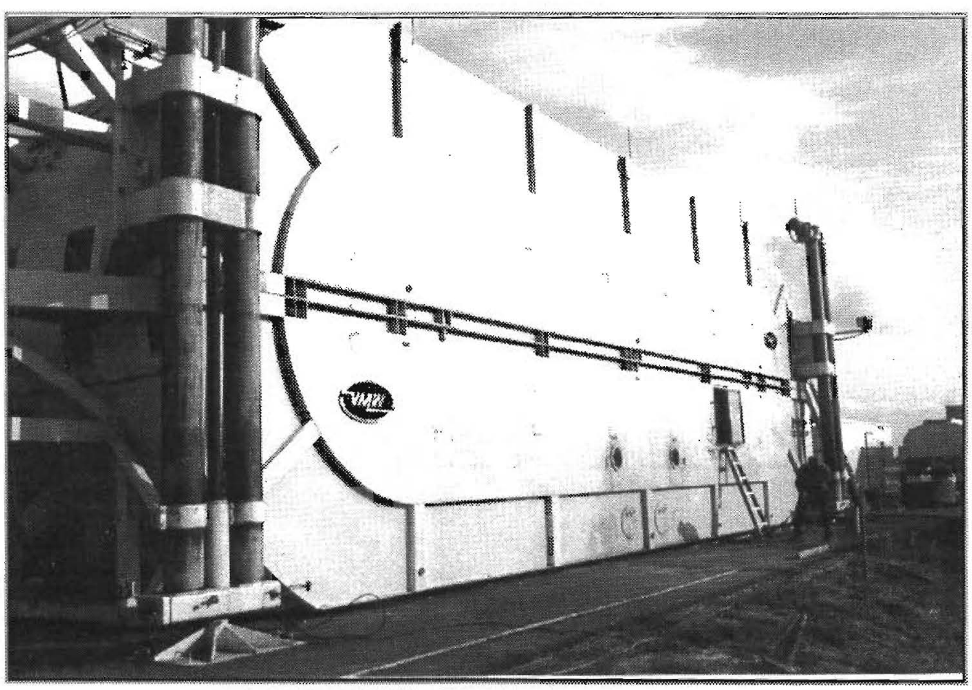

Figure 5-8. Illustration of the MLS

Obviously, it is critical that the overall traffic control set up at a site for this activity provide adequate sight distance to the closure. However, it is also desirable to attempt to provide adequate sight distance to the MLS itself if possible so that anyone who inadvertently stops in the road does not create an unseen hazard to approaching motorists. At the same time, it appears beneficial to try and discourage such stopping behavior in the first place. Researchers recommend the use of portable changeable message signs (CMS) as part of the advance warning signing. The CMS would be positioned 150 to 1000 m (500 to 3700 ft) upstream of the first advance warning sign, depending on roadway type (data collection personnel should refer to the TxDOT standard traffic control plans for the appropriate CMS location for a given facility). Once in place, researchers recommend a two panel message be displayed, each panel approximately 4s long:

PAVEMENT TESTING AHEAD	DO NOT STOP IN LANE

ASSESSMENT OF IN-VEHICLE PAVEMENT DATA COLLECTION EQUIPMENT

During discussions with data collection personnel, researchers also inventoried the equipment required to be installed inside the data collection vehicles. The equipment used or stored inside these vehicles has considerable variety. The following is a list of items found in this group:

- Computer workstation, computer monitor, keyboard, and printer;
- Other electronic devices;
- Paper (including; sheets, printer paper, and rolls of plans);
- Tool box;
- First aid kit;
- Ice box;
- Trash can;
- Cables;
- Aerosol cans;
- Fire extinguisher;
- Hard hats;
- Video camera;
- Cardboard boxes;
- Bins;
- Desks with or without shelves;

- Filing cabinets;
- Additional FWD weights;
- Hydraulic fluid; and
- Six foot boom for the ground penetrating radar.

The team observed cases in which equipment was fully secured. Methods of securing equipment in the vehicle included:

- Bolts with or without metal brackets,
- Straps or bungee cord,
- Velcro, or
- Clips (typically to a table top).

On the other extreme were cases in which items, usually small, were placed in the vehicle without any restraint.

Figure 9 illustrates the case when items are properly secured. As can be seen from the figure, electronic equipment is mounted in cabinets specifically designed for that purpose. Further, these cabinets are properly secured to the vehicle frame using bolts.

Figure 9. Properly Mounted Electronic Equipment.

Figure 10 illustrates a case where researchers believe one of the mounting methods may be deficient. The following is a summary of observations:

- The monitor is secured to the table using a mounting bracket designed for home or office use. The mounting is secured to the monitor housing which is made of plastic. This plastic is not believed to be of sufficient strength to withstand high forces (such as during a sudden deceleration or rollover situation). The bracket could separate from the monitor in this situation, and the monitor could become a dangerous projectile, and

- In this figure, the keyboard is bolted to the table and is fully secured. In other cases, researchers observed similar size objects secured to the table using velcro. This method is acceptable as long as the velcro used is of good quality and sufficient strength to hold the item under collision or rollover conditions.

Figure 10. Example of Potential Monitor Mounting Bracket Problem

Another concern noted during the research vehicle critique was with how the tables were secured to the vehicle. Typically, a desk or table is secured by using bolts only to the vehicle floor. This restraint is sufficient for normal driving conditions. However, it may not be sufficient under all scenarios. The reason is that any sideways movement of the vehicle will cause the tabletop to oscillate left and right. These oscillations can become more pronounced when heavy equipment, whose center-of-mass is above the table, is secured to the tabletop. When this happens, two types of forces will act on the legs of the table:

1. Forces pulling the bolts upward, and
2. Forces that will have a tendency to bend the table legs.

Under severe conditions (collision and/or rollover), there is a possibility that the legs either bend or become loose due to a broken bolt. If this happens, forces generated and the inertia of object on the table can cause an object to become a dangerous projectile. This potential hazard can be virtually eliminated simply by additionally bolting the top part of the table to the vehicle frame (as shown in Figure 11). The same safety rule can be applied to any cabinet/table used for setting or mounting data collection equipment.

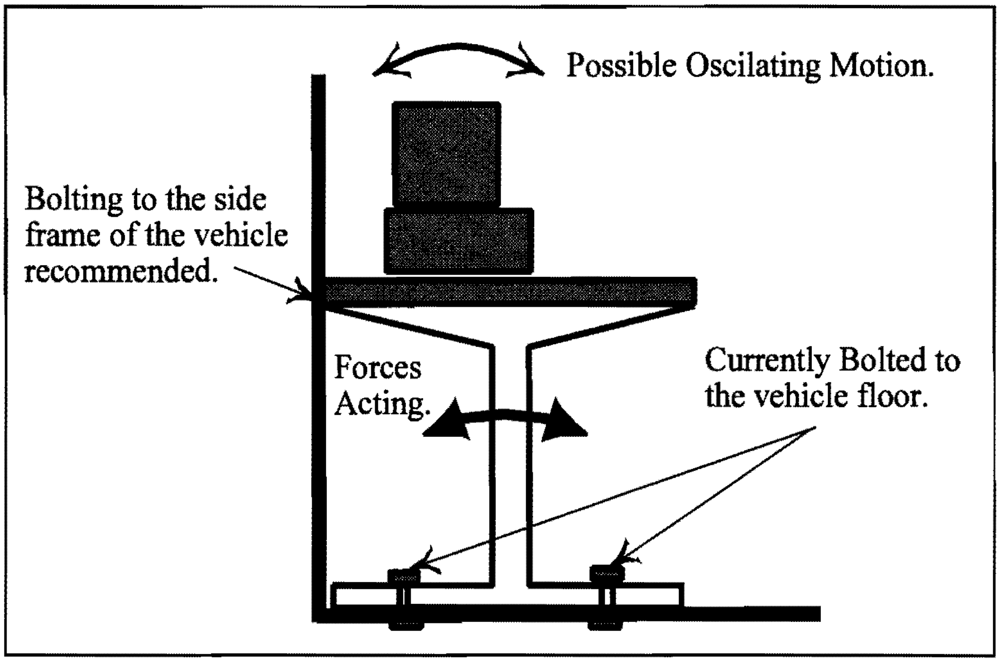

Figure 11. Properly Securing a Computer Desk.

Figure 12 illustrates another case where a computer desk is being used for the electronic equipment and deficiencies are believed to exist in terms of how equipment is secured within the vehicle. Three key observations from this figure are listed below:

- The computer monitor is strapped to brackets that are secured to the table using screws. This method of securing larger items is sufficient for normal vehicle movements (forward or reverse) but may not be sufficient for movements or forces perpendicular to the monitor screen. For instance, the monitor might slip out and become a projectile in a side-impact or rollover situation. The possibility of this happening is higher when the tabletop is not properly secured against the side of the vehicle as described earlier.

Figure 12. Example of Unsecured Equipment in Research Vehicle

- There are unsecured items (equipment, papers, aerosol can, etc.) under the table and between the table and the driver seat. Under normal driving conditions, this does not pose any significant safety threat, however, under extreme conditions, loose items may be potentially dangerous to the vehicle occupants. According to basic laws of dynamics, the force with which a moving object hits something in its path is dependent on the velocity at the time of impact and the mass of the object. Thus, a small object moving at a high velocity can be as dangerous as a larger object moving slowly, and

- The top-left corner of Figure 12 shows a section of mounting boom for the ground penetrating radar when it is transported inside a vehicle. It is 1.8 m (6 ft) long and has a significant weight. Figure 13 illustrates how the boom is stored in the vehicle in a full length U-bracket. This bracket is secured to one side of the vehicle and has plates at the two ends to prevent the boom from sliding out. However, note that the center of mass of the boom is located at a point that is higher then the top edges of the U-bracket. In addition, the radar boom is not secured to the bracket. Under normal driving conditions, the weight of the boom will keep it inside the bracket. However, there is a possibility of the boom falling out if the vehicle traverses a large bump, or if the vehicle is involved in a rollover situation. Thus, researchers strongly recommend that a metal locking bracket or other sort of mechanism be used for properly securing the boom to the vehicle.

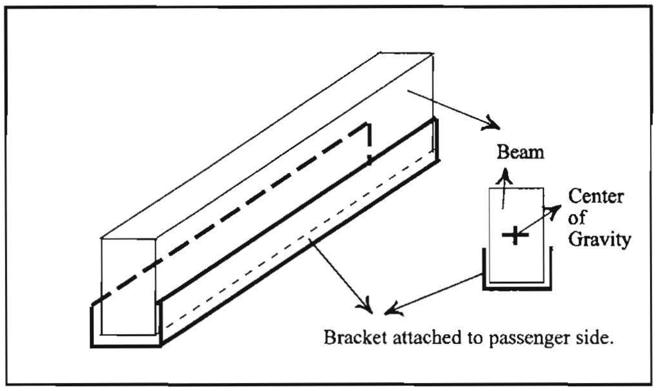

Figure 13. Boom Storage Mechanism.

Figure 14 illustrates an instance where a wooden table was placed between the front seats of the vehicle. Safety consideration regarding this application are discussed below.

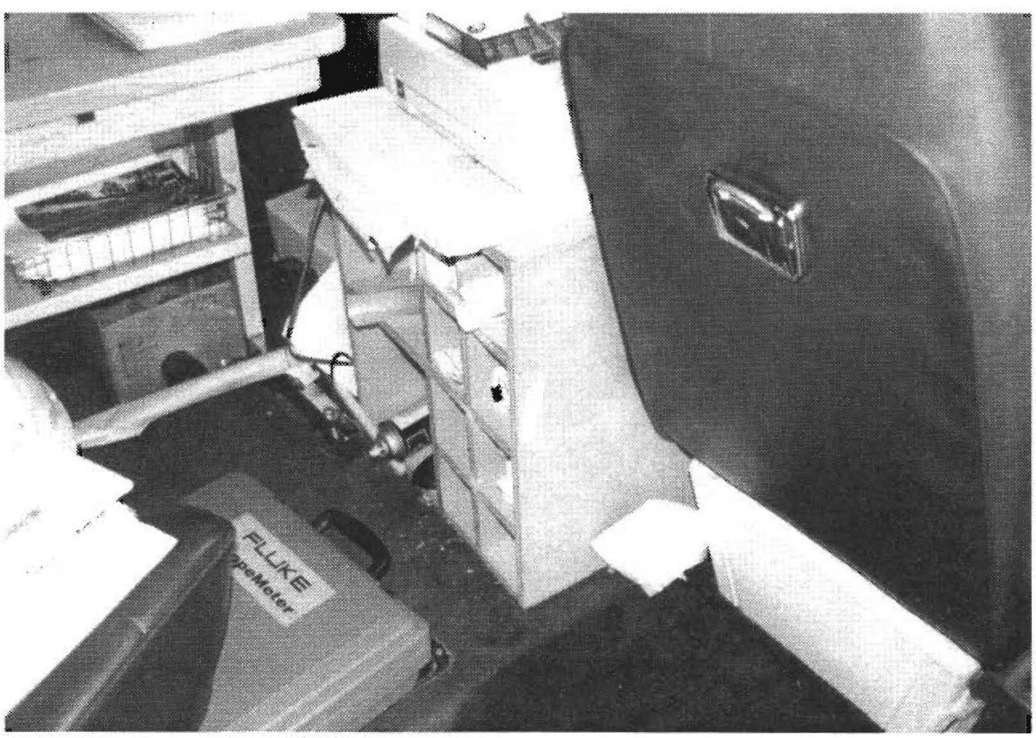

Figure 14. Equipment Added at District

- This table is not secured to the vehicle as discussed above.

- The table has open bins facing backward. Even the normal motion of the vehicle can throw items out of the bins. One way of avoiding any associated hazard would be to either cover the openings with doors or to use top-load bins, and

- TxDOT staff informed the researchers that this table was not installed at the design shop but was placed in the vehicle at the District where it was used. TxDOT can avoid such situations by developing a policy that provides Districts with design/installation guidelines (such as these provided in this chapter) for installing additional equipment in the research vehicles.

Figure 15 shows a case where the back half of a vehicle included several unsecured items, such as: a bottle of hydraulic fluid, a tool box, and several cardboard boxes with miscellaneous equipment. Researchers were also informed that it is also not uncommon to carry, unsecured, weights for the (FWD) inside a vehicle. Under normal driving conditions, these unsecured items may not pose any threat but may turn into deadly projectiles in collision or rollover conditions. Researchers also strongly suggest that provisions be made to secure such items and that the operators secure all items before using a data collection vehicle.

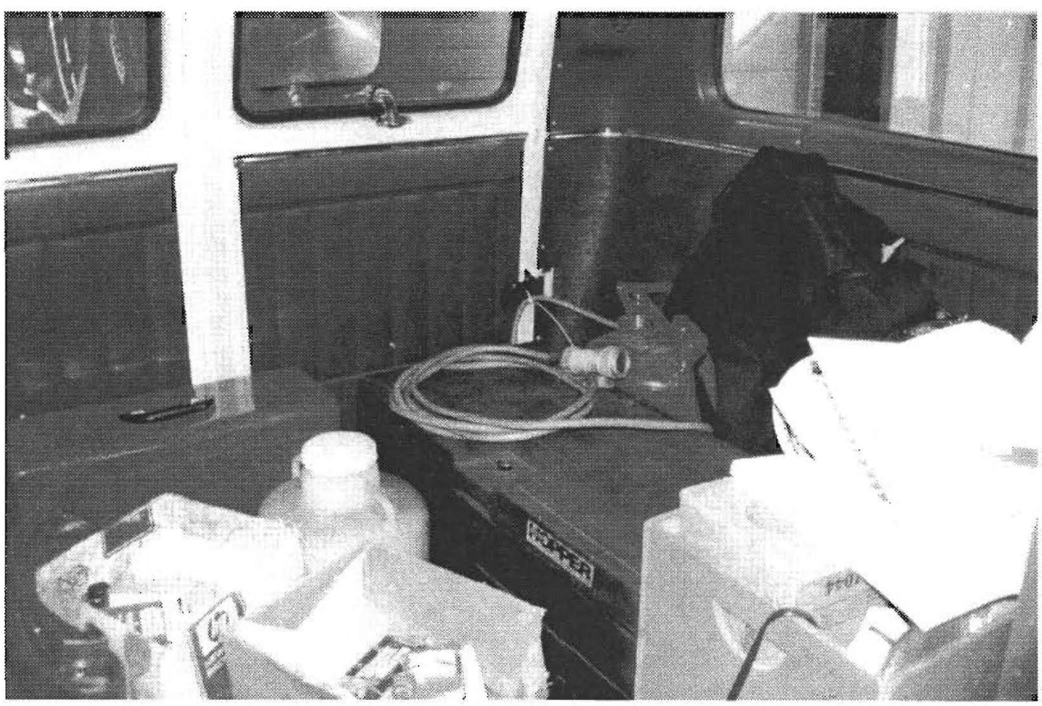

Figure 15. Unsecured Items in a Data Collection Vehicle.

6. SUMMARY AND RECOMMENDATIONS

SPECIAL VEHICLE WARNING LIGHTS

Summary of Research Findings

This report has documented research procedures and results designed to determine how to improve the Department's current vehicle warning light policy. Research tasks included a review of research and application literature, a national survey of vehicle warning light practices, a survey of motorist perceptions associated with different warning light color configurations, and field studies of the effect of alternative warning light color configurations upon the behavior of traffic approaching the warning lights.

The results of the national survey indicated that 12 states utilize at least one other color besides yellow on some of its equipment. Although seven states indicated that they did utilize blue lights, four of them noted that this color was limited to use on their snow removal equipment. Others indicated that the color was included in the light bar assembly mounted on top of their courtesy patrol vehicles (this was generally the case for the use of red and white lights also). Most states indicated that they did not use a single type of warning light technology on their equipment but instead used a variety of rotating beacons, strobes (single or multiple flash), and light bars (full or mini). Four of the states indicated they were also using light "sticks" on a few of their vehicles (courtesy patrols and research vans were specifically mentioned). These sticks have several lights arranged in a row that can be operated in one of several sequencing, simultaneous, or wig-wag patterns.

The motorist survey conducted at DPS driver licensing stations in Dallas-Fort Worth, San Antonio, and Houston was designed to determine whether the use of other light colors on selected vehicles and equipment adds a greater sense of hazard and need to be cautious by motorists as they approach the vehicle. The results of the survey indicated that the combination of blue and yellow lights implies a slightly greater sense of hazard to motorists than does the yellow light alone. However, this greater sense of hazard does not necessarily translate into differences in how motorists believe they need to respond to the different color lights. In fact, when asked what action they should take in response to a yellow light in comparison to a yellow and blue light combination, no statistically significant differences in responses were found. Somewhat surprisingly, it is a yellow and red light combination on top of the vehicle which motorists say is indicative of a higher hazard condition and which implies to them a greater need to respond by applying their brakes. Although this configuration is not judged as hazardous by motorists as the red/blue/yellow configuration now allowed for use on courtesy patrols, it does represent a more significant shift in subject perceptions from the yellow light only configuration.

Field studies conducted at freeway locations in San Antonio and Houston investigated the effect of selected alternative vehicle warning light color configurations upon vehicle speeds, lane choice, and braking activity. The analysis of speeds found a few significant reductions in speeds at a few sites (but not all) for the yellow and blue warning light color combination when compared to speeds observed when only a yellow warning light configuration was used. A rather strange finding was the fact that the presence of a DPS law enforcement vehicle positioned on the shoulder with its lights flashing did not yield significant reductions in average speed relative to the TxDOT courtesy patrol vehicle positioned at the same location with its yellow-only warning light configuration activated.

Meanwhile, lane distribution percentages and lane changing frequencies were also inconclusive as to whether warning light color configuration affected these performance measures. However, analysis of brake light applications did indicate a trend towards increased brake usage for the red/yellow/blue light configuration relative to the yellow light only configuration. There was also evidence that the yellow/blue light configuration may also result in slightly greater frequency of brake applications, although not as dramatic as for the red/yellow/blue configuration. Also, the presence of a law enforcement vehicle (D.S.) at two out of three sites resulted in significantly higher brake light activation frequencies than a TxDOT courtesy patrol vehicle outfitted with the same warning light colors.

The fact that speeds were lower at two sites when the yellow/blue light configuration was tested suggests that this combination can have the desired speed-reducing effect in some instances. This would indicate a need to maintain current TxDOT policy to allow blue and yellow lights to be used together on those vehicles used for activities that place workers or the public in particularly hazardous situation. However, since this speed reduction did not continue when the more elaborate yellow/blue/red light configuration was displayed or even when a law enforcement vehicle was used, one has to question whether those reductions were truly influenced by the presence of the warning lights or by some other factor which could not be controlled. Researchers believe that the brake light activations may actually be a more pure measure of the potential impact of warning light color configurations upon driving behavior. These results from these studies are more consistent with findings from the survey discussed in Chapter 3. Here, a definite trend towards increased motorist response frequency is evident as colors are added to the basic yellow light used on most service (construction, maintenance, utility, etc.) vehicles. Furthermore, the presence of other enforcement cues (i.e., the law enforcement vehicle) further increases this response by motorists. According to these data, the combination of yellow and blue lights may have some incremental benefit above and beyond that of a yellow light only. However, this combination does not generate quite as many brake light activations as the yellow/blue/red warning light configuration.

Relationship to Enforcement (Authorized Emergency Vehicle) Warning Lights

Unfortunately, the results of this research cannot fully lay to rest the concerns expressed by DPS regarding the overuse of blue lights on TxDOT or other service vehicles, a subsequent driver disregard for that color, and an eventual degradation of safety for both authorized emergency and service vehicle equipment. However, survey results from Chapter 3 suggest that most motorists key on a combination of blue and red lights to indicate the presence of law enforcement, and focus on the warning light color red alone or red and white combinations to indicate other types of authorized emergency vehicles (i.e., fire trucks, ambulances). Consequently, the presence of blue lights in conjunction with yellow lights on service vehicles for TxDOT does not appear to conflict with motorist interpretations of any of the currently authorized emergency vehicles within the state. As an alternative, TxDOT policy allows red warning lights to be used on vehicles as well, as long as they are not displayed to the front of the vehicle. Again referring to Chapter 3, a yellow and red color combination is not commonly associated with any authorized emergency vehicle, and conveys a strong sense of hazard to motorists as they approach a vehicle with that color combination. In the event that legislation is passed to prohibit the use of blue warning lights by TxDOT and other service vehicles, the use of yellow and red light combinations should be considered for those vehicles now utilizing a yellow and blue light combination.

Current TxDOT policy to allow yellow, blue, and red lights on courtesy patrols does conflict with a small (13 percent) portion of motorists who expect to see this color combination on enforcement vehicles. However, both courtesy patrols and law enforcement vehicles can play very similar roles in incident response (i.e., disabled vehicle protection, traffic control assistance, etc.). In fact, the motorist assistance patrol in Houston utilizes law enforcement officers to man the patrols, and so employs an authorized emergency vehicle warning light color configuration. For the sake of consistency across the state, a similar warning light color configuration for all types of courtesy or other incident response vehicles (regardless of whether they are manned by TxDOT or law enforcement personnel) would be expected to promote more consistent interpretations by motorists statewide.

TxDOT Vehicle Warning Light Policy Recommendations

In general terms, the current vehicle warning light policy does appear to be justified in terms of allowing certain types of vehicle to utilize both blue and yellow lights. Field personnel have contended for some time that the presence of the blue lights in conjunction with standard yellow lights does affect driving behavior. This information is supported by some (but not all) of the traffic operational data collected through this research. At the same time, statements which allow vehicles to use one pair of yellow or red flashing warning lamps (facing to the rear) in conjunction with a yellow omnidirectional warning light on the cab of the vehicle also appear justified through this research. Discussions with members of the Project Advisory Committee does not indicate that a yellow and red warning light combination is used extensively within TxDOT (although it is used by certain private tow truck operations).

Specific recommended changes to the current warning light policy are enumerated below.

1. Researchers believe that the decision of whether a particular type of vehicle or piece of equipment should be outfitted with both blue and yellow lights should continue to be based on the risk that using the vehicle/equipment for its intended function places upon workers and/or the motoring public. Researchers recommend that the policy statement regarding blue lights explicitly list those characteristics which are judged to warrant the additional blue warning light color. Statements that support the currently-approved vehicles in the policy would read something like the following:

   - A vehicle or piece of equipment used for any activity that requires workers to be out of the vehicle while in a lane of traffic and without the presence of channelizing devices upstream of the vehicle to close the lane, and

   - A vehicle or piece of equipment used in a moving operation in a travel lane that travels at a speed of less than 6 kmph (4 mph) or more than 50 kmph (30 mph) below the operating speed of traffic on a roadway (the actual number used to define this criteria could be changed).

2. Researchers recommend that the statement allowing the use of blue lights by maintenance foremen and assistant maintenance foremen be changed or eliminated. This statement has created negative feelings by other TxDOT personnel within the state who feel that it implies a greater sense of concern for the foremen/assistant foremen than other workers. Researchers suggest the statement be reworded to allow blue lights on vehicles used for incident response activities (as opposed to incident removal or clean-up activities), regardless of who utilize those vehicles. This statement would cover both the motorist assistance (courtesy patrol) and foremen/assistant foremen vehicles explicitly mentioned now in the policy. As a second option, the statement regarding maintenance foremen or assistant maintenance foremen could be embellished to indicate (possibly in parentheses) that "other personnel using these vehicles are allowed to activate the blue lights for the above-mentioned purposes."

A final recommendation regarding TxDOT's vehicle warning light policy concerns the special needs of motorist assistance (courtesy patrol) vehicles. Discussions with courtesy patrol operators in the major metropolitan areas illustrate that these vehicles are often the first on scene of an incident and in many cases are the only vehicle responding. On high-volume roadways, it is imperative that approaching motorists are notified of a hazardous situation ahead so that they can take appropriate actions to safely avoid the incident. Because they often do not have the protection of a full complement of advance signing and channelizing devices to close the lane in which they are located, courtesy patrol vehicles require the maximum amount of visibility and conspicuity possible. In addition, there is a need for them to arrive at the scene of an incident as quickly as possible to provide the conspicuity to an incident scene. Unfortunately, traffic congestion that develops upstream of an incident in an urban area often keeps the courtesy patrol from reaching the incident as quickly as desired. Because of these concerns and the intended function of the patrol vehicles, researchers recommend that legislation be proposed to designate TxDOT authorized incident response vehicles as authorized emergency vehicles under Section 541.201 of the Texas Transportation Code (*15*). This would ensure that these types of vehicles would continue to be able to utilize the reserved vehicle warning light colors reserved for authorized emergency vehicles. Furthermore, this legislation would offer additional protection to the response vehicles in terms of preferential right-of-way and minimum following distances by motorists that would enhance the effectiveness and safety of the courtesy patrol vehicles.

PAVEMENT DATA COLLECTION ACTIVITIES

Pavement data collection activities were investigated through discussions with data collection personnel statewide, through observations of selected pavement data collection activities, and through a limited engineering analysis of equipment inside typical data collection vehicles. Researchers also obtained a limited amount of information about traffic control practices for data collection in other states. The following list represents a summary of recommendations from these activities.

Recommendations for External Equipment

1. Place reflectors on all equipment that extends past the data collection vehicles to make them more noticeable to motorists.

2. Place fresnel lenses on the back of all rear windows of data collection vehicles to provide drivers with better visibility.

3. Consider the use of magnetic signs during testing to inform the public that tests or measurements are being performed by personnel in the vehicle. Specifically, a two-panel magnetic sign was suggested in this research for the GPR:

CAUTION TEST VEHICLE	EQUIPMENT IN FRONT

4. The older FWD units need to have the trailer retro-fitted so that the extra weights that need to be carried can be done so on the trailer rather than in the data collection vehicle.

Although not specifically discussed in this report, data collection personnel should also consider requesting assistance from law enforcement officials when collecting data on high speed, high volume roadways. Pavement data collection activities should also be coordinated with the appropriate maintenance section in each District to ensure that adequate traffic control procedures are being followed for the roadway and traffic conditions that are present.

Recommendations Regarding In-Vehicle Equipment

The following specific recommendations are offered for consideration regarding safety improvements inside pavement data collection vehicles:

1. Ensure that all equipment and instruments are fully secured. These items include tables and cabinets for mounting and setting equipment. When mounting brackets are bolted to pieces of equipment, consideration should be given to the structural integrity of that equipment housing. Bolts through plastic housing are likely to pull loose in the event of a crash and allow the equipment to fly through the vehicle cabin. This significantly increases the potential for bodily injury to data collection personnel.

2. Install top-loading fully secured storage bins for smaller items. These bins should be tall enough to ensure that rolls of plans, paper, and other items stay inside during vehicle operation.

3. Each cabinet or table should be securely bolted to the vehicle floor as well as to the side of the vehicle. The vehicle frame can be used to secure the top of these items to the vehicle.

4. Removable items that are usually set on the floor (e.g., first aid kit, tool box) should be strapped to the vehicle. For this purpose, vehicles should be equipped with straps at several locations.

5. During the data collection process (vehicle moving or stopped), each occupant should use a safety belt when inside the vehicle.

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APPENDIX A: SURVEY FORM

Administrator:_______ **Survey #: B-___________**
Date:_______________ **Location:________________**

Vehicle Warning Light Survey - Project #3972

This survey is being conducted by the Texas Transportation Institute (TTI), which is part of the Texas A&M University System. It is sponsored by the Texas Department of Transportation. The purpose of the survey is to determine motorists' understanding of the flashing warning light colors that are mounted on top of emergency and other authorized vehicles. Your response will be completely confidential, and will be used for statistical purposes only. Now, for comparison purposes we would like to know about your driving experience, please check the appropriate answer.

How many miles do you travel per year?____less than 5,000 ____5,000 to 15,000 ____more than 15,000

Do you have any restrictions on your license? (Check all that apply) ____None ____With glasses/contacts
____Daytime only Other (explain):____

Are you color blind? ____yes ____no

What is your approximate age category? ____less than 25 ____25 to 55 ____over 55

What is your gender? ____male ____female

Part I - The first part of the survey is to help us determine how hazardous you would consider the situation, and what driving action, if any, you would take based on five different colored warning lights used in different combinations mounted on top of emergency or other authorized vehicles. Please **circle** how hazardous you feel the situation would be, along with what driving action, if any, you would take if you saw that particular color or color combinations of flashing vehicle warning lights.

1. **If you saw flashing yellow warning lights mounted on top of a vehicle, how hazardous would you consider the situation you were approaching?**
   a. not hazardous at all c. moderately hazardous e. extremely hazardous
   b. somewhat hazardous d. very hazardous
   What driving action, if any, would you take?
   a. no action c. tap brake e. apply brake firmly
   b. take foot off accelerator d. apply brake gently

2. **If you saw flashing yellow and blue warning lights mounted on top of a vehicle, how hazardous would you consider the situation you were approaching?**
   a. not hazardous at all c. moderately hazardous e. extremely hazardous
   b. somewhat hazardous d. very hazardous
   What driving action, if any, would you take?
   a. no action c. tap brake e. apply brake firmly
   b. take foot off accelerator d. apply brake gently

3. **If you saw flashing blue and red warning lights mounted on top of a vehicle, how hazardous would you consider the situation you were approaching?**
   a. not hazardous at all c. moderately hazardous e. extremely hazardous
   b. somewhat hazardous d. very hazardous
   What driving action, if any, would you take?
   a. no action c. tap brake e. apply brake firmly
   b. take foot off accelerator d. apply brake gently

4. **If you saw flashing <u>red</u> warning lights mounted on top of a vehicle, how hazardous would you consider the situation you were approaching?**
   - a. not hazardous at all
   - b. somewhat hazardous
   - c. moderately hazardous
   - d. very hazardous
   - e. extremely hazardous

   What driving action, if any, would you take?
   - a. no action
   - b. take foot off accelerator
   - c. tap brake
   - d. apply brake gently
   - e. apply brake firmly

5. **If you saw flashing <u>yellow, blue, and red</u> warning lights mounted on top of a vehicle, how hazardous would you consider the situation you were approaching?**
   - a. not hazardous at all
   - b. somewhat hazardous
   - c. moderately hazardous
   - d. very hazardous
   - e. extremely hazardous

   What driving action, if any, would you take?
   - a. no action
   - b. take foot off accelerator
   - c. tap brake
   - d. apply brake gently
   - e. apply brake firmly

6. **If you saw flashing <u>blue</u> warning lights mounted on top of a vehicle, how hazardous would you consider the situation you were approaching?**
   - a. not hazardous at all
   - b. somewhat hazardous
   - c. moderately hazardous
   - d. very hazardous
   - e. extremely hazardous

   What driving action, if any, would you take?
   - a. no action
   - b. take foot off accelerator
   - c. tap brake
   - d. apply brake gently
   - e. apply brake firmly

7. **If you saw flashing <u>red and yellow</u> warning lights mounted on top of a vehicle, how hazardous would you consider the situation you were approaching?**
   - a. not hazardous at all
   - b. somewhat hazardous
   - c. moderately hazardous
   - d. very hazardous
   - e. extremely hazardous

   What driving action, if any, would you take?
   - a. no action
   - b. take foot off accelerator
   - c. tap brake
   - d. apply brake gently
   - e. apply brake firmly

Part II - Part II of the survey is asking you what color or color combination of flashing warning light(s) would you expect to see mounted on top of specific types of vehicles. There may be more than one color of warning lights used for each type of vehicle listed. Please list the color or combination of colors you would expect to be used on the following vehicles. For example, what color or color combination would you expect the flashing warning lights mounted on top of a police vehicle to be?

Type of Vehicle	Color(s)
1. Police Vehicle	
2. Ambulance	
3. Tow Truck	
4. School Bus	
5. Highway Const., Maint. or Service Equipment	
6. Fire Truck	
7. Motorist Assistance or Courtesy Patrol Vehicle	

Comments:____

APPENDIX B: SURVEY STATISTICS

Chi-Square Statistics Between Warning Light Color Responses to "How Hazardous Would You Consider the Situation?"

Colors	Y	B	R	Y/B	Y/R	B/R	Y/B/R
Y		25.70*	220.34*	20.80*	69.25*	155.24*	162.69*
B			152.62*	8.23	31.04*	91.55*	100.88*
R				144.16*	67.38*	20.27*	9.71
Y/B					19.36*	80.92*	90.31*
Y/R						22.95*	28.95*
B/R							2.88
Y/B/R							

* Statistically significant. Researchers used a critical value of $X^2_{(3,\ 0.005)} = 12.84$ to determine statistical significance. This provides an overall level of significance of 0.05 for all comparisons.

Chi-Square Statistics Between Warning Light Color Responses to "What Driving Action Would You Take?"

Colors	Y	B	R	Y/B	Y/R	B/R	Y/B/R
Y		4.63	91.99*	5.72	27.38*	65.10*	58.99*
B			85.31*	4.58	23.63*	57.79*	50.80*
R				67.29*	28.90*	7.19	7.88
Y/B					10.48	39.46*	35.60*
Y/R						10.10	8.87
B/R							2.11
Y/B/R							

* Statistically significant. Researchers used a critical value of $X^2_{(3,\ 0.005)} = 12.84$ to determine statistical significance. This provides an overall level of significance of 0.05 for all comparisons.