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Traffic Control and Work Zone Safety for High Volume Roads

FINAL REPORT

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Submitted by

Kaan Ozbay, Ph.D.
Professor
Rutgers University

Bekir Bartin, Ph.D.
Research Associate
Rutgers University

Hong Yang, Ph.D.
Postdoctoral Associate
Rutgers University

Steven Chien, Ph.D.
Professor
NJIT

In collaboration with The College of New Jersey

NJDOT Project Manager
Edward Stephen Kondrath

In cooperation with
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16. Abstract

The Manual on Uniform Traffic Control Devices (MUTCD) predominantly addresses work performed along the centerline of roadways and low-speed roads. This work does not apply to the majority of situations encountered by New Jersey Department of Transportation (NJDOT) employees who survey or inspect high-speed, high-volume roadways. Therefore, there is a need to review current practices being used by other state DOTs and develop guidance for using traffic control devices (TCD) on high-volume roads for this targeted group.

This research project reviews the current practices employed by the other state DOTs, and new and emerging safety technologies that are consistent with the MUTCD guidelines. Two traffic control devices were selected after the review process: (1) Temporary portable rumble strips and (2) advance warning lights. The effectiveness of these devices was evaluated based on field tests with the land surveying crew of NJDOT. Recommendations on using the traffic control devices and guidelines for surveyors working on/nearby roadways were summarized.

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EXECUTIVE SUMMARY

Many New Jersey Department of Transportation (NJDOT) employees such as geodetic and land surveyors who work on or near roadways are frequently exposed to fast-moving traffic. They take measurements at different sites with varying traffic and roadway characteristics in a relatively short time period (usually between 5 minutes and 3 hours). More importantly, their work site rapidly changes, as they may frequently move around a large area within pre-determined limits. The special characteristics of surveying work restrict the use of widely accepted traffic control devices (TCD) that are specific to stationary work zones for maintenance and construction activities. Therefore, these employees' work presents unique safety challenges. There is a need to develop safety guidelines and recommendations for using TCD to improve the safety of this special group of NJDOT workers.

The main objectives of this research project are threefold:

1. Identify traffic control devices (TCD) that can effectively alert motorists to the presence of short-term, temporary, surveying work zones;
2. Test the effectiveness of the candidate TCDs in laboratory settings and in real-world applications; and
3. Develop safety recommendations for surveyors and inspectors who work in short-term, temporary work sites.

Examination of Potential Traffic Control Devices

As part of the study, a review of the available TCD for short-term and long-term work zones was conducted. Phone interviews with six state DOTs were also conducted to understand current traffic control and safety practices for surveyors and inspectors in their states. The results of the literature review and interviews indicate that limited information is available in existing practices regarding the use of TCD for short-term, temporary, work sites such as surveying sites.

Other than examining existing studies and practices, site visits were also conducted with bridge inspectors, land surveyors, and geodetic surveyors, not only to understand their exposure to traffic, but also to become familiar with the nature of their work. The visits helped to discover how these crews work in the field and identify suitable TCD. Based on the observed work characteristics, six types of TCD were initially examined:

- Turbo flare
- Turbo flare with electronic movement detector (Turbo flare EMD)
- Traffic blanket
- Portable plastic rumble strips (PPRS)
- Advance warning lights
- Personal strobe light

Based on the laboratory tests and the feedback received from NJDOT, it was found that Turbo Flare and Turbo Flare EMD were not suitable for surveyors or bridge inspectors, mostly because of visibility issues during daytime. Personal strobe lights were found to be useful for land surveyors. Although they are more visible in the dark, personal strobe lights are much more effective than Turbo Flares as well as being cheaper and easier to carry around. Advance warning lights are effective when several of them are deployed on a line. They are visible during daytime and are being used in most construction projects because of their effectiveness in alerting drivers. Traffic Blanket is a quick and inexpensive way to alert drivers of work zones, and it would be a useful TCD for geodetic surveyors to use in addition to the strobe lights they use on their work vans; however, NJDOT informed the research team that arrow signs intended to direct traffic are not allowed on New Jersey roadways. Based on the review of these devices and our initial site visits, only the personal strobe light was recommended for surveyors and bridge inspectors, particularly when the light conditions are not good.

Field Evaluation of Selected Traffic Control Devices

The potential of PPRS and advance warning lights for land surveying work sites was further tested in 18 field tests (10 tests on two-way two-lane roadways and 8 eight tests on two-way four-lane roadways). A set of surrogate safety measures are used as indicators of the effectiveness of these two selected TCD. These measures are (1) mean speed, (2) speed variance, (3) 85th percentile speed, (4) speed limit compliance rate, and (5) braking rate. A summary of the field tests results is presented in the Table 1.

Advance warning lights:

- The use of advance warning lights resulted in 6.6 percent reduction in mean speed at two-lane sites, and 4.4 and 7.2 percent reductions in the right and left lane of four-lane sites, respectively.
- The 85th percentile speed was reduced by 7.0 percent at two-lane sites, and by 1.2 and 8.5 percent in the right and left lane of four-lane sites, respectively.
- Speed measurements at some of the tests were significantly shifted (reduced) to a lower level.
- The effect of the advance warning lights on speed limit compliance was not clear, as only about half of the field tests showed significant reductions in the proportion of speeding vehicles.
- The use of advance warning lights did not show a clear effect on braking behavior for the two-lane sites. However, the braking rate increased at the four-lane sites.

PPRS:

- Deployment of PPRS resulted in 15.2 percent reduction in mean speed at two-lane sites, and 10.1 and 13.8 percent reductions in the right and left lane of four-lane sites, respectively.
- The 85th percentile speed was reduced by 12.6 percent at two lane sites, and by 8.3 and 14.5 percent in the right and left lane of four-lane sites, respectively.
- Speed measurements at most of the tests were significantly shifted (reduced) to a lower level.

- The proportion of speeding vehicles was significantly reduced for both the two-lane test sites and the four-lane test sites.
- Similarly, the use of PPRS significantly increased the proportion of braking vehicles compared with baseline scenario (scenario with an advanced warning sign only).

Table 1 - Summary of field test results

Warning Lights	2-Way 2-Lane	2-Way 4-Lane	
Measures		Right Lane	Left Lane
Speed Variance Change	Did not increase	Did not increase	Did not increase
Mean Speed Change	-6.6%	-4.4%	-7.2%
85th Percentile Speed Change	-7.0%	-1.2%	-8.5%
Speed Distribution Change	No clear change	No clear change	No clear change
Speeding Proportion Change	No clear change	No clear change	No clear change
Braking Proportion Change	No clear change	Increased	Increased
PPRS	2-Way 2-Lane	2-Way 4-Lane	
Measures		Right Lane	Left Lane
Speed Variance Change	Did not increase	Did not increase	Did not increase
Mean Speed Change	-15.2%	-10.1%	-13.8%
85th Percentile Speed Change	-12.6%	-8.3%	-14.5%
Speed Distribution Change	Lowered	Lowered	Lowered
Speeding Proportion Change	Reduced	Reduced	Reduced
Braking Proportion Change	Increased	Increased	Increased
Warning Lights + PPRS	2-Way 2-Lane	2-Way 4-Lane	
Measures		Right Lane	Left Lane
Speed Variance Change	Did not increase	Did not increase	Did not increase
Mean Speed Change	-19.7%	-14.9%	-15.1%
85th Percentile Speed Change	-17.0%	-11.6%	-15.4%
Speed Distribution Change	Lowered	Lowered	Lowered
Speeding Proportion Change	Reduced	Reduced	Reduced
Braking Proportion Change	Increased	Increased	Increased

Warning lights + PPRS:

- Deployment of the two devices together further reduced the mean speed at the surveying sites. The use of these devices reduced the mean speed by 19.7 percent at two-lane sites, and by 14.9 and 15.1 percent in the right and left lane of four-lane sites, respectively.
- The 85^{th} percentile speed was reduced by 17.0 percent at two lane sites, and by 11.6 percent and 15.4 percent in the right and left lane of four-lane sites, respectively.
- Speed distributions for most of the tests were significantly shifted to a lower level.
- The proportion of speeding vehicles was significantly reduced for both the two-lane test sites and the four-lane test sites. The magnitude of reduction was larger when each device was deployed separately.
- Similarly, the combined use of PPRSs and warning lights significantly increased the proportion of braking vehicles when compared with baseline scenario (scenario with the advanced warning sign only). The magnitude of increase was larger when each device was deployed separately.

To sum up, the decrease in operating speed coupled with the increase in speed compliance rate and braking vehicles shows that the additional TCD increased driver awareness. The combination of the two devices further enhanced their positive effect on alerting motorists. Unlike other traffic control devices, PPRSs and warning lights can both be easily installed and removed in minutes, which makes them more practical for short-term surveying operations. The tests in the present study were conducted on several urban roadways under different traffic conditions. The positive effects of these TCD shown in different test conditions suggest that traditional traffic control plans at land surveying sites can be improved.

Recommendations

Bridge Inspectors:

It was observed that bridge inspectors' exposure to traffic is minimal, and the only recommended safety device is the personal strobe light. In contrast, land surveyors and geodetic surveyors were highly exposed to traffic and thus would benefit from additional TCD.

Land surveyors:

Other than the personal strobe light, the PPRS is recommended in addition to existing TCD for land surveying work sites, based on the effectiveness of PPRS shown in the field tests. The warning lights show inconsistent effects thus they are not recommended to be used without PPRS.

Besides TCD, the use of advanced surveying technologies such as static LiDAR technology would tremendously increase the safety of surveyors because they offer opportunities for surveyors to automatically take measurements without having to expose themselves to traffic.

Aside from traffic safety devices, it is recommended that having additional surveyors / lookout personnel present in the field benefits the whole crew tremendously in terms of safety.

Geodetic surveyors:

Geodetic surveying crews work at a fast pace and take GPS measurements without having time to set up signs, TCD or cones. At each location, they spend between 3 and 5 minutes to take GPS measurements. Therefore, PPRS or warning lights are unsuitable for geodetic surveyors. Other than the existing practices, personal strobe light is recommended among the potential safety devices. The use of mobile LiDAR technology is recommended for geodetic surveyors since it would reduce their exposure to live traffic. In addition, an attenuator truck should be assigned for the sole use of the surveying department to increase the safety of geodetic surveyors, especially when working on roadways without shoulders.

The recommended use of the selected traffic control devices is not fully consistent with MUTCD. However, as described in the Literature Review section, many DOTs tested these devices with similar goals of assessing their effectiveness in terms of safety. If, in fact in the future, it is decided to adopt one of more of these devices for the type of work zones studied in this report, necessary adjustments have to be made to ensure consistency with the MUTCD requirements.

INTRODUCTION

Many New Jersey Department of Transportation (NJDOT) employees, such as geodetic surveyors, land surveyors, and bridge inspectors who work alongside a roadway or highway, are constantly exposed to fast-moving traffic. Their work presents unique safety challenges, because the duration of their work is relatively short (between 5 minutes and 3 hours), they work at different sites with varying traffic and roadway characteristics, and—more importantly—their workplace rapidly changes. They usually cover a large area within predetermined limits, which restricts the use of widely accepted traffic control devices that are specific to stationary work zones for maintenance and construction activities.

Each state DOT has general safety guidelines for these types of work zones, where employees are required to set up traffic control signs alerting drivers, use a strobe light on their vehicles, set up cones around the workers, and wear reflective safety vests. In addition, the *Manual on Uniform Traffic Control Devices* (MUTCD 2009) predominantly addresses work performed along the centerline of roadways and low-speed roads. However, these guidelines do not address many different situations that surveyors and bridge inspectors face when working at and alongside a roadway or highway. Land surveyors, for instance, often need to take measurements along the centerline, which requires another surveyor with a reflector to stand in the live lane. In contrast, geodetic surveyors set up monuments and take global positioning system (GPS) measurements at predefined intervals alongside a highway, where they spend only 3 to 5 minutes at each location and do not have time to set up cones or warning signs to alert drivers.

Limited information is available in the literature regarding the effectiveness of traffic control devices (TCD) for short-term, temporary work zones. Furthermore, other short-term work zones, such as maintenance and utility work, do not have the same characteristics of short-term work zones that surveyors and bridge inspectors work in. Surveyors, especially, are constantly exposed to traffic, and stand in or cross live lanes as a part of their work. Therefore, the TCD applicable to maintenance or utility work are not applicable to these types of work zones.

Therefore, there is a need to develop safety guidelines and recommendations for using TCD on high-volume roads for this special group of NJDOT employees. This goal can be achieved by performing the following steps:

1. Review current practices used by other state DOTs.
2. Review new and emerging TCD consistent with MUTCD guidelines.
3. Assess the effectiveness of these technologies by conducting laboratory and field tests to understand the performance of the most promising technologies under New Jersey–specific conditions.
4. Develop work zone control guidelines and recommendations for TCD for NJDOT surveyors and inspectors on high-volume roadways.

The main objectives of this research project are to:

1. Identify traffic control devices that can effectively alert motorists to the presence of short-term, temporary work zones;
2. Test the effectiveness of the selected candidate traffic control devices in real-world and laboratory settings; and
3. Develop safety guidelines and recommendations for surveyors and inspectors who work in short-term, temporary work zones.

This report is organized as follows: In the next section, a review of the available TCD for short-term and long-term work zones is presented. Later, the potential devices suitable for surveyors and inspectors are described. Candidate devices are then selected based on our initial site visits with geodetic and land surveying crews and bridge inspectors in New Jersey. Based on our laboratory tests and consultation with the surveying and bridge inspection crews, two traffic safety devices were selected: (1) portable plastic rumble strips and (2) warning lights. The impact of these selected devices on traffic speed and driver awareness is based on field tests, and statistical analyses of the results are presented in later sections. Safety recommendations based on the statistical analyses of field tests are also presented.

LITERATURE REVIEW

The following section provides an overview of the literature on the available TCD applicable to regular work zones of either long or short duration as well as work zones specific to surveyors and inspectors. It also includes the summary of phone interviews the research team conducted to determine the current practices used by other state DOTs.

Traffic Control Devices for Regular Work Zones

Despite many efforts in the past, highway work zones remain a serious safety concern. For instance, in 2010, there were a total of 6,837 work zone accidents in New Jersey. A total of 215 accidents were at maintenance zones, with 1,552 injuries and 18 fatalities.

Many work zone related accidents occur as a result of disregarded traffic control, alcohol impairment, and speeding. [(1)] It is clear that the severity of an accident correlates with the mean speed of traffic. Therefore, it is essential to assure motorists' compliance with reduced speed limits at work zones.

According to a Texas Transportation Institute study conducted by Fontaine [(2)], most maintenance work performed on low-volume rural roads is completed in a single day, but the safety challenges are greater. There are limited law enforcement agencies patrolling these areas, where the regulatory speed limit is 70 mph, so work crews rely on traffic control devices for safety protection. The study identified innovative TCD that could be used to improve the safety of short-term rural maintenance work zones. Several innovative countermeasures were examined using the following criteria:

- Evaluating devices not currently used by the Texas DOT (TxDOT) in temporary traffic control zones for reducing speeds, improving worker visibility, or increasing awareness of the work zone;
- Determining the impact of the devices by conducting field evaluations; and
- Assessing the feasibility of using these devices for short-term work zones.

In Fontaine [2], the research team selected five significant countermeasures for field tests: a speed display trailer, a radar drone, portable rumble strips, alternative work vests, and roll-up orange signs. These devices were tested at mid-day on four-lane and two-lane roadways, with the length of activity areas between 1/2 and 1/4 mile long. The devices were evaluated to establish the measures of effectiveness (MOEs) shown in Table 2.

Table 2 - Measures of effectiveness for each device [2]

Device	Traffic Speed	Conflicts	Worker Comments	Driver Comments
Speed display trailer	✓	✓	✓	
Radar drone	✓	✓	✓	
Portable rumble strips	✓	✓	✓	
Alternative worker vests			✓	✓
Fluorescent orange roll-up sign			✓	✓

In Fontaine [2] traffic speeds were measured using light detection and ranging (LiDAR) speed guns and traffic counters to determine reductions in speed as a result of the TCD. In addition, video recording of traffic was used to determine the braking patterns of vehicles approaching work zones. Workers and drivers were interviewed at the sites on the potential benefits of these applications. Closed-course evaluations were also used to assess the luminance and contrast ratio of worker vests.

In Fontaine [2] the use of speed display trailers resulted in the largest speed reduction (5 mph) of all devices tested. The radar drone produced less than a 1-mph reduction in speed, while there was a reduction of between 1.5 and 4 mph in motorist speed when rumble strips were used in the short-term work zone. Workers preferred to use the speed display trailers, as their setup time is shorter than that of rumble strips. Also, yellow–green was favored as possessing a higher luminance and contrast ratio than the orange vests, which is not in compliance with the current American National Standards Institute standards. Drivers felt that the fluorescent orange signs were more visible.

Finley et al. [3] studied the effectiveness of a flashing warning light system for work zone lane closures. The system was composed of a series of interconnected, synchronized flashing warning lights producing the illusion of motion. The study showed that the flashing warning light system was perceived positively and was not confusing to motorists. The results showed that when the warning light system was used at an urban freeway test site that was a new closure, there was a 23 percent to 63 percent reduction in vehicles in the closed lane 1,000 ft upstream of the lane closure. However, the system did not significantly affect lane choice at a rural road test site, where the lane closure had been in place for 6 months. The study concluded that the warning light system was most useful when it was used for short-term or intermediate-term lane closures.

Hajbabaie et al.[4] investigated the effects of four different speed-management techniques for reducing speed and speeding in interstate highway work zones. The techniques used were a speed feedback trailer, a police car, a speed feedback trailer plus police car (trailer + police), and automated speed photo-radar enforcement. The results showed that in moderate and extensive speeding sites, all law enforcement techniques reduced the mean speeds and the degree of speeding significantly. In a moderate speeding site, the trailer + police technique reduced the mean speeds by 8.4 mph to 48.6 mph in the median lane, while the other techniques reduced the mean speeds by 6.1 to 6.4 mph. In the extensive speeding work zone, the trailer plus police technique and the speed photo-radar enforcement technique reduced the mean speed by 7.8 mph to 55.9 mph.

Similarly, Oliveira et al. [5] investigated the impact of radar transmissions on the mean speed of drivers. Radar detectors can provide motorists of radar detector–equipped vehicles with advance warning about the presence of speed enforcement activity, allowing them to slow down before their speeds are recorded. This strategy is often called *drones.* However, the results showed no significant reduction in speeds, which was attributable to the low density of radar detectors.

McCoy and Pesti [(6)] evaluated the effects of condition-responsive, reduced-speed-ahead messages on reducing traffic speed. The results showed that during periods of uncongested-flow conditions, the messages were not effective in reducing speeds. However, during congested traffic periods, the messages were effective when drivers were aware of the presence of a work zone ahead, and they were likely to recognize the need to slow down.

Mattox et al. [(7)] evaluated the effect of a speed-activated sign on the reduction of 85th-percentile traffic speed and the percentages of vehicles exceeding the speed limit. The speed-activated sign was designed to trigger a flashing beacon when a predetermined speed threshold was exceeded. Mean speed reductions ranged from 2 to 6 mph, with an average reduction of 3.3 mph. The average reduction improved to 4.1 mph at sites where more than 50 percent of the vehicles were speeding prior to the introduction of the sign. Also, the percentage of vehicles exceeding the speed limit by 10 percent was reduced by a range of 7.8 to 20.6.

NJDOT and other DOTs use several technologies to enhance safety (http://www.road-tech.com/traffic_control_equip.html; see Figure 1 and Figure 2):

1. Portable changeable message signs (CMSs)
2. Radar speed display trailers
3. Automated flagger assistance devices (AFADs)
4. Portable traffic signals
5. Arrow boards
6. Truck-mounted attenuators
7. Truck-mounted CMSs and AFADs

Figure 1. Automated flagger assistance devices (AFADs)[8]

Figure 2. A typical truck-mounted attenuator and arrow board used for moving lane closures [9]

Most DOTs routinely use the technologies shown in Figure 1 and Figure 2 to improve safety at their work zones. However, several emerging wireless high-tech solutions are becoming available to work zone crews. These advanced solutions should be designed to satisfy the following criteria to be deployable:[10]

1. **They should be "rapidly deployable."** The most important feature of a technological solution for short-term work zones is that it has to be deployed quickly, because these work zones are active for just a few hours at a time.
2. **They should be inexpensive.** The cost of any technology solution must be kept

to a minimum, because a short-term work zone is a temporary deployment that will be quickly removed after the task has been completed.

3. **They should not require skilled maintenance.** Maintenance of the system must be easy, without any requirement for professional personnel to operate it; rather, these maintenance operations should be easily performed by the work zone crews themselves.

Among these technologies, the most promising are:

1. **The SonoBlaster® Dual Alert™ Work Zone Intrusion Alarm.** This alarm, shown in Figure 3, is "an impact-activated safety device that warns roadway workers and errant vehicle drivers simultaneously to help prevent crashes and injuries in roadway work zones."[11] The SonoBlaster alarm mounts on typical work zone barricades, cones, drums, delineators, A-frames, and other barriers and is accepted by National Cooperative Highway Research Program Report 350. When impacted by an errant vehicle, the SonoBlaster alarm emits a loud (125 dB or more) sound for 15 seconds.

   Despite the innovative features, a recent study for NJDOT showed that the intrusion alarm was not practically useful. [12] It was found that the quality control of the device is still questionable because of issues such as time-consuming and tedious procedures needed to deploy the device and short durability. In addition, its reliability as a safety-promoting device is a shortcoming because of misfires.

Figure 3. The SonoBlaster Dual Alert work zone intrusion alarm (http://www.transpo.com/sonoblaster.htm)

2. **Safety Line SL-D12 work zone intrusion alarm.** This alarm, shown in Figure 4, consists of a transmitter and receiver. The transmitter is placed at the start of a taper just inside the channelizing devices. The receiver can be placed up to 1,000 ft away, closest to the workers. The transmitter projects a dual infrared beam to the receiver. If a vehicle enters the buffer area, the dual transmitted beams would be obstructed, thus causing the receiver to activate the 147-dB air horn, alerting the workers.

Figure 4. Safety Line SL-D12 work zone intrusion alarm [13]

This technology has potential benefits for short-term and long-term work zones. However, the product, initially developed by SHRP, is no longer manufactured.

3. **Wireless Warning Shield.** This device, shown in Figure 5, uses a coded repeater-style radio system. The unit, which is triggered via the internal shock sensor, transmits a radio signal that is picked up and retransmitted by the next two or three PRT-300 repeaters, each of which repeat as well, and so on. Because our range is up to 300 ft, several cones should be triggered at once, causing redundancy of repeater points. This repetition increases the reliability of the repeater chain. The signal is also picked up by any of the receiving alarm systems that are within range. These alarms, whether area alarms, personal body alarms, or headphone alarms, will all signal a “hit,” indicating possible danger.

Figure 5. Wireless warning shield [13]

Current Safety Devices for Surveyors and Inspectors

Surveyors are required to use TCD to provide the maximum level of safety for their crews and the traveling public when working on or adjacent to a roadway. According to the practices of many transportation agencies, [14-22] the implementations of temporary traffic control when surveying usually include use of (1) appropriate signing, (2) personnel such as flaggers and lookouts, and (3) other procedures outlined in survey manuals or handbooks, if available. Generally, surveyors are required to wear high–visibility safety vests when working near vehicular traffic.[23] The principle advance warning signs such as those announcing “Survey Crew Ahead” (see Figure 6 b) have to be installed in accordance with Part VI of *MUTCD for Streets and Highways.*[24] In addition, channelizers may be used according to field conditions. Historical surveyor-involved crashes show that these control devices can play an important role to prevent the occurrence of the crash. Besides, flaggers using stop–slow paddles may be positioned as needed to warn drivers. Supplementary TCD such as arrow displays, variable message signs, and vehicle-warning lights are also frequently advised.

(a) High-visibility vest (b) Advance warning sign (c) Flagger sign

Figure 6. General safety devices for surveyors and inspectors

Other than the general safety countermeasures described in those manuals and handbooks, there is limited guidance on what and how countermeasures can be used to improve the safety of surveyors as well as road users in surveyor work sites. Surveyors do not work in stationary work areas. Therefore, temporary traffic control devices and strategies described by MUTCD for traditional work zones cannot be used directly. Emerging high-tech solutions such as intrusion alarms and speed display trailer are also mainly focused on work zones. Therefore, more specific technologies and TCD thus should be investigated.

Current Practices in Other Agencies

We conducted phone interviews with six state DOTs to understand the current traffic control and safety practices for surveyors and inspectors in their states. The following section summarizes our findings.

TxDOT considers surveying on high-speed roadways a regular work zone and uses a customized version of MUTCD named the *Texas Manual on Uniform Traffic Control Devices* (TMUTCD) for this type of surveying. The current version of TMUTCD has information similar to MUTCD regarding the safety of survey work zones, and it does not specifically address the safety problems surveyors or inspectors encounter during the majority of situations on high-speed, high-volume roadways. A new task force aimed at determining alternative surveying standards for low-speed roadways has been formed according to information obtained during the telephone interview. TxDOT also uses mobile LiDAR technology for highway overhead-obstruction clearances and bridge layouts and is currently investigating more possibilities for this technology.

Rhode Island DOT (RIDOT) uses police cars and flaggers for surveying jobs in high-volume, high-speed roadways and follows the MUTCD guidelines. For other types of surveying work, RIDOT aims to follow MUTCD standards as much as possible and does not have guidelines specific to surveyors. The DOT believes that more than any advanced technology and traffic control devices, the experience of the surveyor and the presence of a spotter is of utmost importance in ensuring safety in surveying work zones.

Oregon DOT (ODOT) uses portable CMSs, additional lighting, and more dominant devices, such as high-intensity rotating, flashing, oscillating, or strobe lights, on work vehicles at the surveying work zones in addition to advanced warning signs. ODOT mandates several spotter guidelines to enhance the safety of surveyors. In a phone interview, ODOT indicated that it hires consultants that specialize in mobile laser scanning and low-altitude aerial photogrammetry for major geodetic surveying jobs. Currently, ODOT does not use any additional traffic control devices besides those mandated in MUTCD.

New York State DOT (NYSDOT) follows MUTCD guidelines for all surveying work. If the surveying work zone is not specified in MUTCD, NYSDOT coordinates with the maintenance crew to enhance the safety of surveyors. For big projects, the DOT uses variable message signs and rumble strips to increase the awareness of drivers.

Pennsylvania DOT (PennDOT) has a photogrammetry department and uses aerial surveys. It also uses static LiDAR equipment. PennDOT contracts out large geodetic surveying jobs to consultants who use mobile LiDAR technologies. During our phone interview with PennDOT, we were told that using the advance surveying technologies, surveyors' exposure to traffic is minimal. However, if there is a need for them to be on the roadway for various surveying jobs, maintenance crews help ensure safety.

North Carolina DOT (NCDOT) has been using static LiDAR technology for 7 years in-house. It owns one LiDAR unit and contracts five firms that use static LiDAR technology. Approximately 50 to 60 percent of LiDAR scanning is conducted by consultants; overall, 20 percent of surveying work is contracted out. NCDOT also uses mobile scanning technology through consultants. With the increased use of LiDAR technology, the DOT has not been using low-altitude photogrammetry as often as it did in the past. During our phone interview, we learned that with the use of advanced surveying technologies, NCDOT never closes lanes for surveying work, and surveyors rarely work on shoulders. However, when there is a need for shoulder work or lane closures, the DOT coordinates with the maintenance department for help.

We contacted other state DOTs, and most DOT representatives informed us that they consider any type of surveying work to be a regular work zone and thus apply MUTCD guidelines for regular work zones.

It is apparent from our phone interviews that many state DOTs are moving in the direction of adopting advanced surveying technologies, such as static and mobile LiDAR. As explained in the Recommended Traffic Control Devices section, although the cost of LiDAR technology is higher than those of traffic safety devices tested in this project, LiDAR surveys offer great benefits including a wealth of information and the possibility of data sharing with other departments within DOT and with other local and state government agencies.

INITIAL SITE VISITS

Site visits were conducted with bridge inspectors, land surveyors, and geodetic surveyors not only to collect safety data and understand how much they are exposed to traffic but also to become familiar with the nature of their work. The visits helped us discover how these crews work and ensure their safety during field tests.

Depending on the nature of the field work, surveyors or inspectors could be working on the shoulder, on the roadway, or both. Because their workplace is rapidly changing, they usually cover a large area within predetermined limits. For the surveyors, for instance, data collection should be between the first road sign warning drivers about the survey activity (e.g., "Survey Crew Ahead") and the point where the survey teams conduct their work.

Traffic conflicts are of particular interest for data collection, because they can be used as a "proxy" for traffic accidents. Conflicts are more frequent than actual accidents, so identifying traffic conflicts allows assessment of the risk of a location in terms of traffic safety. Studies suggest that a few days of conflict observation provide better estimates of a location's accident potential than years of accident data.[25] One reason is that accidents can be events with low-occurrence frequencies and therefore can be subject to misinterpretation. In contrast, conflicts are more frequent and therefore better from a statistical perspective for providing information regarding traffic safety.

The data collection plan is summarized in Table 3. Measures of effectiveness selected for data collection are lane volume distribution, traffic conflicts, and speed. The equipment for collecting these data was portable high-definition camcorders. Camcorders must be positioned at least 10-ft above the ground to capture detailed vehicle maneuvers.

Table 3 - Data collection plan

Measure of Effectiveness	Data Type	Locations	Methods
Lane volume distribution	Traffic counts	After "Survey Crew Ahead" sign	Camcorder
Traffic conflicts	Percentage lane changes	After "Survey Crew Ahead" sign	Camcorder
Speed	Average speed by lane Variance of speed by lane	After "Survey Crew Ahead" sign	Radar gun

The research team obtained the selected measures of effectiveness by carefully extracting data from the video recordings.

Geodetic Surveyors

According to NJDOT, geodetic surveying maintains and expands the geodetic control network within New Jersey through GPS technology and leveling. Geodetic surveyors also maintain files of state and federal horizontal and vertical control data.

Table 4 shows the dates when the research team visited the geodetic surveying group.

Table 4 - Site visits with geodetic surveyors

Location	Date
Route 30, Absecon, NJ	11/12/2010
Route 30, Absecon, NJ	11/18/2010
Route 70, Cherry Hill, NJ	11/19/2010
Route 55, Millville, NJ	05/03/2011
Route 55, Millville, NJ	05/05/2011

Geodetic surveying crews work at a fast pace and take GPS measurements without having time to set up signs or cones. The only safety devices they use are the strobe lights on their work vans and their safety vests. There are no specific guidelines on how to ensure their safety while working alongside a highway, but from our observations, surveyors maintain their own safety procedure and make sure they visit the locations during off-peak periods, reducing exposure to traffic. If the location where they have to take measurements is close to a live lane, they either come back another time or take measurements close to the original location but away from the roadway.

We observed during the initial site visit that geodetic surveyors do not spend more than 3 to 5 minutes at each location (see Figure 7). They take GPS measurements of the predetermined locations on the map and move to another location. Therefore, a detailed setup, including several video cameras and radar speed guns for data collection, would not be appropriate for this type of surveying.

Figure 7. Preliminary site visit on November 12, 2010 (Rt. 30, Absecon, NJ)

Based on this visit, we decided to modify our data-collection strategy. Because the surveyor spends only 3 to 5 minutes at each location, we would have to start recording the traffic without losing time for deploying the equipment. Therefore, we decided to use an easily extendable yet durable pole with a camcorder attached (see Figure 8). This type of setup allowed us to record traffic at an elevation of 12 ft (extended from 5 ft) without interfering with the surveyor's work.

Figure 8. Portable setup for video recording

The research team analyzed each video frame by frame to measure accurate speed information for each vehicle traveling on the lane closest to the surveyor. To extract speed from the video, Windows® Movie Maker was used. Each video was played at the lowest speed (1/100th of a second) to extract the time elapsed for each vehicle between predetermined monuments in the video. Based on the distance between the monuments and time elapsed, the speed of the vehicles was accurately extracted.

Table 5 shows the extracted data during the site visits to Route 70 and Route 30. Speed distributions of vehicles on the closest lane to the surveyor are shown in Figure 9 and Figure 10. It can be observed that at each location where the geodetic surveyor takes GPS readings for 3 to 5 minutes, there are vehicles going as fast as 65 mph, where the speed limit for both roadways is 45 mph. More than 80 percent of vehicles were speeding during the surveyor operation at the site on Route 70, and all vehicles were speeding at the site on Route 30. Also, results show that vehicles change their lanes at a rate of 1 percent to 7.5 percent when they see a surveyor van with strobe lights.

Table 5 - Traffic data extracted from site visits with a geodetic survey crew

Location	Duration (min)	Lane 1** (veh)	Lane 2 (veh)	Lane 3 (veh)	Lane Change (%)	Total Volume (veh)
Route 70*	3:16	35	49	49	7.5	133
Route 70*	4:24	19	53	49	6.6	121
Route 70	3:27	85	74	–	5.7	159
Route 70	3:08	54	42	–	1.0	96
Route 30	1:03	22	13	–	5.7	35

*Indicates downstream of a signalized intersection.
**Indicates the lane closest to the surveyor.

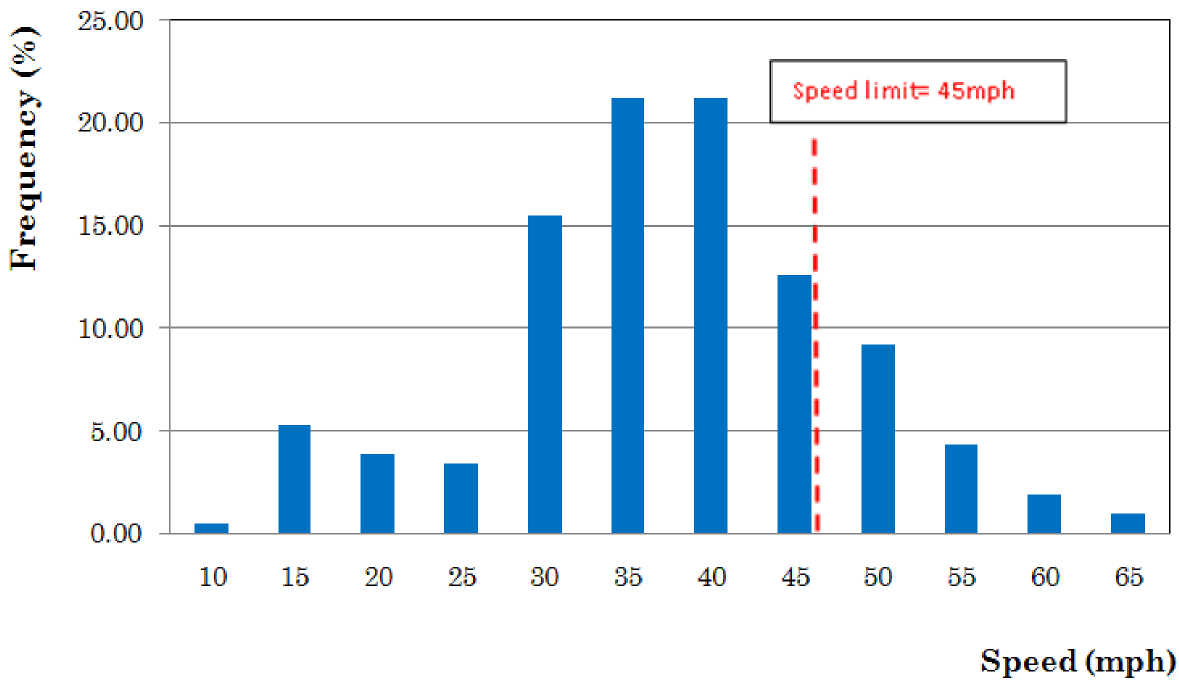


Figure 9. Speed Distribution of vehicles on Route 70

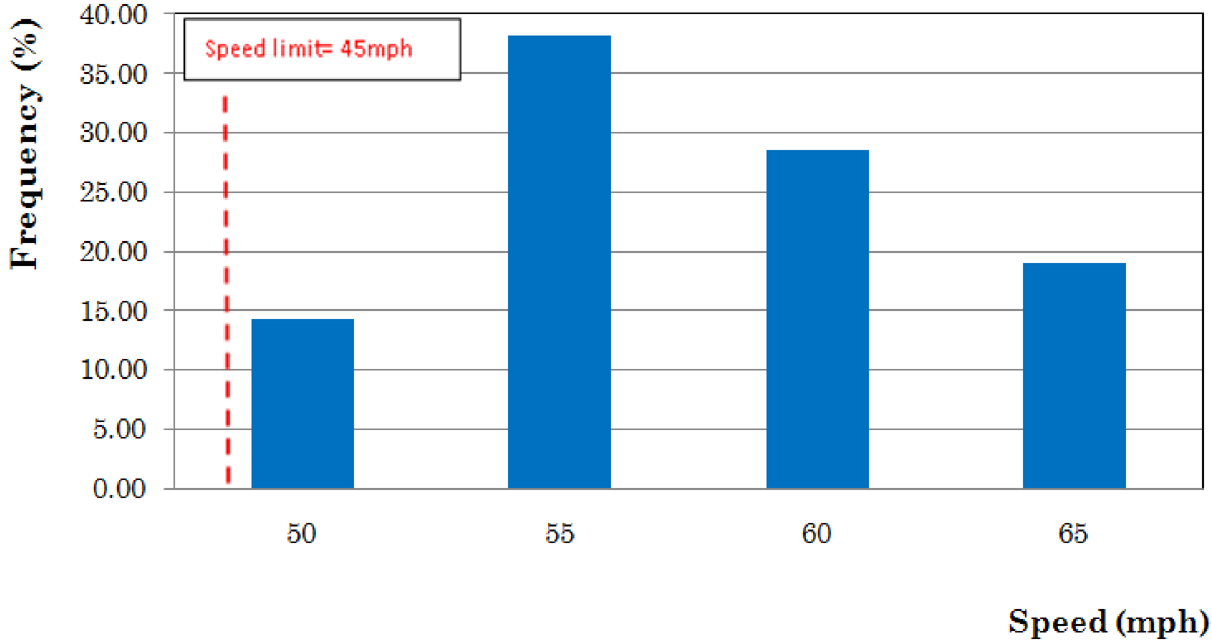


Figure 10. Speed distribution of vehicles on Route 30

The extracted data clearly show that geodetic surveyors are exposed to traffic; their only safety precaution is working in front of the work van.

Land Surveyors

Land surveyors determine horizontal and vertical locations of existing features and provide computer-aided drafting (CAD) files and base maps that other design sections in the NJDOT can use.(26)

Table 6 shows the dates when the research team visited the land surveying crews.

Table 6 - Site visits with land surveyors

Location	Date
Lower Ferry Road, Ewing, NJ	05/13/2010
Route 64, Princeton, NJ	06/04/2010
Route 35, Belmar, NJ	06/09/2011
Route 33, Neptune, NJ	09/16/2011

Land surveyors that the research team visited mostly worked on state highways and county roads, taking horizontal and vertical readings of features at and around railroad tracks and intersections (see Figure 11). The duration of their work varied between 45 minutes and 3 hours. There are no specific guidelines for assuring the safety of surveyors at these types of roadways. Regardless of what the technology has to offer, the safety of surveyors is first and foremost in the hands of the surveyors themselves. Although there are no written guidelines on safety for these specific types of surveying work, there are various rules that surveyors have abided by over the years. Having additional surveyors present in the field benefits the whole crew more than anything else in terms of safety. Ideally, land surveying jobs include three surveyors in the crew. If only two surveyors are present, one surveyor works the transit, and the other surveyor uses the leveling rod while the traffic is coming in two directions. They have to check the traffic, make sure it is safe while they are working, and communicate with each other. If there is a third surveyor, he or she would be responsible for flagging the traffic and making sure his or her crew is safe.

Figure 11. Preliminary site visit on 05/13/2010 (Lower Ferry Rd., Ewing, NJ)

Land surveyors set up “Survey Crew Ahead” signs ahead of the work area in both directions of the roadway. The only safety precaution they have is the safety vests they wear and the help of a flagger, if available.

The research team used the same portable data collection setup shown in Figure 8. A tripod was used to stabilize the rod that the camcorder is attached to. Traffic immediately after the “Survey Crew Ahead” sign was captured by video while the survey crew was working. Using the recorded traffic video, the speed of each vehicle was extracted in the lab by analyzing the recordings frame by frame using Windows Movie Maker.

Speed distributions of vehicles are shown in Figure 12 and Figure 13. While the land surveyors were working on and around the roadway, vehicles were observed going as fast as 65 mph, where the speed limit for Route 35 is 40 mph and for Route 33 45 mph.

Today, the roads are populated with commercial signs and traffic lights; in addition, drivers are more and more distracted because of technology such as cell phones, navigation systems, and onboard electronics. There is a need to make sure that drivers are alerted in an effective manner regarding the work zone ahead and ensure that they slow down.

The extracted data and the research team’s observations during site visits showed that land surveyors are highly exposed to traffic. They work mostly on local streets and state and county roads, where the traffic speed limit varies between 25 and 50 mph. Given the nature of their work, they are mobile and often stand in moving traffic with almost no safety protection other than reflective safety vests.

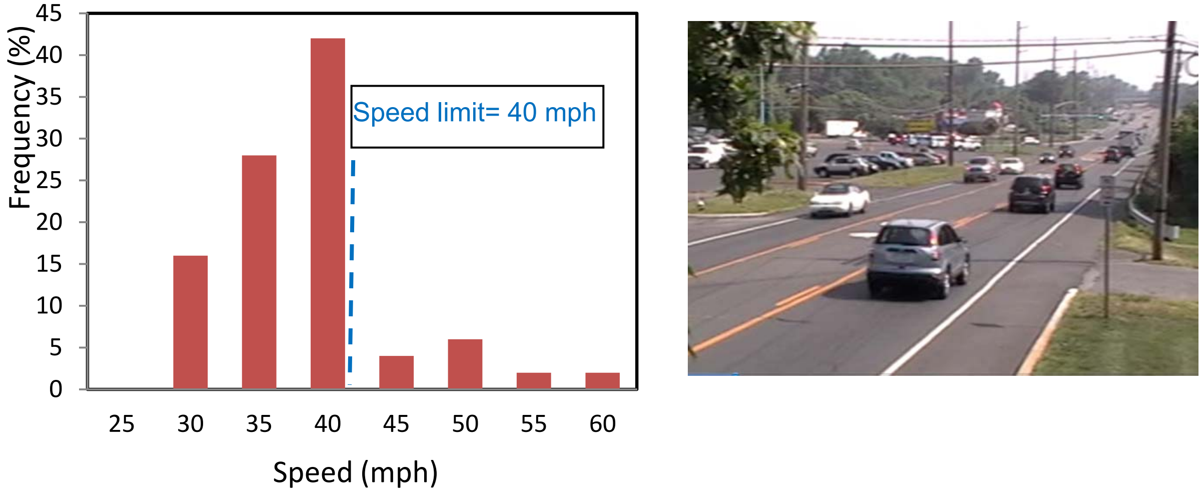


Figure 12. Speed distribution of vehicles on Route 35 (06/09/2011)

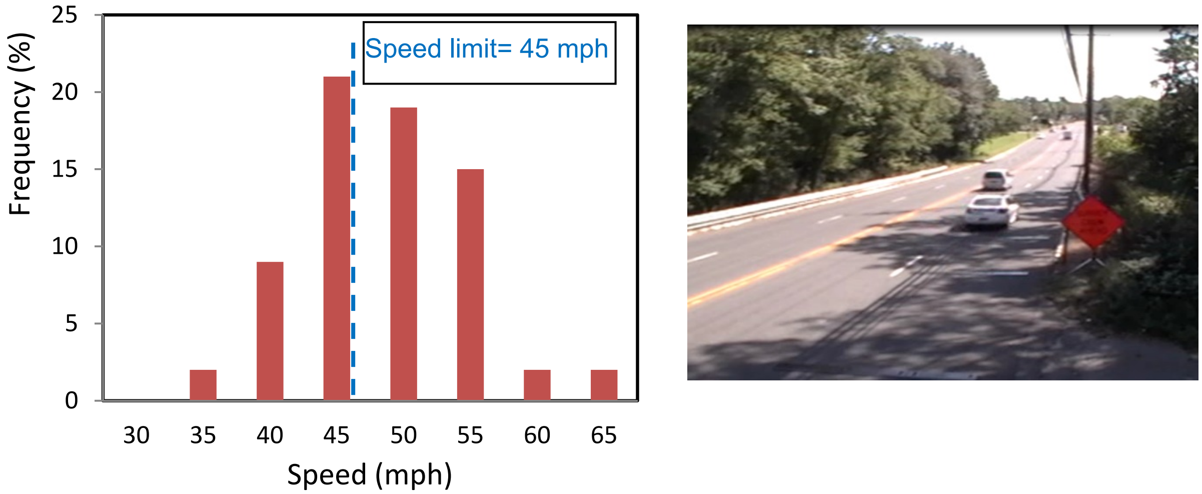


Figure 13. Speed distribution of vehicles on Route 33 (09/16/2011)

Bridge Inspectors

NJDOT administers various bridge and structure inspection programs and performs other activities to ensure the safety of all major structures on state roads as well as various other structures. The bridge inspection program assures statewide compliance with the National Bridge Inspection Standards. As part of this program, bridge inspectors perform bridge inspections and report on findings. Each bridge in New Jersey is required to be inspected every 2 years.

Table 7 shows the dates when the research team visited the bridge inspectors. The research team used the same portable data collection setup shown in Figure 8. A tripod was used to stabilize the rod that the camcorder is attached to.

Table 7 - Site visits with bridge inspectors

Location	Date
I-78, Lebanon, NJ	06/14/2011
Route 33, Howell, NJ	06/15/2011
Route 31, Lebanon, NJ	06/28/2011
I-78, Bloomsbury, NJ	06/28/2011
Route 41, Lakeland, NJ	06/30/2011
Route 55, Vineland, NJ	07/13/2011
Route 130, Camden, NJ	07/15/2011
Route 33, Neptune, NJ	09/16/2011

Bridge inspectors are required to be accompanied by an attenuator truck when working on any roadways that has speed limit of 45 mph. However, on any other roadway, they either park their work van with a strobe light on by the shoulder or, if possible, park their work van off the road and walk to the structure. If parked by the shoulder or off the shoulder, bridge inspectors set up cones by the van (see Figure 14). In other cases, bridge inspectors are not exposed to traffic, because they mostly work off the road and behind the guardrails while inspecting the structure.

Figure 14. Preliminary site visit on Route 18, Piscataway

Based on our site visits, the research team did not observe any significant safety issues, because bridge inspectors are not exposed to traffic.

POTENTIAL TRAFFIC CONTROL DEVICES FOR SURVEYORS AND INSPECTORS

Although substantial guidance is provided for setting up standard traffic control zones, the extant literature does not include any studies investigating the advanced TCD to improve the safety of surveyors working on or adjacent to roadways. The research team identified and examined many commercially available alternative TCD according to the non-stationary nature of the short-term work activities of surveys and inspection. The following devices were initially considered for laboratory and field tests.

Turbo Flare

Turbo Flare, manufactured by Traffix Devices, is an electronic flare that uses light-emitting diodes (LEDs) to warn oncoming traffic about the presence of roadway activity ahead (see Figure 15). It is weatherproof and highly durable (resistant to vehicle weight) and lasts up to 30 hours on a charge. It can be used either with an orange pennant or a spring cone. Mesloh et al.(27) evaluated chemical flares and several electric flares, including Turbo Flare. The durability, portability, and factors affecting their performance were documented. The Turbo Flare was found to be durable, as it was not damaged when researchers dropped it from increasing heights and drove over it repeatedly. In addition, the carrying case made it easy to deploy multiple flares. According to the field test, the Turbo Flare became less visible as the distance increased.(27) Its ground-based visibility index was about zero when the distance was 0.5 miles. The test results also indicated that the flash pattern and its relative height above the ground can limit its visibility.

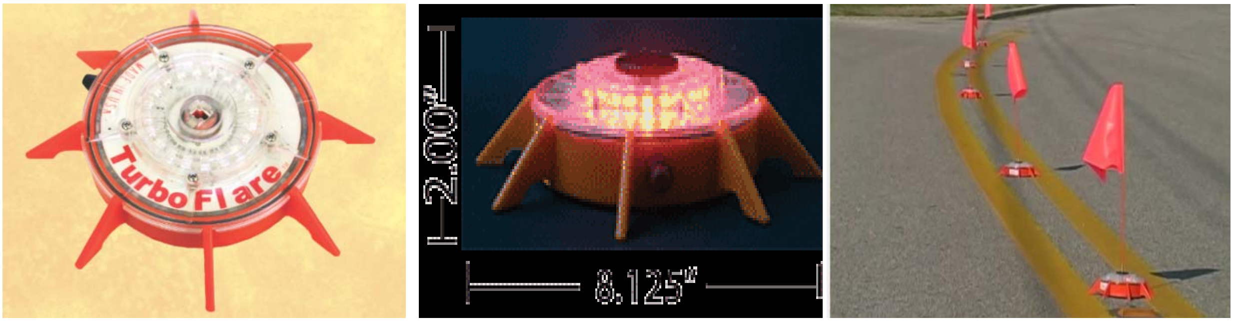


Figure 15. Turbo Flare [28]

Product information

Dimensions (width × height): 2 in × 8.125 in

Weight: <1 lb

Light source: 20 high-output LEDs

Viewing angle: 4° below horizontal to 14° above horizontal

Different LED colors are available. The Turbo Flare has a single rotating light pattern. The product is made of DuPont™ Surlyn® plastic, the same material golf balls are made of. It has a weatherproof O-ring seal, and it is spring loaded and has a moisture-resistant on/off switch. The flare is powered by four AA batteries and operates at 160 nominal rotations per minute.

Turbo Flare with Electronic Movement Detector

An electronic movement detector (EMD) can be added to Turbo Flare to notify the worker or surveyor of any interference from vehicles entering the area surrounded by Turbo Flares or if any flare is removed. A constant beep is sent to the receiver attached to the shoulder flap on the surveyors' uniform or belt. The Turbo pennants that attach to the top of each flare are used to increase the visibility of turbo flares and to easily deploy and pick up the flares.

Product information

In addition to the properties of a regular Turbo Flare, the receiver works with multiple Turbo Flares within 250 yards and sends a constant beep when any of the Turbo Flares is moved or driven over.

The research team bought four Turbo Flares with EMD for testing. As mentioned, the Turbo Flare EMD sends out a signal to a receiver when it moves. The research team designed an experiment to observe how effectively Turbo Flare operates in real-world conditions. The research team tested two properties of Turbo Flare: (1) the false alarm rate caused by passing vehicles on adjacent lanes without touching the unit and (2) the sensitivity of the receiver. The tests were conducted at a vacant roadway at the Rutgers University campus.

Table 8 through Table 11 present the results of these tests.

Table 8 - Effect of passing vehicles on turbo flare without flag

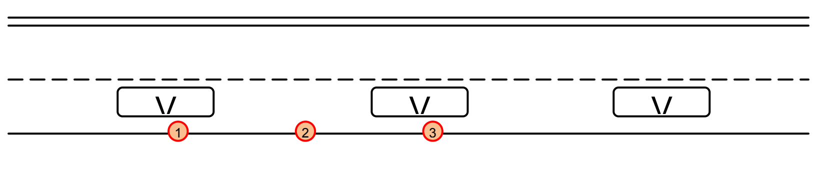
			
Vehicle passes by the sensor at different speeds (two runs/scenario)			
Vehicle Speed	**Test with 1 Sensor**	**Test with 2 Sensors**	**Test with 3 Sensors**
20–25 mph	No false alarms	No false alarms	No false alarms
30–35 mph	No false alarms	No false alarms	No false alarms
40–45 mph	No false alarms	No false alarms	No false alarms

Table 9 - Effect of passing vehicles on Turbo Flare with flag

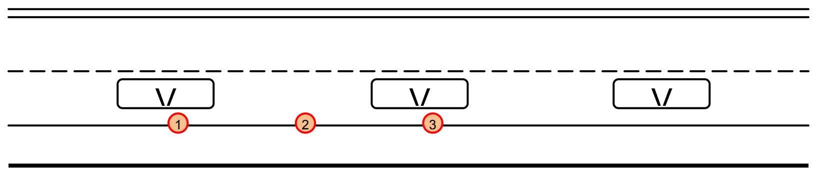
			
Vehicle passes by the sensor at different speeds (two runs/scenario)			
Vehicle Speed	**Test with 1 Sensor**	**Test with 2 Sensors**	**Test with 3 Sensors**
20–25 mph	No false alarms	No false alarms	No false alarms
30–35 mph	No false alarms	No false alarms	No false alarms
40–45 mph	No false alarms	No false alarms	No false alarms

Table 10 - Intrusion alarm sensitivity of Turbo Flare without flag

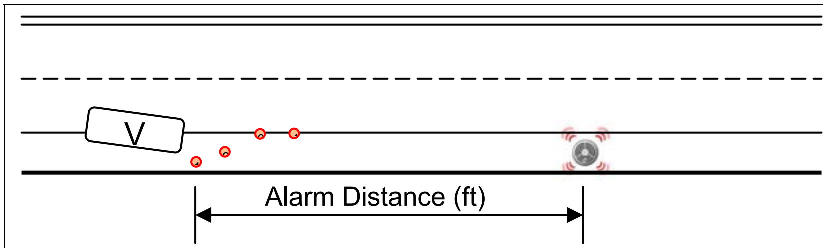
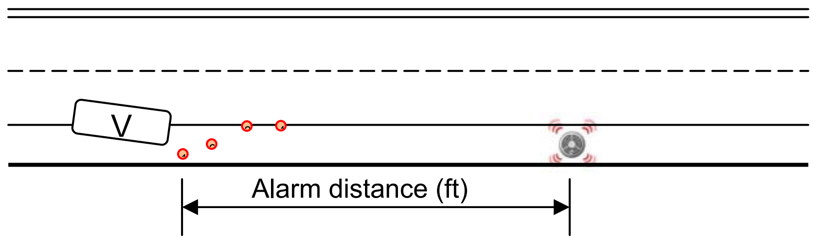
			
Investigator manually touches the sensor (10 runs/scenario)			
Receiver Location	**100 ft**	**150 ft**	**200 ft**
Manually moving	Alarm on 0/10	Alarm on 0/10	Alarm on 0/10
Manually flipping 1	Alarm on 8/10	Alarm on 3/10	Alarm on 0/10
Manually flipping 2	Alarm on 7/10	Alarm on 1/10	Alarm on 0/10

Table 11 - Vehicle driving over Turbo Flare without flag

			
Investigator drives car over one of the sensors (one run/scenario)			
Receiver Location	**100 ft**	**150 ft**	**Sensor Status**
Below 10 mph	Alarm on 1/1	Not test	Successful
20–25 mph	Not test	Alarm on 0/1	Sensor broken
30–35 mph	Not test	Alarm on 0/1	Sensor broken
40–45 mph	Not test	Alarm on 0/1	Sensor broken

Traffic Blanket

Traffic Blanket is an amber LED device that attaches to the back of the vehicle with magnets or through its eyelets (see Figure 16). The device has two distinct flashing patterns that can be used to warn drivers.

Figure 16. Traffic Blanket [28]

Product Information

Dimensions (height × width): 1.5 ft × 4.0 ft
Weight: 6 lb

The Traffic Blanket contains 36 super-bright red LED bulbs hidden inside a waterproof clear cap. The device serves a double function: lighted warning and reflecting with arrows in the reflector. The flash or glow LED can be seen up to 2,500 yd away; self-illuminated reflective lights can be seen up to 200 yd away. A strong magnet and grommet on four sides are provided to hang on any place and prevent them from coming loose or blowing away in the wind.

Portable Plastic Rumble Strip

The RoadQuake portable plastic rumble strip (PPRS) shown in Figure 17 is a temporary strip designed by Plastic Safety Systems, Inc. It can be used to alert motorists to changing road conditions caused by short-term work operations.

Figure 17. RoadQuake Rumble Strip [29]

Several recent field tests have demonstrated the benefits of deploying PPRSs at work zones. For instance, Schrock et al.[30] tested the vibration and sound generated by the rumble strips and found that RoadQuake can be an effective warning device to alert drivers through in-vehicle vibration and sound. Sun et al.[31,32] showed that with the use of temporary rumble strips, the percent of braking vehicles increased by about 10.5 percent, and the speed of braking vehicles on average decreased by up to

3.71 mph. Speed compliance increased about 2.9 percent. The results of other studies in the literature also show that rumble strips produce a reduction in vehicle speeds and have no adverse impact on users such as those with motorcycles or bicycles.[33,34] These results show that temporary rumble strips are effective in alerting drivers regarding the short-term work zone ahead. Also, a more qualitative analysis showed that use of rumble strips at work zones is effective and sufficient to provide the results required for the usual short duration of most maintenance jobs.[35]

Product Information

RoadQuake is made from engineered polymer material.[29] Three pieces (each 44 in long, 12 in wide, 13/16 in thick, and weighing 33 lb) form an 11-ft-long strip to span an entire lane. Unlike traditional rumble strips, RoadQuake does not require fasteners or adhesives for installation (see Figure 17). It is also portable: no additional installation equipment is needed, and a crew of two can install a three-piece strip in minutes. According to the instructions, RoadQuake is designed to be used where the posted speed does not exceed 65 mph and the temperature is between 0°F and 180°F.[29] RoadQuake is currently approved in 11 states (Alabama, Colorado, Florida, Georgia, Kansas, Minnesota, New Mexico, Nevada, Oklahoma, Tennessee, and Utah), with tests pending in many others.

Advanced Warning Lights

Advanced warning lights meeting specifications published by the Institute of Transportation Engineers [36] can be used to provide warning functions for travelers at the surveying operation area. Their effectiveness has been studied in a number of contexts.[37] For instance, previous tests[3] showed that significant operational or safety benefits in actual work zone lane closures could be obtained if similar types of discrete stationary flashing lights were arranged sequentially to create the illusion of motion.

Product Information

A LED warning light, shown in Figure 18, has 400 LEDs, which is 16 times brighter than the Turbo Flare, making it more visible during daylight. The warning light operates with two 6-volt batteries. The lights are easily deployable on the pavement, because they have a flat base; they can also be mounted on a barricade, if needed.

Figure 18. LED Warning Light

Personal Strobe Light

Personal strobe lights can be used to increase the visibility of workers and get drivers' attention to reduce their speeds (see Figure 19).

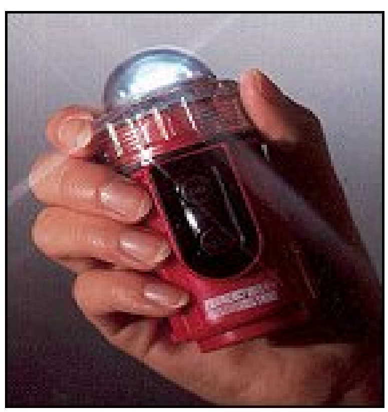


Figure 19. Personal Strobe Light

<u>Product Information</u>

Dimensions: 4 in × 1.34 in
Weight: 5.2 oz

The light has a 3-mile visibility in the dark and a half-mile visibility in daylight. It is powered by one D alkaline battery, which lasts 60 hours. The strobe light is waterproof and flashes 50 to 70 times per minute.

Intrusion Alarm

Intrusion alarm consists of a detection unit and a receiving unit with an alarm. The alarm is activated when the detection unit is triggered. The first intrusion alarm system was developed under the Strategic Highway Research Program (SHRP) where ultrasonic and infrared beams were used for detection. Since then, other intrusion alarms have been developed using microwave, pressure activated tubes and laser technologies. SonoBlaster (Figure 3), SafetyLine SL-D12 (Figure 4) and Wireless Warning Shield (Figure 5) are some examples to these intrusion alarm systems.

However, these off-the-shelf products are more geared towards traditional work zones where the start and end location of a work zone is predefined, and workers stay within a confined area inside the work zone limits. As explained before, surveyor and inspector work zones are different than traditional work zones, which make the use of intrusion alarm systems difficult to deploy and use effectively.

In addition, these devices have many shortcomings as stated in Wang et al. [34]. For instance, work zones are very noisy and workers are not able to hear an audible warning over the loud background noise. Furthermore these devices produce many false alarms that eventually create trust issues and cause workers to ignore the system. Also the distance between the detection unit and the siren must be long enough to yield enough time for workers to react to any vehicles entering the work zone, which necessitates a wireless data link. However, today, roadways electromagnetic noise which could interfere with signal communication [34].

RITS team decided to create a prototype laser intrusion device that can address some of the shortcomings of the previously developed similar devices mainly in terms of cost and response speed and strength of the alarm. The system designed in a way that when the laser beam is broken a siren is activated to warn the crew. Below is the circuit designed for a laser intrusion system.

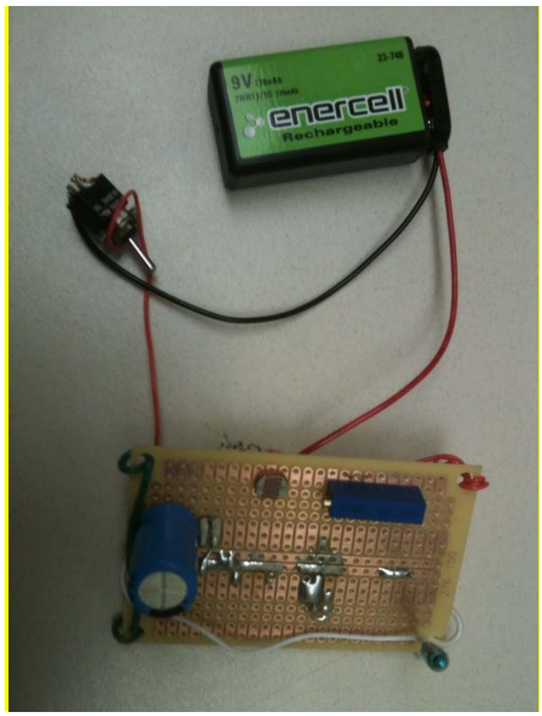


Figure 20. Laser intrusion alarm circuit design

The research team tested the laser intrusion alarm system in a laboratory environment. However, the device was not effective in detecting if the beam was broken when the distance between the detection unit and the siren was more than approximately 50 feet indoors. In addition, the device was only a prototype and not an off-the-shelf product. Given the problems described above it was not pursued for further development for use in an actual surveyor/inspector work site.

FM Radio Signal Jammer

Another idea to warn the motorist about an approaching work zone was to broadcast a brief message to vehicles' FM radios by installing a device before the work zone. Unlike the Highways Advisory Radio, which generally has a range of 3-5 miles radius, the intended device would send out radio messages within 300-500 feet radius. However, in order to achieve this goal, FM radio signals would have to be "jammed". Radio jamming is the deliberate use of radio noise or signals to disrupt communications. After reviewing the issues related to the use of this type of devices, the research team found out that this activity of "jamming" was illegal, and therefore did not pursue the idea.

Recommendations

Table 12 presents a review of the potential safety devices presented in detail above. Based on the laboratory tests and the feedback received from NJDOT, it was decided that Turbo Flare and Turbo Flare EMD were not suitable for surveyors or bridge inspectors, mostly because of visibility issues during daytime. Personal strobe lights were thought to be useful for land surveyors. Although they are more visible in the dark, personal strobe lights are much more effective than Turbo Flare as well as cheaper and easier to carry around. Warning lights are effective when several of them are deployed in a line. They are visible during daytime and are being used in most construction projects because of their effectiveness in alerting drivers. Traffic Blanket is a quick and inexpensive way to alert drivers of work zones, and it would be a useful safety device for geodetic surveyors to use in addition to the strobe lights they use on their work vans; however, NJDOT informed the research team that arrow signs intended to direct traffic are not allowed on New Jersey roadways.

Table 13 presents the safety devices that are recommended for surveyors and bridge inspectors based on the review of these devices and our initial site visits. These devices are recommended on roadways with speed limits less than 45 mph.

Table 12 - Review of potential TCD devices

Device	Installation Time	Advantages	Disadvantages
RoadQuake	5 min	Driver awareness Reduced speed Durable	Requires two people to install
TurboFlare TurboFlare EMD	<1 min	Inexpensive Easy to deploy	Visibility issues during daytime Durability issues
Personal strobe lights	<1 min	Inexpensive Easy to deploy Can be mounted around the signs	Visibility issues during daytime
Advanced warning light	<1 min	Inexpensive Easy to deploy	5–10 lights required to have the desired impact during daytime
Traffic Blanket	N/A	Inexpensive	According to New Jersey regulations, traffic cannot be directed with an arrow, except for MUTCD-approved control signs Visibility issues during daytime

Table 13 - Recommended safety devices for surveyors and inspectors

Work Type	Traffic Exposure	Work Duration	Current Safety Precaution	Recommended Safety Devices
Bridge inspectors	Minimum	30 min to 1.5 h	Reflective vests Strobe lights Attenuator truck	Mobile (e.g., personal strobe lights)
Land surveyors	High	45 min to 2.5 h	Reflective vests Signs	Mobile (personal strobe lights) Stationary (e.g., temporary rumble strips before signs, strobe lights around the signs)
Geodetic surveyors	High	About 5 min	Reflective vests Strobe lights	Mobile (personal strobe lights)

Based on our review, two of the potential TCD devices were selected for field test evaluations: (1) PPRS (RoadQuake) and (2) Advanced warning lights.

The following section explains in detail the field tests conducted to evaluate the effectiveness of these two devices.

FIELD STUDY APPROACH

Data Collection and Reduction

To evaluate the effectiveness of the selected TCD devices, 18 field tests were conducted according to the work schedule of NJDOT land surveyor crews. The specific location of each site is shown in the maps of Appendix A. Detailed illustration of each site is shown in Appendix B. All the testing sites are approach lanes of highway rail–grade crossings located in different New Jersey cities. Figure 21 provides an example of the field test site. Usually a "Survey Crew Ahead" sign is placed at the upstream of the test site in each direction. Figure 21 just shows the sign placed on the opposite direction.

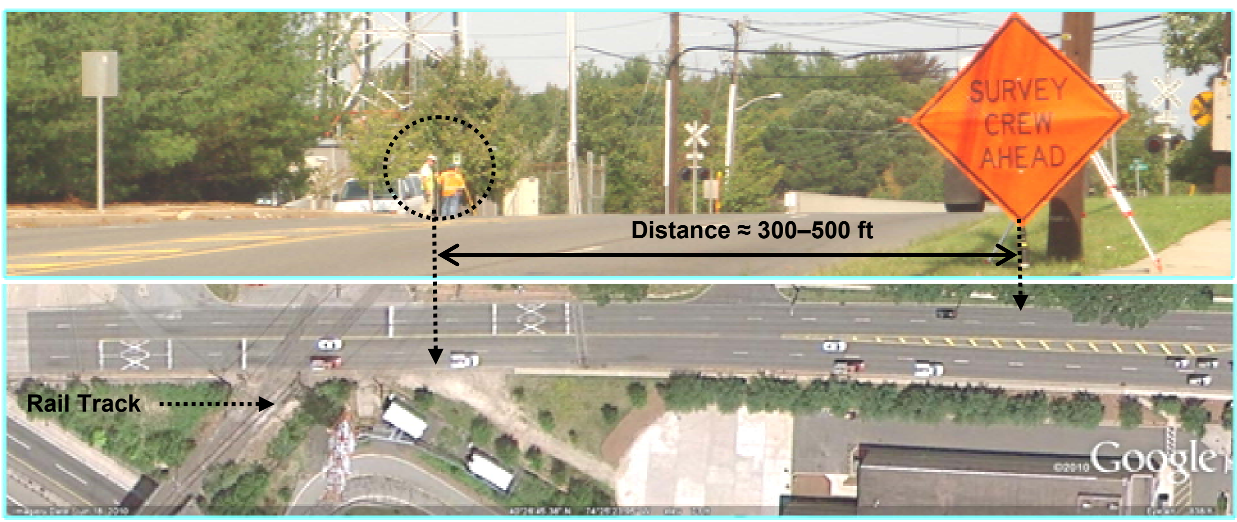


Figure 21. Illustration of a field test site

Test sites are classified into two categories according to the number of lanes: (1) two-way two-lane roads and (2) two-way four-lane roads. Table 14 and Table 15 summarize the background information of these test sites. It can be seen from the tables that these test sites represent various traffic flow conditions and posted speed limits. The variety of traffic flow conditions in the test sites provides an opportunity to examine the performance of the selected TCD from a larger scope.

Table 14 - Background of field test sites on two-way two-lane roads

Test	Name	Direction	Shoulder	Lanes	Speed Limit	Date	Time	Total Volume (veh)
1	Veronica Ave.	SB	No	1	40 mph	10/05/2011	09:30–11:30	480
2	Fieldcrest Ave.	SB	No	1	25 mph	03/14/2012	09:30–11:30	367
3	Fieldcrest Ave.	SB	No	1	25 mph	03/19/2012	09:30–11:30	416
4	Fieldcrest Ave.	SB	No	1	25 mph	03/20/2012	09:30–11:30	366
5	Jersey Ave.	NB	No	1	25 mph	10/21/2011	09:30–11:30	638
6	Jersey Ave.	SB	Yes	1	40 mph	11/01/2011	09:30–11:30	603
7	Jersey Ave.	SB	Yes	1	40 mph	11/02/2011	09:30–11:30	576
8	South Clinton Ave.	NB	Yes	1	40 mph	11/04/2011	09:30–11:30	642
9	South Clinton Ave.	NB	Yes	1	40 mph	11/09/2011	09:30–11:30	724
10	Veronica Ave.	SB	No	1	40 mph	10/07/2011	09:30–11:30	533

Table 15 - Background of field test sites on two-way four-lane roads

Test	Name	Direction	Shoulder	Lanes	Speed Limit	Date	Time	Total Volume (veh)
1	Ryders Ln.	NB	No	2	45 mph	09/30/2011	09:30–11:30	1,545
2	Woodbridge Ave.	WB	Yes	2	40 mph	11/21/2011	09:30–11:30	1,779
3	Raritan Center Pkwy.	SB	No	2	25 mph	02/28/2012	09:30–11:30	688
4	Raritan Center Pkwy.	SB	No	2	25 mph	03/02/2012	09:30–11:30	624
5	Woodbridge Ave.	EB	Yes	2	50 mph	01/11/2012	09:30–11:30	1,653
6	Route 27	SB	No	2	40 mph	10/11/2011	09:30–11:30	1,366
7	Route 27	SB	No	2	40 mph	10/17/2011	09:30–11:30	1,364
8	Woodbridge Ave.	WB	Yes	2	50 mph	01/17/2012	09:30–11:30	1,518

The selected TCD were deployed before the “Survey Crew Ahead” sign to alert drivers as they approach the work site. Appendix C illustrates the deployment of each type of control device. Four experimental scenarios were designed:

(1) “Survey Crew Ahead” sign only,

(2) “Survey Crew Ahead” sign and warning lights,

(3) “Survey Crew Ahead” sign and PPRSs, and

(4) “Survey Crew Ahead” sign, warning lights, and PPRSs together.

Scenario 1 was used as the control experiment, because it represents a typical traffic control setting for a land surveying site. The other scenarios are used to evaluate the impact of additional TCD. Figure 22 illustrates the test scenarios on different roadways. When the warning lights were tested, they were aligned along the curb or shoulder so that the lanes were not blocked. When PPRSs were tested, three sets of rumble strips in series were placed perpendicular to the direction of traffic. They were deployed about 20 feet apart from each other. In scenarios 3 and 4, PPRSs were deployed in the right lane and left lane individually in each test listed in Table 15.

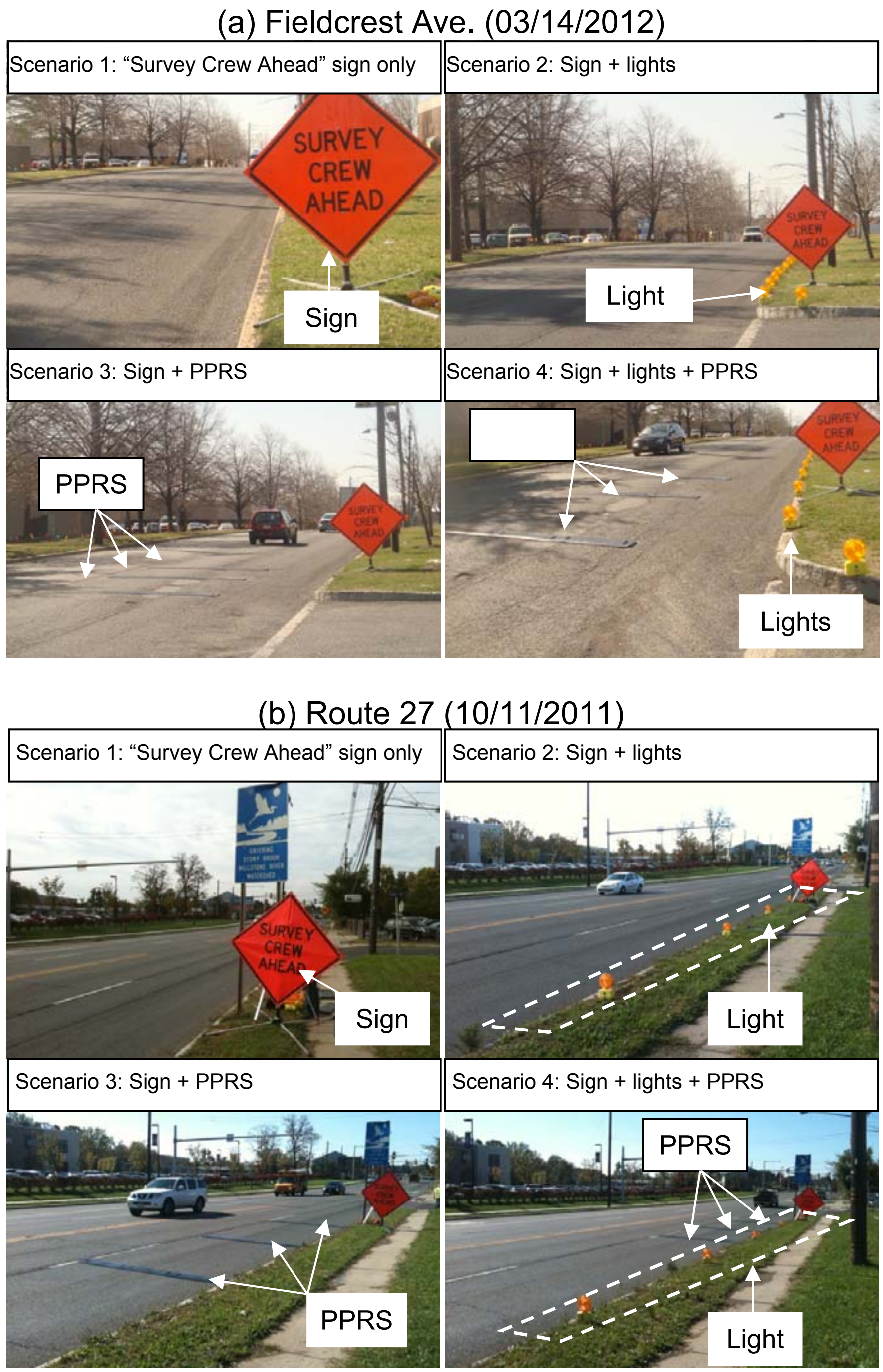


Figure 22. Illustration of field test scenarios

Instead of using traffic sensors to collect data, we recorded all field tests in videos. Despite time-consuming, the videos provide richer information than that of traffic sensors because more detailed driver behavior such as braking can be reviewed. Post-field data processing was conducted in the laboratory to extract various traffic data, including time stamp, vehicle type, speed, headway, and braking action for each vehicle. It takes more than eight hours to process one-hour video. Information for more than 10,000 vehicles and 3,400 vehicles was obtained at four-lane two-way and two-lane two-way roadways, respectively. However, to avoid the confounding effect of vehicle platoons on the performance of the tested devices, only the measurements of leading (free-flowing) vehicles (assumed with time headway no less than 4 seconds) were extracted. The final sampled vehicles at test sites in Table 15 were about 4,000, which represent approximately 40 percent of the vehicles observed. Similarly, the total number of sampled vehicles is 3,421 at test sites in Table 14, which represents more than 60 percent of all observed traffic during the 10 field tests.

Measures of Effectiveness

The purpose of deploying TCD is to alert drivers to the work site ahead, and to improve safety in terms of reductions in the number of crashes and crash severity. The best measures to test the effectiveness of the TCD are the reduction in crashes and crash severity for both drivers and workers in the vicinity of a worksite. However, crashes are random events, which may not occur in a short time period. In addition, we do not want to wait until the crash occurs. Therefore, a set of surrogate safety measures is used as indicators of the effectiveness of the selected TCD. These measures are (1) mean speed, (2) speed variance, (3) 85th percentile speed, (4) speed limit compliance rate, and (5) braking rate.

Mean and Variance of Vehicle Speed

Previous studies suggested that the occurrence and severity of crashes were related to both vehicle speeds and speed variation.[38,39,40] As higher speed at impact increases the severity of a crash, the reduction of speed is expected to improve road safety.(41) A small standard deviation of the mean speed for vehicles approaching a work site is preferred, as the research showed that the more a vehicle deviates from the average speed, the more likely it would be involved in a crash.(18) Therefore, the mean speed reduction and the speed variance are frequently used as an indicator to test a TCD.(42)

85th Percentile Speed

The 85th percentile speed is the most commonly referred measure of operating speed used in design and traffic control decision processes.(43) This percentile is used in evaluating or recommending posted speed limits based on the assumption that 85 percent of vehicles are traveling at a speed that drivers perceive to be safe.(44)

Speed Compliance Rate

Excess speed is one of the notable contributing factors in many work zone crashes, which emphasizes the need for drivers to comply with the posted speed limits in work zones.(45) an effective TCD is expected to increase the percentage of drivers who comply with the speed limit.

Braking Rate

The proportion of vehicles that brake before a work site was also observed. It is assumed that drivers will be inclined to brake if they are aware of the presence of TCD when approaching a work site. The vehicles' brake lights were monitored to identify the braking action in response to deployed control devices.

Statistical Methods of Analysis

The evaluation of different TCD involves comparing the surrogate safety measures without and with the deployment of proposed TCD. *F* test, two-sample *t*-test, two-sample Kolmogorov–Smirnov (*KS*) test, and Fisher's exact test were used to support the comparative analysis. Five specific tasks presented in Table 16 examine the proposed surrogate safety measures individually. The test results are presented in the next section.

Table 16 - Assessing the effect of TCD by hypothesis testing

Analysis	Statistical Method	Null Hypothesis (H_0) & Alternative Hypothesis (H_1)
1	*F* test	H_0: The speed variance does not change when the TCD is used.
		H_1: The speed variance changes when the TCD is used.
2	*t*-test	H_0: The mean speed does not change when the TCD is deployed.
		H_1: The mean speed changes when the TCD is deployed.
3	*KS* test	H_0: The speed distribution does not change when the TCD is deployed.
		H_1: The speed distribution changes when the TCD is deployed.
4	Fisher's exact test	H_0: The proportion of speeding vehicle changes when the TCD is deployed.
		H_1: The proportion of speeding vehicles does not change when the TCD is deployed.
5	Fisher's exact test	H_0: The braking rate does not change when the TCD is deployed.
		H_1: The braking rate changes when the TCD is deployed.

POTENTIAL IMPACT OF THE SELECTED CONTROL DEVICES

Through the field tests, we aimed to examine whether the control devices enhance the awareness of motorists. Before quantitatively comparing the performance of the control devices, first the relationship between driver actions and the deployment of these control devices was investigated. Two categories of driver actions were analyzed: speeding action and braking action, given the presence of control devices. Each action can be denoted as a dichotomous outcome (i.e., $y = 1$ for speeding and $y = 0$ for not speeding; $y = 1$ for braking and $y = 0$ for not braking) when a vehicle approaches the land surveying site. Naturally, such a dichotomous nature facilitates the use of a binomial or binary logistic regression model to examine the influence of not only the control devices but also other factors on the probability of a vehicle speeding or braking at the sites.

Let us define π(x) as the probability of a vehicle speeding at a work site and 1- π(x) as the probability of a vehicle not speeding. A similar definition is used when examining braking action. The binary logistic regression model identifies the relationship between the log odds of the dichotomous outcome and various risk factors. It can be formulated as follows:

$$\text{logit}\left[\pi(x)\right] = \log\left[\frac{\pi(x)}{1-\pi(x)}\right] = \alpha + X'\beta$$

Based on the above equation, the probability that a vehicle driving above the speed limit can be described by the logistic distribution shown in following equation:

$$P(y=1|X) = \pi(x) = \frac{exp(\alpha + X'\beta)}{1 + exp(\alpha + X'\beta)}$$

where π(x) is the conditional probability of the form P(y=1|X); X is the vector of explanatory variables (contributing factors) that could be continuous or dichotomous; β is the corresponding vector of the coefficients; and α is the intercept parameter. A maximum-likelihood estimation technique was used to determine the regression model's parameters. A Chi-square test was used to test the overall significance of the logistic regression model. The significance of individual risk factors within the model was evaluated using the Wald *z* statistic. Moreover, the unique contribution of j^{th} factor on speeding or braking can be expressed by the odds ratio (OR), defined as:

$$\mathrm{OR} = exp(\beta_j)$$

where the 95 percent confidence interval of OR is $\left[\exp(\beta_j - 1.96\mathrm{SD}_{\beta_j}), \exp(\beta_j + 1.96\mathrm{SD}_{\beta_j})\right]$ and SD_{β_j} is the standard error of the coefficient β_j. OR measures the ratio of the predicted odds for a one-unit increase in a continuous variable x_j or the presence of an indicator variable x_j when other variables in the model are held constant.

The variables considered for speeding and braking analysis are listed in Table 17. Note that “speed” is only included in the braking model. “Left lane” is only included in speeding and braking models for four-lane sites.

Table 17 - Variables considered in speeding and braking action analysis

Variables	**Type**	**Description**
Truck	Dummy	=1 if vehicle is a truck; =0 otherwise
Speed	Numerical	Observed speed of a vehicle (only used in braking model)
Speed limit	Numerical	The posted speed limit at the site
Hourly volume	Numerical	The average hourly volume at the site
Left lane	Dummy	=1 if the vehicle is in left lane; =0 otherwise
Shoulder	Dummy	=1 if there is a shoulder; =0 otherwise
Warning lights	Dummy	=1 if the lights are present; =0 otherwise
PPRS	Dummy	=1 if the PPRS is present; =0 otherwise
Warning lights + PPRS	Dummy	=1 if both devices are present; =0 otherwise

Table 18 and Table 19 show the modeling results for speeding analysis at four-lane test sites and two-lane test sites, respectively. If the vehicle is a truck, it is less likely to exceed the speed in both types of test sites. Specifically, the ORs of a truck versus a car are 0.223 for the four-lane sites and 0.180 for the two-lane sites. Interestingly, a one-unit increase in speed limit is expected to see about a 5 percent increase in the odds of speeding at four-lane test sites. In contrast, the odds decrease by about 19 percent at the one-lane test sites. This difference might be attributed to the relatively low speed limit (i.e., 25 mph) at the one-lane test sites. Motorists can easily exceed the speed limit at nonresidential sites with low speed limits. One unit increase in the average hourly volume slightly reduces the odds of speeding in both cases. If the vehicle is driving in the left lane, the odds of speeding are almost doubled. If a shoulder is present, the odds of speeding are about 2.1 times higher for the four-lane sites and 6.2 times higher for the two-lane sites, respectively.

Compared to using the “Survey Crew Ahead” sign, the deployment of the warning lights or PPRSs greatly decreases the odds of speeding. The deployment of the warning lights, PPRSs, and their combination versus the “Survey Crew Ahead” sign only decreased the OR to 0.476, 0.240, and 0.209, respectively, for four-lane test sites. Similarly, the ORs were 0.504, 0.287, and 0.212, respectively, for two-lane test sites. The small ORs suggest that the deployment of the selected traffic control devices is relatively effective; in particular, the combined use of the warning lights and PPRSs resulted in additional positive impact.

Table 18 - Speeding action modeling results for four-lane test sites

Variable	**Estimate**	**Std. Error**	***z* value**	**Pr(>|z|)**	**OR**
Intercept	4.198	0.259	16.221	0.000	-----
Truck	−1.502	0.132	−11.398	0.000	0.223
Speed limit	0.048	0.011	4.603	0.000	1.050
Hourly volume	−0.019	0.001	−18.542	0.000	0.981
Left lane	0.680	0.081	8.421	0.000	1.974
Shoulder	0.758	0.105	7.190	0.000	2.135
Warning lights	−0.742	0.101	−7.353	0.000	0.476
PPRS	−1.426	0.116	−12.304	0.000	0.240
Warning lights + PPRS	−1.566	0.114	−13.696	0.000	0.209

Table 19 - Speeding action modeling results for two-lane test sites

Variable	Estimate	Std. Error	*z* value	Pr(>|z|)	OR
Intercept	7.768	0.385	20.169	0.000	-----
Truck	−1.712	0.110	−15.636	0.000	0.180
Speed limit	−0.213	0.011	−20.079	0.000	0.809
Hourly volume	−0.002	0.001	−2.399	0.016	0.998
Shoulder	1.834	0.162	11.324	0.000	6.258
Warning lights	−0.685	0.118	−5.784	0.000	0.504
PPRS	−1.247	0.116	−10.720	0.000	0.287
Warning lights + PPRS	−1.550	0.120	−12.933	0.000	0.212

Similar to speeding action analysis, Table 20 and Table 21 present the modeling results of the braking action. The ORs of braking for a truck versus a car were 1.039 and 0.739 for four-lane and two-lane test sites, respectively. These results suggest that the braking proportion of trucks is less likely to change when traveling on four-lane roads. One unit increase in the speed decreased the odds of braking by about 3.5 percent and 3.2 percent at four-lane sites and two-lane sites, respectively. The odds were about 8.4 percent higher for a unit increase in the speed limit at four-lane test sites, whereas it was reduced by about 2.8 percent at two-lane test sites. An increase in the average hourly volume would slightly reduce the odds of braking at both types of test sites. If a vehicle is in the left lane, the odds of braking are 0.905 of that of a vehicle in the right lane. The presence of a shoulder did not significantly change the ORs of braking for both sites. When additional TCD are present, the odds of braking would be about 5 times higher at the four-lane test sites and 2 to 4 times higher at the two-lane test sites.

Table 20 - Braking action modeling results for four-lane test sites

Variable	Estimate	Std. Error	*z* value	Pr(>|z|)	OR
Intercept	−3.881	0.364	−10.671	0.000	–
Truck	0.038	0.138	0.278	0.781	1.039
Speed	−0.036	0.007	−4.956	0.000	0.965
Speed limit	0.081	0.015	5.535	0.000	1.084
Hourly volume	−0.004	0.001	−3.303	0.001	0.996
Left lane	−0.099	0.102	−0.974	0.330	0.905
Shoulder	−0.017	0.130	−0.128	0.898	0.983
Warning lights	1.659	0.189	8.770	0.000	5.254
PPRS	1.698	0.193	8.789	0.000	5.461
Warning lights + PPRS	1.593	0.192	8.277	0.000	4.919

Table 21 - Braking action modeling results for two-lane test sites

Variable	Estimate	Std. Error	*z* value	Pr(>|z|)	OR
Intercept	0.291	0.386	0.755	0.450	–
Truck	−0.302	0.115	−2.629	0.009	0.739
Speed	−0.032	0.006	−5.084	0.000	0.968
Speed limit	−0.029	0.009	−3.122	0.002	0.972
Hourly volume	−0.003	0.001	−2.521	0.012	0.997
Shoulder	0.070	0.153	0.461	0.645	1.073
Warning lights	0.817	0.165	4.945	0.000	2.263
PPRS	1.025	0.158	6.496	0.000	2.788
Warning lights + PPRS	1.526	0.156	9.795	0.000	4.601

The modeling results on speeding action and braking action imply that the deployment of additional TCD overall positively affected driver behavior at the land surveying sites. The next two sections provide detailed analyses of their effects at each test site.

TEST RESULTS OF TWO-LANE ROADWAYS

The main focus of the field tests was to investigate whether deploying additional TCD would affect motorists' awareness of the work zone. The extracted data from field tests allowed us to explore several aspects of driving behaviors with and without these devices. The changes in driving behaviors such as speeding and braking were used as surrogate safety measures. Test results for sites on two-lane roadways are presented and discussed in this section.

Effects on Speed Variation and Mean Speed

Table 22 shows the effect of the TCD on the mean speed and speed variances of vehicles in free-flowing traffic condition. An *F*-test was first used to test the null hypothesis that the speed variances under the deployment of additional TCD are equal to that of the base case (scenario 1). The test results show that the null hypothesis cannot be rejected for all scenarios, except the ninth test in scenario 2 and the first test in scenario 4 at a significance level of 0.05. During the ninth test in scenario 2 and the first test in scenario 4, the speed variations were reduced by 1.91 mph [$F(86, 105) = 1.810$, p-value = 0.004] and 1.80 mph [$F(61, 49) = 1.842$, p-value = 0.029], respectively. The reduction in the speed variance is beneficial, as more stable traffic is sure to enhance road safety.(18) Therefore, these results suggest that neither independent deployment nor combined deployment of the selected TCD adversely affected the stability of traffic flow.

Table 22 - Effects of different TCD on free-flow speed

Test Device	Field Test	Sample Size	Mean Speed (mph)	Mean Change (mph)[a]	Mean Change (%)[a]	SD, (mph)[c]	SD Change (mph)[a]
"Survey Crew Ahead" sign only (Scenario 1: Base case)	1	62	33.07	Base	Base	6.84	Base
	2	66	32.26	Base	Base	7.32	Base
	3	87	30.86	Base	Base	6.99	Base
	4	61	28.26	Base	Base	5.17	Base
	5	79	33.25	Base	Base	7.19	Base
	6	132	40.82	Base	Base	6.89	Base
	7	101	43.82	Base	Base	6.93	Base
	8	110	33.44	Base	Base	6.82	Base
	9	87	37.41	Base	Base	7.43	Base
	10	97	34.94	Base	Base	5.48	Base
"Survey Crew Ahead" sign and warning light (Scenario 2)	1	54	32.29	−0.77	−2.34	6.39	−0.45
	2	53	27.87	**−4.39[b]**	**−13.62**	7.34	0.02
	3	53	27.04	**−3.82[b]**	**−12.37**	5.77	−1.22
	4	68	26.96	−1.30	−4.61	5.38	0.21
	5	105	31.28	**−1.98[b]**	**−5.95**	7.12	−0.07
	6	114	37.71	**−3.11[b]**	**−7.61**	6.56	−0.34
	7	55	43.42	−1.50	−3.43	6.58	−0.35
	8	60	33.10	−0.35	−1.04	6.59	−0.23
	9	106	34.04	**−3.37[b]**	**−9.01**	−5.52	**−1.91[b]**
	10	78	32.66	**−2.27[b]**	**−6.51**	5.26	−0.22
"Survey Crew Ahead" sign and PPRS (Scenario 3)	1	114	31.77	−1.30	−3.92	6.23	−0.61
	2	73	23.25	**−9.01[b]**	**−27.93**	7.09	−0.22
	3	64	25.40	**−5.46[b]**	**−17.71**	5.72	−1.27
	4	62	24.15	**−4.11[b]**	**−14.56**	6.25	1.08
	5	112	28.50	**−4.75[b]**	**−14.28**	6.25	−0.94
	6	90	37.74	**−3.08[b]**	**−7.55**	8.07	1.18
	7	107	41.20	**−2.62[b]**	**−5.98**	6.90	−0.03
	8	109	23.91	**−9.54[b]**	**−28.52**	6.34	−0.48
	9	128	30.27	**−7.14[b]**	**−19.08**	6.83	−0.60
	10	70	30.74	**−4.20[b]**	**−12.02**	5.88	0.40
"Survey Crew Ahead" sign, warning lights, and PPRS (Scenario 4)	1	50	30.76	**−2.31[b]**	**−6.98**	5.04	**−1.80[b]**
	2	43	20.70	**−11.56[b]**	**−35.83**	6.56	−0.76
	3	78	22.09	**−8.77[b]**	**−28.42**	7.25	0.26
	4	66	23.86	**−4.40[b]**	**−15.57**	5.45	0.28
	5	130	25.70	**−7.55[b]**	**−22.70**	7.17	−0.01
	6	112	37.19	**−3.63[b]**	**−8.89**	7.12	0.23
	7	131	39.03	**−4.79[b]**	**−10.93**	7.83	0.90
	8	99	23.73	**−9.72[b]**	**−29.06**	6.67	−0.15
	9	77	28.32	**−9.10[b]**	**−24.31**	7.34	−0.09
	10	78	29.79	**−5.15[b]**	**−14.73**	6.28	0.80

[a] Value <0 indicates a reduction when the control device is used.
[b] Indicates a statistically significant effect at a significance level of α = 0.05.
[c] SD: standard deviation of measured speed.

The mean speeds were compared among different scenarios. According to Table 22, a general trend in the reduction in mean speed was observed given the deployment of the TCD at each site. When the warning lights were deployed with the warning sign (scenario 2), the two-sample *t*-test confirmed that the mean speeds in six tests were significantly reduced compared to scenario 1. The maximum reduction was about 13.62 percent. The average reduction during the 10 field tests was about 6.65 percent. When the PPRS was deployed (scenario 3), significant reductions in the mean speed were observed in all tests, except the first. The maximum reduction was about 28.52 percent, and the average reduction of the 10 tests was about 15.16 percent. When the warning lights and PPRSs were used together (scenario 4), the reduction in the mean speed was the highest. All sites had significant reductions ranging from 6.98 percent to 35.83 percent. The average reduction of the 10 tests in scenario 4 was about 19.74 percent.

The use of the tested TCD generally reduced the mean speed at these test sites. The reduction in the mean speed was an indicator that the motorists were aware of the unusual traffic conditions at the survey sites. Reducing vehicle speed may also improve the safety for both drivers and surveyors at temporary work zones. Particularly, these reductions can decrease the severity of crashes as accidents involving high-speed vehicles are generally more severe than those occurring at low speed.[(18)] PPRSs outperform warning lights in terms of a significant reduction in mean speed at more sites. The use of the warning lights and PPRSs together further enhance the reduction in speed.

Effects on Speed Distribution

The distributions of observed free-flow speeds were compared. Figure 23 provides an example of cumulative distributions of observed free-flow speed at different sites. Similar illustrations for all tests were shown in Appendix D. The KS test was used to examine whether the deployment of the TCD would change the speed distribution. When only the warning lights were used with the “Survey Crew Ahead” sign, the speed distributions in four tests (tests 3, 6, 9, and 10) were significantly changed. In these four tests, the cumulative speed distribution curves shifted to the left side compared to the base case (scenario 1). When the PPRSs were used, the speed distribution curves in all tests but the first and the seventh also successfully shifted to the left side compared to the base case (scenario 1). Similarly, when the warning lights and the PPRSs were deployed together, the speed distribution curves in all tests consistently shifted to a lower level compared to the base case. Specifically, the speed distributions statistically changed at a significance level of $\alpha = 0.05$. As shown in Figure 23, the combination of warning lights and PPRSs performed better in most tests in terms of the magnitude to shift the speed distribution to a lower level.

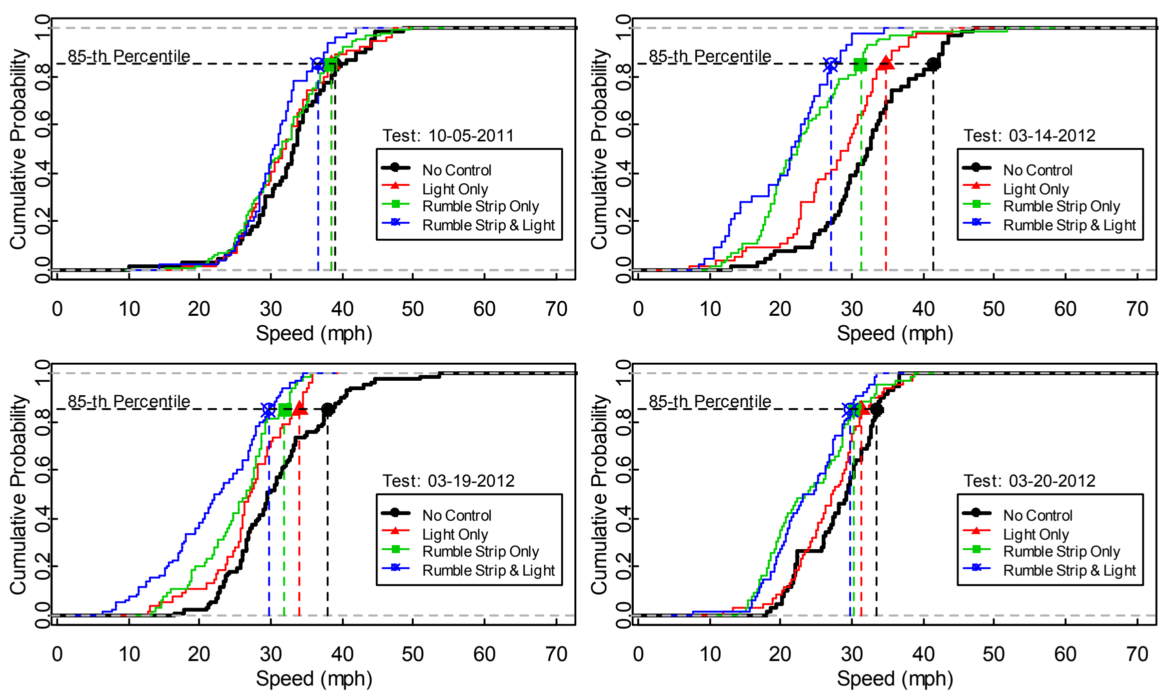


Figure 23. Examples of speed distribution change

In addition to speed distributions, the 85th percentile speeds were compared in Table 23 for scenarios with and without the deployment of additional TCD. The 85th percentile speed is one of the useful indicators for determining the effectiveness and adequacy of speed limits. It is usually assumed to be the highest safe speed for a roadway section.[(44)] As shown in Table 23, the 85th percentile speeds for all scenarios were reduced. When the warning lights were used, the reduction in the 85th percentile speed ranged from 1.33 percent to 15.73 percent. The average reduction of the 10 tests was about 7.03 percent. When the PPRSs were deployed, the reduction ranged from 1.41 percent to 24.55 percent. The average reduction of these tests in scenario 2 was 12.59 percent. Higher reductions were obtained when the these two devices were used together with the warning sign, resulting in a maximum reduction in the 85th percentile speed of 34.86 percent and an average reduction of 17.03 percent for the 10 tests. Despite the positive effect, the 85th percentile speeds under the deployment of these TCD were still slightly above the speed limit in some tests.

Table 23 - Changes in the 85th percentile speed and speed distributions

Test Device	Field Test	85th Percentile Speed (mph)	Change (mph)[a]	Change (%)[a]	KS Test (*p*-value)[b]
"Survey Crew Ahead" sign only (Scenario 1: Base case)	1	38.96	Base	Base	Base
	2	41.39	Base	Base	Base
	3	38.1	Base	Base	Base
	4	33.57	Base	Base	Base
	5	40.91	Base	Base	Base
	6	47.73	Base	Base	Base
	7	50.91	Base	Base	Base
	8	40.45	Base	Base	Base
	9	44.19	Base	Base	Base
	10	40.11	Base	Base	Base
"Survey Crew Ahead" sign and warning light (Scenario 2)	1	38.44	**−0.52**	**−1.33**	0.819
	2	34.88	**−6.51**	**−15.73**	0.099
	3	34.09	**−4.01**	**−10.52**	**0.043**
	4	31.42	**−2.15**	**−6.40**	0.225
	5	38.59	**−2.32**	**−5.67**	0.214
	6	43.89	**−3.84**	**−8.05**	**0.001**
	7	48.27	**−2.64**	**−5.19**	0.372
	8	39.22	**−1.23**	**−3.04**	0.970
	9	39.12	**−5.07**	**−11.47**	**0.003**
	10	38.96	**−1.15**	**−2.87**	**0.019**
"Survey Crew Ahead" sign and PPRS (Scenario 3)	1	38.41	**−0.55**	**−1.41**	0.343
	2	31.25	**−10.14**	**−24.50**	**0.000**
	3	31.91	**−6.19**	**−16.25**	**0.000**
	4	30.35	**−3.22**	**−9.59**	**0.003**
	5	33.73	**−7.18**	**−17.55**	**0.000**
	6	46.94	**−0.79**	**−1.66**	**0.003**
	7	49.01	**−1.90**	**−3.73**	0.079
	8	30.52	**−9.93**	**−24.55**	**0.000**
	9	36.71	**−7.48**	**−16.93**	**0.000**
	10	36.20	**−3.91**	**−9.75**	**0.001**
"Survey Crew Ahead" sign, warning lights, and PPRS (Scenario 4)	1	36.52	**−2.44**	**−6.26**	**0.042**
	2	26.96	**−14.43**	**−34.86**	**0.000**
	3	29.65	**−8.45**	**−22.18**	**0.000**
	4	29.74	**−3.83**	**−11.41**	**0.002**
	5	33.53	**−7.38**	**−18.04**	**0.000**
	6	44.07	**−3.66**	**−7.67**	**0.000**
	7	46.56	**−4.35**	**−8.54**	**0.001**
	8	30.71	**−9.74**	**−24.08**	**0.000**
	9	35.41	**−8.78**	**−19.87**	**0.000**
	10	35.38	**−4.73**	**−11.79**	**0.000**

[a] Value <0 indicates a reduction when the control device is used.
[b] A *p*-value ≤0.05 indicates a statistically significant effect given a significance level of α = 0.05.

Effects on Speed Limit Compliance

Table 24 summarizes the effects of different TCD on speed limit compliance in free flowing traffic.

Table 24 - Effects of different control devices on speed limit compliance

Test Device	Field Test	Speed Limit (mph)	Below Limit	Above Limit	Speeding (%)	*p*-value[a]
"Survey Crew Ahead" sign only (Scenario 1: Base case)	1	40	53	9	14.5	Base
	2	25	10	56	84.8	Base
	3	25	16	71	91.6	Base
	4	25	16	45	73.8	Base
	5	25	8	71	89.9	Base
	6	40	54	78	59.1	Base
	7	40	31	70	69.3	Base
	8	40	91	19	17.3	Base
	9	40	61	26	29.9	Base
	10	40	77	20	20.6	Base
"Survey Crew Ahead" sign and warning light (Scenario 2)	1	40	48	6	11.1	0.783
	2	25	19	34	64.2	**0.011**
	3	25	15	38	71.7	0.209
	4	25	23	45	66.2	0.443
	5	25	19	86	81.9	0.146
	6	40	72	42	36.8	**0.001**
	7	40	19	36	65.5	0.720
	8	40	53	7	11.7	0.380
	9	40	95	11	10.4	**0.001**
	10	40	71	7	9.0	**0.037**
"Survey Crew Ahead" sign and PPRS (Scenario 3)	1	40	103	11	9.6	0.332
	2	25	47	26	35.6	**0.000**
	3	25	27	37	57.8	**0.002**
	4	25	34	28	45.2	**0.002**
	5	25	34	78	69.6	**0.001**
	6	40	58	32	35.6	**0.001**
	7	40	50	57	53.3	**0.023**
	8	40	107	2	1.8	**0.000**
	9	40	116	12	9.4	**0.000**
	10	40	66	4	5.7	**0.007**
"Survey Crew Ahead" sign, warning lights, and PPRS (Scenario 4)	1	40	48	2	4.0	0.108
	2	25	31	12	27.9	**0.000**
	3	25	46	32	41.0	**0.000**
	4	25	36	30	45.5	**0.002**
	5	25	66	64	49.2	**0.000**
	6	40	74	38	33.9	**0.000**
	7	40	70	61	46.6	**0.001**
	8	40	99	0	0.0	**0.000**
	9	40	72	5	6.5	**0.000**
	10	40	76	2	2.6	**0.000**

[a] A *p*-value ≤0.05 indicates a statistically significant effect given a significance level of α = 0.05.

Fisher's exact test for count data was used to statistically examine the null hypothesis that the proportions of speeding vehicles were equal for scenarios that include the deployed TCD and the base case (scenario 1: "Survey Crew Ahead" sign only). Overall, the proportions of speeding vehicles were reduced when additional control devices were deployed. Specifically, four out of the 10 tests showed significant reductions in the proportion of speeding vehicles under scenario 2 ("Survey Crew Ahead" sign and warning lights). In contrast, when the PPRS (scenario 3) or their combination (scenario 4) with the warning lights were used, significant reductions in speeding vehicles were observed in all field tests, except the first test. The proportions of speeding were less than half of that when using a "Survey Crew Ahead" sign only.

Effects on Drivers' Braking Behavior

The impact of the deployed TCD on driver behavior was also investigated by observing the braking action when vehicles approached work zones. Table 25 summarizes the changes in braking action.

Table 25 - Effects of different control devices on braking behaviors

Test Device	Field Test	Not Brake	Brake	Braking Rate (%)	*p*-value[a]
"Survey Crew Ahead" sign only (Scenario 1: Base case)	1	57	5	8.1	Base
	2	61	5	7.6	Base
	3	81	6	6.9	Base
	4	48	13	21.3	Base
	5	71	8	10.1	Base
	6	123	9	6.8	Base
	7	94	7	6.9	Base
	8	107	3	2.7	Base
	9	85	2	2.3	Base
	10	90	7	7.2	Base
"Survey Crew Ahead" sign and warning light (Scenario 2)	1	46	8	14.8	0.377
	2	43	10	18.9	0.095
	3	43	10	18.9	**0.050**
	4	46	22	32.4	0.172
	5	81	24	22.9	**0.030**
	6	105	9	7.9	0.809
	7	48	7	12.7	0.250
	8	52	8	13.3	**0.017**
	9	95	11	10.4	**0.040**
	10	66	12	15.4	0.093
"Survey Crew Ahead" sign and PPRS (Scenario 3)	1	99	15	13.2	0.456
	2	50	23	31.5	**0.001**
	3	49	15	23.4	**0.008**
	4	37	25	40.3	**0.031**
	5	82	30	26.8	**0.005**
	6	67	23	25.6	**0.000**
	7	87	20	18.7	**0.013**
	8	99	10	9.2	**0.049**
	9	113	15	11.7	**0.018**
	10	57	13	18.6	**0.031**
"Survey Crew Ahead" sign, warning lights, and PPRS (Scenario 4)	1	35	15	30.0	**0.005**
	2	24	19	44.2	**0.000**
	3	44	34	43.6	**0.000**
	4	36	30	45.5	**0.005**
	5	87	43	33.1	**0.000**
	6	81	31	27.7	**0.000**
	7	103	28	21.4	**0.003**
	8	80	19	19.2	**0.000**
	9	55	22	28.6	**0.000**
	10	56	22	28.2	**0.000**

[a] A *p*-value ≤0.05 indicates a statistically significant effect given a significance level of $\alpha = 0.05$.

The Fisher's exact test was used to statistically check the null hypothesis that the deployment of the selected TCD does not change braking behavior. When no additional TCD was used, the proportions of vehicles braking ranged from 2.3 percent to 21.3 percent. When the warning lights were used, the braking rate significantly increased in four out of the 10 tests by about 8.1 percent to 12.8 percent. Increases ranging from 1.1 percent to 11.3 percent were also observed in other tests, but they were not as significant. As shown in Table 25, except in the first test, the deployment of PPRSs significantly increased braking rates in all other tests. Braking rates ranged from 9.2 percent to 40.3 percent. If PPRSs and warning lights were used at the same time, the braking rates in all tests were further increased. The braking rates under scenario 4 ranged from 19.2 percent to 45.5 percent.

Based on these results, we can see that additional TCD can greatly affect drivers' braking reaction. The PPRS had a larger impact in terms of increasing braking rate. The change in the braking rate suggests that motorists were aware of and responded to the presence of unusual traffic conditions at surveying sites.

TEST RESULTS OF FOUR-LANE ROADWAYS

This section presents the results of field tests on four-lane roadways listed in Table 15. Because there are two travel lanes, PPRSs were deployed in each lane separately. The impact of the PPRS and the warning lights on motorists in each lane was examined and discussed.

Effects on Speed Variation and Mean Speed

Table 26 shows the effects of TCD on the mean speed and speed variances of vehicles in each lane. An *F*-test was first used to test the null hypothesis that the speed variances when using two different TCD are equal. The test results show that the null hypothesis cannot be rejected at a significance level of 0.05 for all test scenarios in the right lane and 19 tests in the left lane. Moreover, the speed variances for the remaining five tests in the left lane (scenario 2: test 2 and test 8; scenario 3: test 2; and scenario 4: test 2 and test 5) were greatly reduced. Thus, these results suggest that the deployment of these TCD (warning lights or PPRSs) did not significantly reduce the speed variations in both lanes. In addition, a reduction in speed variation in the left lane was observed.

According to Table 26, when warning lights (scenario 2) were deployed, the mean speed in the right lane in field tests 1, 2, 5, 7, and 8 were significantly reduced (4.75 percent to 10.70 percent). The other three tests showed slightly changes: −2 percent to 1 percent in the mean speed. The mean speed in the left lane was reduced at five field tests by about 6 percent to 12 percent. When the PPRSs were deployed in the right lane, mean speeds were significantly reduced. The reduction ranged from 6.59 percent to 17.76 percent. When PPRSs and warning lights were deployed together, further reductions—ranging from 5.28 percent to 21.87 percent—were observed in the right lane. The analyses for the left lane showed similar findings—namely, that the use of PPRSs or their combination with warning lights can result in a reduction in mean speed by up to 23.87 percent. However, the use of warning lights alone cannot achieve comparable effects.

Table 26 - Effects of different TCD on free-flow speed

Test Device	Field Test	Right Lane Speed						Left Lane Speed					
		Sample Sizes	Mean (mph)	Change (mph)[a]	Change (%)[a]	SD (mph)[c]	SD Change (mph)[a]	Sample Sizes	Mean (mph)	Change (mph)[a]	Change (%)[a]	SD (mph)[c]	SD Change (mph)[a]
"Survey Crew Ahead" sign only (Scenario 1: Base case)	1	81	41.56	Base	Base	6.50	Base	93	41.49	Base	Base	6.64	Base
	2	115	33.23	Base	Base	6.55	Base	90	37.52	Base	Base	7.98	Base
	3	98	31.20	Base	Base	5.90	Base	36	36.79	Base	Base	7.27	Base
	4	50	31.81	Base	Base	5.72	Base	36	33.07	Base	Base	6.45	Base
	5	76	43.99	Base	Base	8.19	Base	47	50.77	Base	Base	8.84	Base
	6	65	34.41	Base	Base	5.90	Base	61	40.37	Base	Base	6.57	Base
	7	64	39.74	Base	Base	5.63	Base	60	42.89	Base	Base	6.42	Base
	8	132	46.88	Base	Base	8.44	Base	84	53.73	Base	Base	8.56	Base
"Survey Crew Ahead" sign and warning light (Scenario 2)	1	85	39.54	**−2.02**[b]	**−4.86**	7.59	1.09	101	40.68	−0.81	−1.96	6.26	−0.38
	2	65	31.65	**−1.58**[b]	**−4.75**	5.45	−1.10	47	33.98	**−3.55**[b]	**−9.45**	5.89	**−2.10**[b]
	3	50	31.46	0.26	0.84	7.05	1.16	30	33.35	**−3.44**[b]	**−9.34**	5.89	−1.39
	4	30	32.08	0.28	0.87	7.18	1.46	40	32.74	−0.33	−1.00	7.83	1.38
	5	65	39.92	**−4.07**[b]	**−9.25**	8.90	0.70	52	44.47	**−6.30**[b]	**−12.41**	6.98	−1.86
	6	85	33.73	−0.67	−1.95	5.90	0.00	75	37.73	**−2.64**[b]	**−6.54**	5.57	−1.00
	7	68	35.49	**−4.25**[b]	**−10.70**	6.67	1.04	79	38.18	**−4.70**[b]	**−10.96**	7.38	0.96
	8	97	44.48	**−2.41**[b]	**−5.13**	8.09	−0.35	77	50.49	**−3.24**[b]	**−6.04**	6.53	**−2.02**[b]
"Survey Crew Ahead" sign and PPRS (Scenario 3)	1	36	38.41	**−3.15**[b]	**−7.57**	5.21	−1.29	74	41.22	−0.27	−0.66	5.88	−0.76
	2	68	27.33	**−5.90**[b]	**−17.76**	5.91	−0.64	51	31.71	**−5.81**[b]	**−15.49**	5.98	**−2.01**[b]
	3	38	29.14	**−2.06**[b]	**−6.59**	6.91	1.01	30	29.55	**−7.24**[b]	**−19.67**	7.46	0.18
	4	40	28.83	**−2.98**[b]	**−9.37**	6.67	0.95	45	26.95	**−6.12**[b]	**−18.52**	7.64	1.19
	5	52	40.38	**−3.61**[b]	**−8.20**	9.10	0.90	51	43.13	**−7.64**[b]	**−15.06**	8.71	−0.13
	6	64	29.77	**−4.63**[b]	**−13.46**	6.07	0.17	67	33.93	**−6.44**[b]	**−15.95**	5.48	−1.09
	7	72	35.42	**−4.32**[b]	**−10.87**	5.59	−0.04	63	36.48	**−6.41**[b]	**−14.94**	5.78	−0.64
	8	68	43.58	**−3.31**[b]	**−7.05**	7.67	−0.78	60	48.21	**−5.52**[b]	**−10.27**	7.31	−1.25
"Survey Crew Ahead" sign, warning lights, and PPRS (Scenario 4)	1	99	36.28	**−5.27**[b]	**−12.68**	6.80	0.30	129	38.96	**−2.53**[b]	**−6.06**	6.07	−0.57
	2	71	25.96	**−7.27**[b]	**−21.87**	7.11	0.56	48	30.28	**−7.24**[b]	**−19.29**	5.22	**−2.77**[b]
	3	48	26.48	**−4.72**[b]	**−15.14**	5.60	−0.30	22	29.82	**−6.96**[b]	**−18.93**	6.83	-0.44
	4	46	25.62	**−6.18**[b]	**−19.44**	7.29	1.57	21	25.18	**−7.90**[b]	**−23.87**	8.25	1.80
	5	59	36.39	**−7.60**[b]	**−17.28**	9.15	0.96	49	43.11	**−7.66**[b]	**−15.09**	5.49	**−3.35**[b]
	6	62	29.62	**−4.79**[b]	**−13.92**	7.43	1.53	61	33.10	**−7.27**[b]	**−18.00**	6.03	−0.54
	7	68	34.19	**−5.55**[b]	**−13.97**	6.51	−0.88	58	37.81	**−5.07**[b]	**−11.83**	5.65	−0.77
	8	89	44.41	**−2.48**[b]	**−5.28**	7.40	−1.04	50	49.48	**−4.25**[b]	**−7.91**	7.16	−1.40

[a] Value <0 indicates a reduction when the control device is used.
[b] Indicates a statistically significant effect at a significance level of $\alpha = 0.05$.
[c] SD: standard deviation of speed.

Effects on Speed Distribution

The change in speed distributions was also examined: The speed distributions under each tested scenario are shown in Appendix E. Table 27 shows the KS test results of whether the deployment of the TCD can change the speed distribution. The results of several tests suggest that individual use of the warning lights or PPRSs cannot greatly shift the speed distribution curve of the right lane to a lower level. However, their combination can significantly shift the speed curves of both lanes to a lower level. Unlike the right lane, the individual deployment of the TCD also performed better in terms of shifting the speed distributions to a lower level in the left lane.

Inconsistent changes in the 85^{th} percentile speed in the right lane were found when only the warning lights or the PPRSs were used. When they were deployed together, the 85^{th} percentile speed in the right lane showed a reduction ranging from 6.44 percent to 15.69 percent. For the left lane, except in the first test, the 85^{th} percentile speed showed a reduction ranging from 1.42 percent to 15.08 percent when the warning lights were used. The deployment of the PPRSs showed obvious reductions in the 85^{th} percentile speed, with a reduction ranging from 0.36 percent to 20.55 percent in the left lane. Similarly, when the PPRSs and warning lights were deployed together, the reduction ranged from 3.69 percent to 22.41 percent.

Therefore, the reduction of the 85^{th} percentile speed and the change in speed distribution suggest that PPRSs and their combination with warning lights can be a useful tool for adjusting vehicle speed when approaching the two-way four-lane surveying sites.

Table 27 - Changes in 85th percentile speed and speed distributions

Test Device	Field Test	Right Lane Speed				Left Lane Speed			
		85th Percentile (mph)	Change (mph)[a]	Change (%)[a]	KS test (*p*-value)[b]	85th Percentile (mph)	Change (mph)[a]	Change (%)[a]	KS test (*p*-value)[b]
"Survey Crew Ahead" sign only (Scenario 1: Base case)	1	47.02	Base	Base	Base	47.19	Base	Base	Base
	2	38.96	Base	Base	Base	45.95	Base	Base	Base
	3	36.81	Base	Base	Base	43.99	Base	Base	Base
	4	36.20	Base	Base	Base	40.87	Base	Base	Base
	5	52.20	Base	Base	Base	60.61	Base	Base	Base
	6	40.74	Base	Base	Base	47.98	Base	Base	Base
	7	45.45	Base	Base	Base	49.83	Base	Base	Base
	8	55.66	Base	Base	Base	62.77	Base	Base	Base
"Survey Crew Ahead" sign and warning light (Scenario 2)	1	47.35	0.33	0.70	0.064	47.85	0.66	1.40	0.631
	2	37.06	**−1.90**	**−4.88**	0.314	39.02	**−6.93**	**−15.08**	**0.033**
	3	39.53	2.72	7.39	0.937	37.88	**−6.11**	**−13.89**	**0.036**
	4	39.14	2.94	8.12	0.675	40.29	**−0.58**	**−1.42**	0.889
	5	48.19	**−4.01**	**−7.68**	**0.004**	51.80	**−8.81**	**−14.54**	**0.000**
	6	39.86	**−0.88**	**−2.16**	0.900	43.84	**−4.14**	**−8.63**	0.154
	7	42.44	**−3.01**	**−6.62**	**0.003**	46.27	**−3.56**	**−7.14**	**0.001**
	8	53.07	**−2.59**	**−4.65**	0.096	57.55	**−5.22**	**−8.32**	**0.015**
"Survey Crew Ahead" sign and PPRS (Scenario 3)	1	41.96	**−5.06**	**−10.76**	**0.013**	47.02	**−0.17**	**−0.36**	0.989
	2	32.47	**−6.49**	**−16.66**	**0.000**	37.63	**−8.32**	**−18.11**	**0.000**
	3	37.32	0.51	1.39	0.082	34.95	**−9.04**	**−20.55**	**0.001**
	4	34.59	**−1.61**	**−4.45**	0.099	34.19	**−6.68**	**−16.34**	**0.000**
	5	49.01	**−3.19**	**−6.11**	0.107	52.45	**−8.16**	**−13.46**	**0.001**
	6	35.49	**−5.25**	**−12.89**	**0.000**	38.73	**−9.25**	**−19.28**	**0.000**
	7	42.03	**−3.42**	**−7.52**	**0.001**	41.59	**−8.24**	**−16.54**	**0.000**
	8	50.51	**−5.15**	**−9.25**	**0.049**	55.83	**−6.94**	**−11.06**	**0.000**
"Survey Crew Ahead" sign, warning lights, and PPRS (Scenario 4)	1	43.99	**−3.03**	**−6.44**	**0.000**	45.45	**−1.74**	**−3.69**	**0.030**
	2	32.86	**−6.10**	**−15.66**	**0.000**	36.83	**−9.12**	**−19.85**	**0.000**
	3	31.66	**−5.15**	**−13.99**	**0.000**	36.29	**−7.70**	**−17.50**	**0.003**
	4	32.59	**−3.61**	**−9.97**	**0.000**	31.71	**−9.16**	**−22.41**	**0.000**
	5	45.69	**−6.51**	**−12.47**	**0.001**	47.68	**−12.93**	**−21.33**	**0.000**
	6	35.49	**−5.25**	**−12.89**	**0.006**	39.86	**−8.12**	**−16.92**	**0.000**
	7	39.86	**−5.59**	**−12.30**	**0.000**	43.91	**−5.92**	**−11.88**	**0.000**
	8	50.51	**−5.15**	**−9.25**	**0.030**	56.82	**−5.95**	**−9.48**	**0.004**

[a] Value <0 indicates a reduction when the control device is used.
[b] Indicates a statistically significant effect at a significance level of α = 0.05.

Effects on Speed Limit Compliance

Table 28 summarizes the effects of different TCD on speed limit compliance of free-flowing traffic in both lanes.

When only the warning lights were used, Fisher's exact test showed no consistent changes in speed limit compliance rates compared to the base case using a "Survey Crew Ahead" sign only. When PPRSs or their combination with warning lights were deployed, the proportions of speeding vehicles in most of the field tests were significantly by up to 39.9 percent in the right lane and 53.6 percent in the left lane. The reductions in scenario 3 on average were about 18 percent and 29 percent in the right lane and left lane, respectively. The proportions of speeding vehicles on average were 23 percent and 32 percent less in scenario 4 than in the base case. These reductions in speeding vehicles are a positive indicator, showing that motorists were aware of the special TCD at the temporary work zones.

Table 28 - Effects of different TCD on speed limit compliance

Test Device	Field Test	Speed Limit, mph	Right Lane				Left Lane			
			Below Limit	Above Limit	Speeding (%)	*p*-value[a]	Below Limit	Above Limit	Speeding (%)	*p*-value[a]
"Survey Crew Ahead" sign only (Scenario 1: Base case)	1	45	58	23	28.4	Base	64	29	31.2	Base
	2	40	99	16	13.9	Base	57	33	36.7	Base
	3	25	14	84	85.7	Base	4	32	88.9	Base
	4	25	6	44	88.0	Base	4	32	88.9	Base
	5	50	55	21	27.6	Base	17	30	63.8	Base
	6	40	51	14	21.5	Base	31	30	49.2	Base
	7	40	30	34	53.1	Base	16	44	73.3	Base
	8	50	82	50	37.9	Base	24	60	71.4	Base
"Survey Crew Ahead" sign and warning light (Scenario 2)	1	45	58	27	31.8	0.735	74	27	26.7	0.529
	2	40	60	5	7.7	0.238	41	6	12.8	**0.003**
	3	25	10	40	80.0	0.478	1	29	96.7	0.366
	4	25	5	25	83.3	0.739	5	35	87.5	1.000
	5	50	57	8	12.3	**0.036**	41	11	21.2	**0.000**
	6	40	73	12	14.1	0.279	50	25	33.3	0.079
	7	40	53	15	22.1	**0.000**	47	32	40.5	**0.000**
	8	50	74	23	23.7	**0.031**	36	41	53.2	**0.022**
"Survey Crew Ahead" sign and PPRS (Scenario 3)	1	45	33	3	8.3	**0.016**	54	20	27.0	0.610
	2	40	66	2	2.9	**0.019**	47	4	7.8	**0.000**
	3	25	14	24	63.2	**0.008**	7	23	76.7	0.206
	4	25	9	31	77.5	0.256	16	29	64.4	**0.018**
	5	50	46	6	11.5	**0.030**	38	13	25.5	**0.000**
	6	40	60	4	6.2	**0.020**	61	6	9.0	**0.000**
	7	40	58	14	19.4	**0.000**	48	15	23.8	**0.000**
	8	50	56	12	17.6	**0.004**	40	20	33.3	**0.000**
"Survey Crew Ahead" sign, warning lights, and PPRS (Scenario 4)	1	45	87	12	12.1	**0.008**	107	22	17.1	**0.016**
	2	40	69	2	2.8	**0.019**	47	1	2.1	**0.000**
	3	25	18	30	62.5	**0.003**	6	16	72.7	0.156
	4	25	21	26	54.3	**0.000**	10	11	52.4	**0.004**
	5	50	57	2	3.4	**0.000**	44	5	10.2	**0.000**
	6	40	60	2	3.2	**0.002**	52	9	14.8	**0.000**
	7	40	59	9	13.2	**0.000**	40	18	31.0	**0.000**
	8	50	73	16	18.0	**0.002**	29	21	42.0	**0.001**

[a] A *p*-value ≤0.05 indicates a statistically significant effect given a significance level of α = 0.05.

Effects on Drivers' Braking Behavior

The impact of the deployment of TCD on driver behavior in both lanes was investigated by comparing braking actions. Table 29 summarizes the results.

When there was no special control, few vehicles in either lane braked when approaching surveying sites. When the warning lights were used, the proportions of vehicles braking increased by about 6 percent to 18.8 percent in the right lane and 5 percent to 16.5 percent in the left lane. When PPRSs were deployed, the braking proportions increased by about 7.9 percent to 26.6 percent in the right lane and 4.4 percent to 22.0 percent in the left lane. When these two devices were simultaneously deployed, the proportions of vehicles braking increased by 6.1 percent to 21.2 percent in the right lane and 4.7 percent to 23.6 percent in the left lane. Except for several tests in left lane, the Fisher's exact test further confirmed that the use of one or both devices can greatly affect the braking behavior of motorists. The change in the braking rate implies that the motorists were aware of the presence of surveying teams.

Table 29 - Effects of different TCD on braking behaviors

Test Device	Field Test	Right Lane				Left Lane			
		Not Brake	Brake	Braking (%)	*p*-value[a]	Not Brake	Brake	Braking (%)	*p*-value[a]
"Survey Crew Ahead" sign only (Scenario 1: Base case)	1	81	0	0.0	Base	93	0	0.0	Base
	2	99	2	1.7	Base	89	1	1.1	Base
	3	98	0	0.0	Base	36	0	0.0	Base
	4	49	1	2.0	Base	36	0	0.0	Base
	5	71	5	6.6	Base	46	1	2.1	Base
	6	62	3	4.6	Base	58	3	4.9	Base
	7	60	4	6.2	Base	57	3	5.0	Base
	8	120	12	9.1	Base	82	2	2.4	Base
"Survey Crew Ahead" sign and warning light (Scenario 2)	1	75	10	11.8	**0.002**	87	14	13.9	**0.000**
	2	59	6	9.2	**0.027**	42	5	10.6	**0.018**
	3	47	3	6.0	**0.037**	26	4	10.0	**0.038**
	4	25	5	16.7	**0.026**	38	2	5.0	0.495
	5	52	13	20.0	**0.022**	45	7	13.5	0.062
	6	69	16	18.8	**0.012**	61	14	18.7	**0.019**
	7	51	17	25.0	**0.004**	62	17	21.5	**0.007**
	8	75	22	22.7	**0.005**	69	8	10.4	**0.049**
"Survey Crew Ahead" sign and PPRS (Scenario 3)	1	33	3	8.3	**0.027**	70	4	5.4	**0.037**
	2	59	9	13.2	**0.003**	44	7	13.7	**0.003**
	3	35	3	7.9	**0.021**	26	4	10.0	**0.038**
	4	34	6	15.0	**0.042**	43	2	4.4	0.500
	5	42	10	19.2	**0.047**	43	8	15.7	**0.032**
	6	44	20	31.2	**0.000**	54	13	19.4	**0.016**
	7	57	15	20.8	**0.024**	46	17	27.0	**0.001**
	8	53	15	22.1	**0.016**	50	10	16.7	**0.004**
"Survey Crew Ahead" sign, warning lights, and PPRS (Scenario 4)	1	93	6	6.1	**0.033**	123	6	4.7	**0.042**
	2	63	8	11.3	**0.007**	40	8	16.7	**0.001**
	3	45	3	6.2	**0.034**	18	4	18.2	**0.017**
	4	39	7	15.2	**0.027**	18	3	14.3	**0.045**
	5	44	15	25.4	**0.003**	40	9	18.4	**0.016**
	6	46	16	25.8	**0.001**	46	15	24.6	**0.004**
	7	52	16	23.5	**0.007**	47	11	19.0	**0.023**
	8	72	17	19.1	**0.041**	37	13	26.0	**0.000**

[a] A *p*-value ≤0.05 indicates a statistically significant effect given a significance level of α = 0.05.

RECOMMENDED TRAFFIC CONTROL DEVICES

It was mentioned earlier that during our initial site visits it was observed that land surveyors and geodetic surveyors were highly exposed to traffic and would benefit from additional TCD. It was also mentioned that bridge inspectors' exposure to traffic is minimal, and the only recommended safety device is the personal strobe light (see Table 13). The following sections discuss the recommended TCD for land and geodetic surveyors.

Land Surveyors

The results of the field tests show that PPRSs and warning lights have a significant impact on reducing traffic speed and the number of speeding vehicles and increasing driver awareness. Their combination has an even more significant impact. However, any safety device recommended for land surveyors should be deployed quickly (no more than five minutes). The PPRSs that the research team tested were made of three pieces that, when connected, form an 11-foot-long rumble strip (see Figure 17). Land surveyors can easily store mounted portable rumble strips in their work vans and deploy them in less than a couple of minutes after they set up the “Survey Crew Ahead” sign. However, warning lights are not recommended to be used without PPRS, because of their inconsistent effects when used alone.

The results in Table 24 show that for two-lane two-way roadways with 25 mph and 40 mph speed limits, the proportion of vehicles exceeding the speed limit was 54.7 percent and 19.6 percent on average, respectively. Similarly, the results in Table 28 show that for four-lane two-way roadways with 25 mph, 40 mph, and 50 mph roadways, the proportion of vehicles exceeding the speed limit was 72 percent, 14.7 percent, and 21.6 percent on average, respectively. These results show that at most roadways with 25 mph speed limits, the proportion of vehicles exceeding the speed limit is significant. It can be seen in Table 14 and Table 15 that most roadways land surveying crews work on have speed limits between 25 mph and 40 mph.

Results presented in the previous section showed that with the use of portable rumble strips only, traffic speed was reduced by 10.1 percent to 15.2 percent, and the 85th percentile speed was lowered by 8.3 percent to 14.5 percent. In addition, speed limit compliance and driver awareness were significantly increased.

There is overwhelming evidence in the literature that shows the positive correlation between vehicle speed and the severity of pedestrian accidents. For example, the World Health Organization[46] reported that an average increase in speed of 1 km per hour (0.625 mph) is associated with a 3 percent higher risk of a crash involving an injury. Pedestrians have a 90 percent probability of surviving a car crash at 18 mph or below but less chance of surviving impacts at 28 mph or above. The National Highway Traffic Safety Administration[47] reported that vehicle speeds predict both the frequency and the severity of pedestrian injuries. For instance, about 5 percent of pedestrian accidents would be fatal when a pedestrian was struck by a vehicle at 20 mph, about 40 percent for a vehicle traveling at 30 mph, about 80 percent for vehicles traveling at 40 mph, and about 100 percent for speeds above 50 mph.[47]

In light of the above statistics, it is evident that the use of portable rumble strips can have a tremendous benefit for the safety of surveyors in return for a cost of approximately $8,000 for six 11-foot-long rumble strips (three rumble strips in each direction before the work zone). In addition, the use of portable strobe lights can enhance the visibility of land surveyors at intersections (see Figure 19).

In addition, regardless of what type of traffic safety device is being used, the safety of surveyors is first and foremost in the hands of the surveyors themselves. Although, there are various rules that surveyors have abided by over the years to assure their safety, having additional surveyors / lookout personnel present in the field benefits the whole crew more than anything else in terms of safety.

Besides traffic control devices, the use of advanced surveying technologies offers opportunities for surveyors to automatically take measurements without having to expose themselves to traffic. LiDAR technology takes both GPS and laser range finder measurements (see Figure 24). According to surveys conducted by Minnesota DOT in 2009 [48], 14 out of 27 state DOTs surveyed were either contracting firms that use static LiDAR scanners or use them in house.

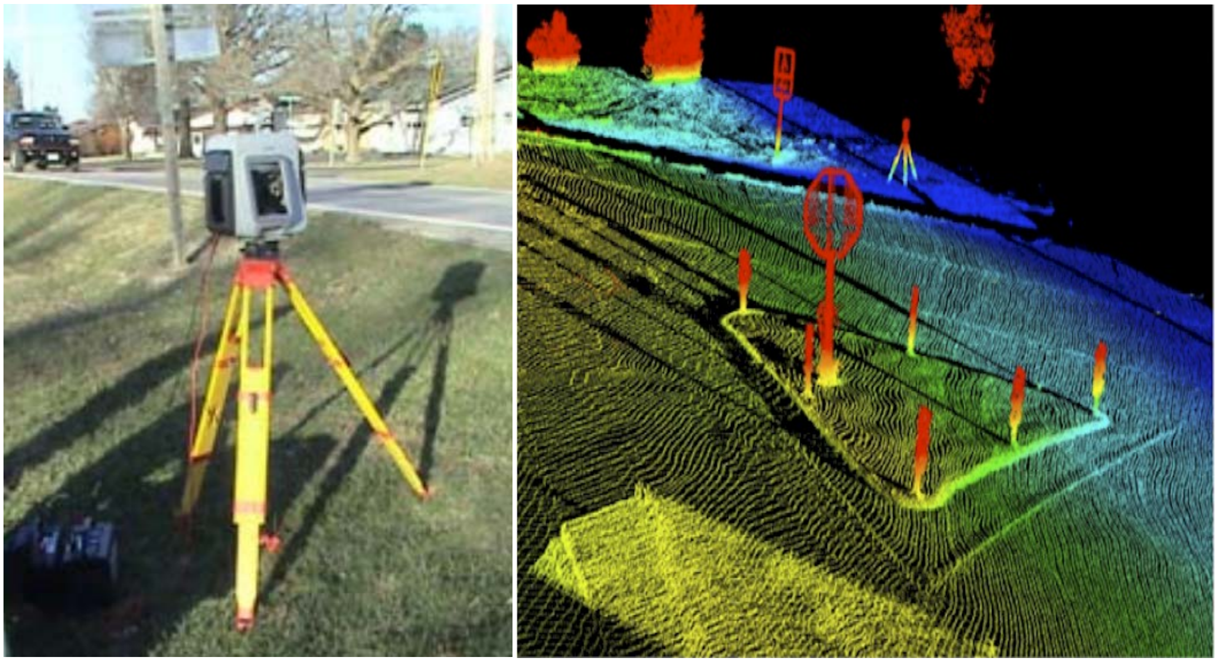


Figure 24. Static LiDAR Scanner for surveying[49]

Static LiDAR is suitable for high-detail local area surveys, such as tunnels, enhancement projects, traffic intersections, or rail crossings. It reduces the safety risk of surveyors as well as potential schedule delays over traditional surveying methods; for extensive amounts of survey data, however, it requires additional specialized software and hardware.[49]

Clearly, the use of static LiDAR technology would tremendously increase the safety of surveyors. Based on our phone interviews with the state DOTs that use static LiDAR, the estimated cost of this technology varies between $75,000 and $150,000.

Geodetic Surveyors

As mentioned, geodetic surveying crews work at a fast pace and take GPS measurements without having time to set up signs or cones. At each location, they spend between 3 and 5 minutes to take GPS measurements. Therefore, rumble strips or warning lights are unsuitable for geodetic surveyors. Personal strobe lights were the only inexpensive and practical devices used among the potential safety devices presented earlier in this report.

In addition, it is recommended that NJDOT should internally discuss the possibility of assigning an attenuator truck for the sole use of surveyors. Based on our discussions with the surveying department it was learned that it is not always possible to obtain attenuator trucks, since they are operated by the maintenance department, and it would create scheduling issues when needed for urgent surveying work. Having an attenuator truck follow geodetic surveyor crews would significantly increase their safety especially working on roadways with no shoulders.

LiDAR technology is also applicable to the work conducted by the geodetic surveyors. Mobile LiDAR surveying method has been practiced by other state DOTs and consultants. The research team attended two seminars on mobile LiDAR technology organized by NJDOT on December 10, 2010, and May 4, 2011. Based on the information provided at these seminars, it was evident that mobile LiDAR technology (see Figure 25) is a viable option for enhancing the safety of geodetic surveyors.

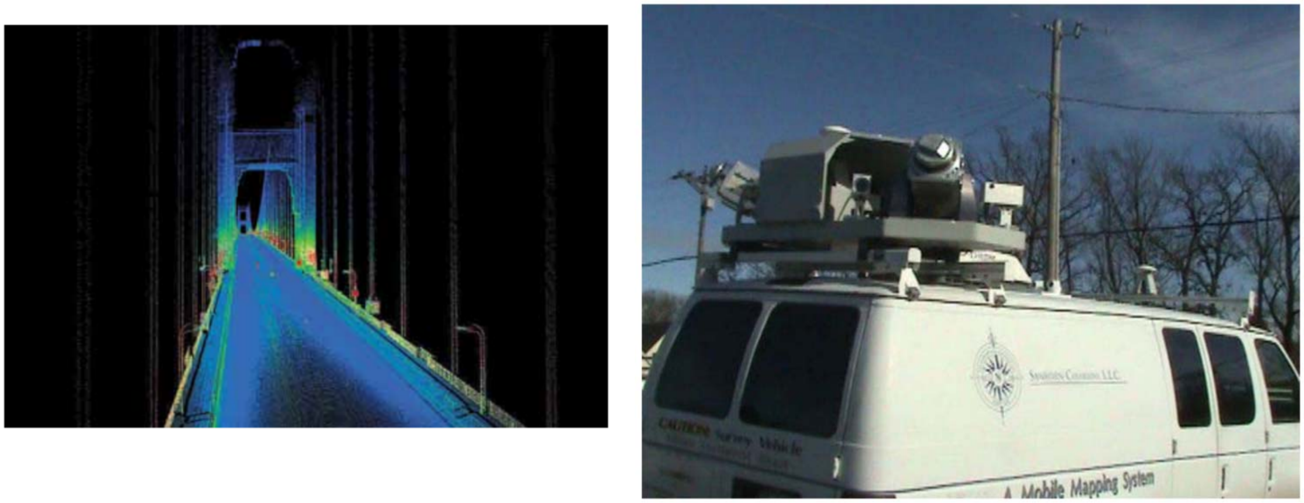


Figure 25. Mobile LiDAR Scanner for surveying[49,50]

Mobile LiDAR is an emerging technology that combines laser scanners, GPS, and an inertial measurement unit on a mobile platform to produce accurate geospatial data.[50] Mobile LiDAR scanners have the lowest safety risk and offer rapid collection over conventional survey techniques.[49] According to an analysis conducted by Caltrans, using mobile LiDAR technology rather than traditional methods results in an estimated cost savings between $200,000 and $300,000 to Caltrans and the city of San Francisco in a single 15-mile project with highly restricted lanes. Because mobile LiDAR eliminates the need for lane closures and field crews collecting terrestrial topography on the ground, the risk to field crew was significantly reduced.[50]

Based on our phone interviews with the state DOTs that use mobile LiDAR technology, the cost of mobile LiDAR scanners is between $500,000 and $1 million. The benefits of using this technology are the acquisition of vast amount of data in a short amount of time with less manpower, reduced equipment needs, increased safety, and the potential for multiple future uses of the data by other end users.[50] NJDOT's geodetic surveying crews are also in agreement with the potential benefits of this advanced surveying technology.

More on LiDAR Technology

LiDAR technology allows surveyors to collect fast and vast amount of data in the field. The technology reduces the amount of time they spent in the field, which in turn reduces their exposure to traffic and enhances their safety.

There are many pros and cons of LiDAR surveys compared to traditional surveys. The most important advantage of LiDAR surveys is the speed and the abundance of data collection. The speed of LiDAR and the amount of data collected cannot be easily matched by any traditional surveying methods. According to a study conducted by Missouri DOT [51], conventional aerial mapping is still the most cost effective way to collect elevation data since it is twice as fast to conduct aerial surveying compared to mobile surveying. However, LiDAR surveys provide more data, and additional and rich information such as traffic signs, manholes, drains, parking meters, sidewalks, curbs, poles, wires, etc. In addition, LiDAR data can be filtered from highly rich survey data points to less detailed datasets and can be shared by other departments within DOT and with other local and state government agencies, as shown in Figure 26.

With abundant amount of additional data comes the need for significant amount of processing power and additional time required to process the data. Therefore, when purchasing LiDAR technology – whether static or mobile – DOT will not only have to invest in the capital cost of the LiDAR equipment, but also in the hardware and software products, and also in training of its staff who will be using these equipment, and process the data.

Static and mobile LiDAR have varying accuracy levels and data collection speed, making their use warranted for various types of applications. For example, mobile LiDAR is most suited for high traffic areas where it is dangerous for surveyors to expose themselves to fast moving traffic, whereas static LiDAR is suited for smaller scale projects such intersection design and enhancements.

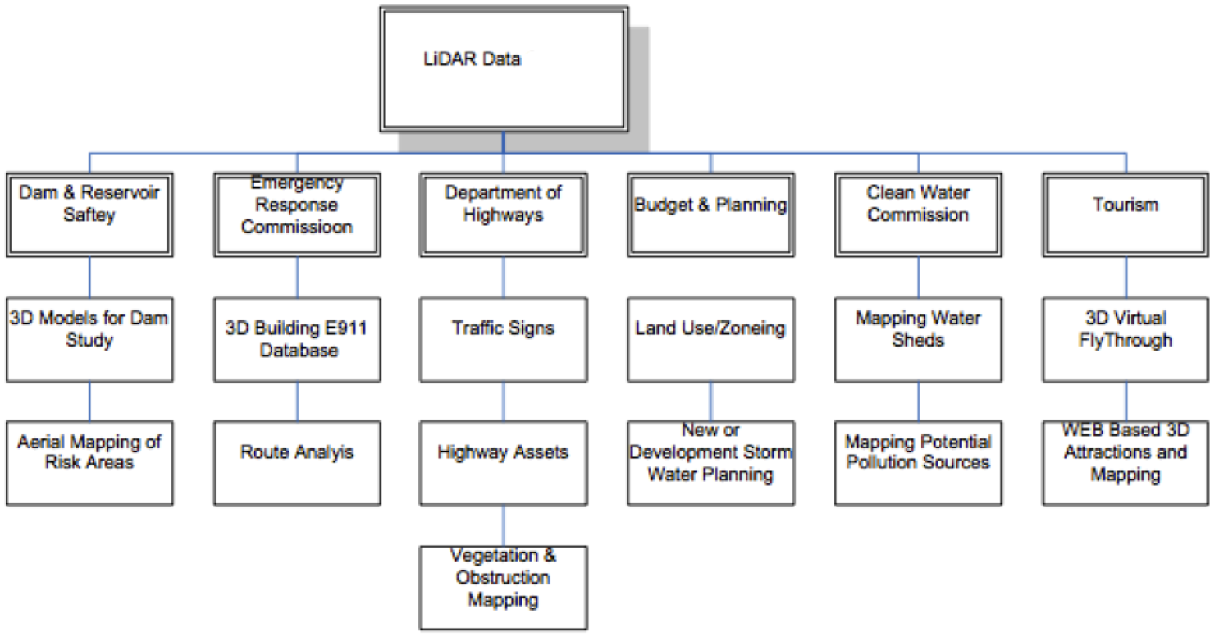


Figure 26. Potential data sharing opportunities with other departments and agencies. [51]

Considering the high capital costs, the need for additional hardware and software investments and training costs, traditional surveying methods are still more cost effective compared to LiDAR technology. However, an extensive benefit cost analysis that takes into account the reduction in site visits and traffic disruptions, and the possibility of sharing the rich data with other departments in DOT and other agencies, is still warranted as a follow-up study.

It should be noted that although LiDAR technology could be cost effective when all benefits are taken into account, it still might not be suitable for all surveying needs or might not meet the required surveying accuracy standards of many DOTs. However, with increasing interest in this technology, it is highly likely that the accuracy level and the capital cost of LiDAR technology will meet the expectations of the department. Until then the technology can be used in aiding the traditional surveying methods, which will reduce the number of site visits by surveyors, and will therefore enhance their safety.

In addition to the recommended use of temporary rumble strips to reduce vehicle speeds and increase driver awareness, NJDOT should internally investigate the possibility of using LiDAR technology to stay ahead of the curve, since this technology will be prevalent in the near future and shape the surveying science. LiDAR technology, if not completely eliminate, will certainly reduce the exposure of surveyors to traffic, and in addition provide rich data in a short period of time.

RECOMMENDED GUIDELINES FOR SURVEYORS

This purpose of this section is to recommend safety guidelines for geodetic and land surveyors when working in various roadway types under the jurisdiction of NJDOT. As mentioned in the previous section, there is overwhelming evidence in the literature that shows the positive correlation between vehicle speed and severity of pedestrian accidents. Today, roads are populated with commercial signs, and drivers are more and more distracted due to cell phones, navigation systems, and onboard electronics. Therefore, there is a need to make sure that drivers are alerted in an effective manner regarding the work zone ahead and ensure that they slow down.

It should be mentioned that although NJDOT Surveyors need to have a basic understanding of necessary safety requirements, they should first and foremost have a clear safety consciousness and be alert at all times. As stated in Illinois Department of Transportation Survey Manual [(52)], "*It shall be the duty of every employee to consider no job so important and service so urgent that time cannot be taken to work and drive safely*."

The following subsections present the safety guidelines for geodetic and land surveyors. It should be noted that these are general guidelines and must be revised and improved by certified Traffic Control Coordinators to ensure that all guidelines are according to the MUTCD standards.

Geodetic Surveyors

Geodetic surveying maintains and expands the geodetic control network within New Jersey through GPS technology and leveling. Geodetic surveyors also maintain files of state and federal horizontal and vertical control data.

Work Beyond The Shoulder

Geodetic surveyors who work beyond the shoulder should follow the instructions given on page 3 of NJDOT Work Zone Safety Set-up Guide [(53)].

Mobile Operation on Right Shoulder

This type of work is common for geodetic surveyors, where they work at a fast pace and take GPS measurements along a long stretch of roadway without having time to set up signs or cones. They work behind their work van and use the vehicle's strobe light to warn drivers (See Figure 7).

Geodetic surveyors are advised to follow the instructions given on page 4 and page 7 of the NJDOT Work Zone Safety Set-up Guide [53] where they are followed by a Truck with Attached Attenuator (TMA) located behind the surveyor van on roadways where the speed limit is greater than 45 mph. As recommended in the previous section, NJDOT should investigate the possibility of assigning a TMA for the sole use of the surveying department to eliminate scheduling issues between the maintenance department and the surveying department.

Based the data collected during our site visits, the research team found that geodetic surveyors are highly exposed to fast moving traffic. As shown in Figure 9 and Figure 10, a very high percentage of drivers travel at speeds higher than the posted speed limits. Especially on Route 30, where the posted speed limit was 45 mph, nearly all vehicles were observed to travel above the posted speed limit. Furthermore, it was observed that on average, 5.5 percent of vehicles change lanes before the surveyor van, as shown in Table 5. Therefore, a variable message sign may be deployed as an optional traffic control device to advise the traveling public of surveyor work and to stay in lane, in addition to the mandated Roadwork Ahead and Shoulder Closed signs.

For any other work type where geodetic surveyors must take measurements on the roadway lanes, appropriate Work Zone Safety Set-up instructions given in Work Zone Safety Set-up Guide [53] should be followed.

In addition, geodetic surveyors should consider various factors that might affect traffic hazards such as peak traffic hours, sight distances, pavement conditions and traffic speed. They are advised to take baseline measurements off active lanes as much as possible. If a measurement must be taken on an active lane, the site should be visited during off-peak periods and reduce their exposure to heavy traffic.

Land Surveyors

Land surveyors that the research team observed mostly work on state highways and county roads, taking horizontal and vertical readings of features at and around railroad tracks and intersections (see Figure 11). During our observations described in the Initial Site Visits section of this report, the duration of their work varied between 45 minutes and 3 hours. Land surveyors set up “Survey Crew Ahead” signs ahead of the work area in both directions of the roadway. The only safety precaution they have is the safety vests they wear and the help of a flagger, if available.

Land surveyors usually cover a large area within predetermined limits, which restricts the use of widely accepted traffic control devices that are specific to stationary work zones for maintenance and construction activities. They are highly exposed to traffic as observed during our site visits.

As mentioned in the previous section, for two-lane two-way roadways with 25 mph and 40 mph speed limits, the proportion of vehicles exceeding the speed limit was 54.7 percent and 19.6 percent on average, respectively. Similarly, for four-lane two-way roadways, the proportion of vehicles exceeding the speed limit was as high as 72 percent. Therefore, the need for safer work zones for land surveying crews is apparent.

The following subsections present recommended set up guidelines for various types of work areas on roadways with speed limits less than 45 mph. It is advised that for any other roadway types, and for similar roadways with higher speed limits than 45 mph, land surveying crews should follow the work zone safety set up instructions given in NJDOT Work Zone Safety Set-up Guide. [53]

Moreover, as recommended in the previous section, having additional surveyors / lookout personnel present in the field will benefit the whole crew more than any device or technology in terms of safety. NJDOT employee safety division and surveying department should internally seek possibilities of mandating a minimum number of surveyors at any giving surveying job so that one person is always assigned specifically for flagging / lookout purposes.

Work Beyond The Shoulder

Land surveyors who work beyond the shoulder should follow the instructions given on page 3 of NJDOT Work Zone Safety Set-up Guide. [53]

Two-Lane Two-Way Roadway

For land surveying crews working between active traffic lanes and the speed limit is less than 45 mph.

As shown in Figure 27, which is adopted from the surveyor safety guidelines of Florida DOT [54], land surveying crews should use a flagger / lookout and the recommended devices presented in the Recommended Traffic Control Devices section. The results of this research project showed significant impact of the selected safety devices on traffic speed and drivers' awareness, as presented in detail in the Test Results of Two-Lane Roadways section of this report.

PPRS should be deployed at each approach at 20 feet apart, and the last PPRS should be aligned with the Survey Crew Ahead sign. A minimum of ten advance warning lights should be aligned 20 feet apart where half of the warning lights should be deployed before the Survey Crew Ahead sign.

Set up instructions shown in Figure 27 should be followed when land surveying crews work on the shoulders.

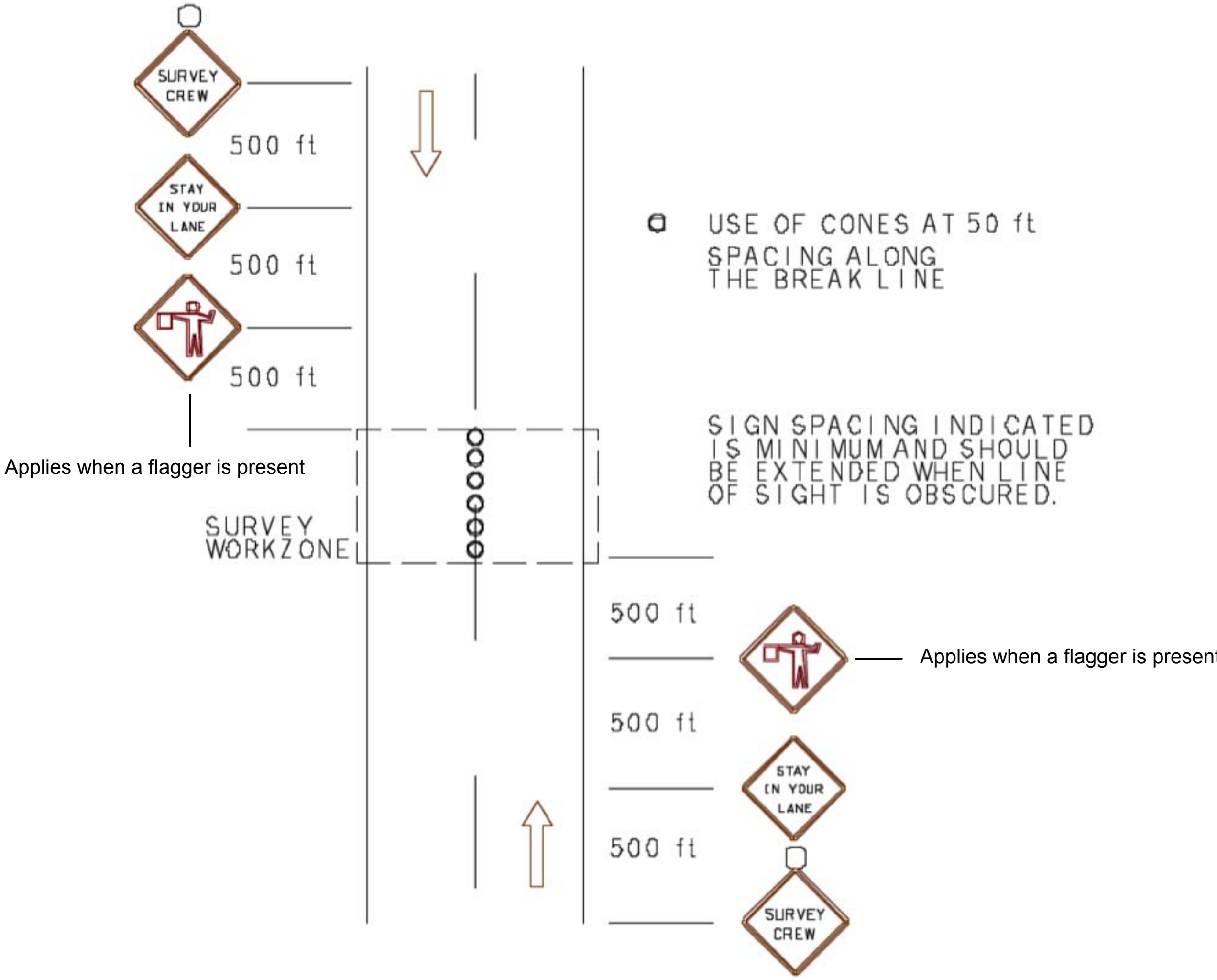


Figure 27. Two-lane roadway median work [54]

(Adopted with slight modifications from the surveyor safety guidelines of Florida State DOT)

Multi-Lane Roadway

This section is intended for land surveying crews working between active traffic lanes and the speed limit is less than 45 mph.

As shown in Figure 28, which is adopted from the surveyor safety guidelines of Florida DOT [54], land surveying crews are advised to use a flagger / lookout. PPRS and advance warning lights may be used as additional safety devices, since our test results indicate significant impact of these devices on traffic speed and drivers' awareness, as shown in the Test Results of Four-Lane Roadways section.

Set up instructions shown in Figure 28 should be followed when surveying crews work on the median or on the right shoulder of multilane roadways. Similarly, the same set up instructions should be followed when land surveying crews work on the active lanes or on the shoulders of one-way two-lane roadways.

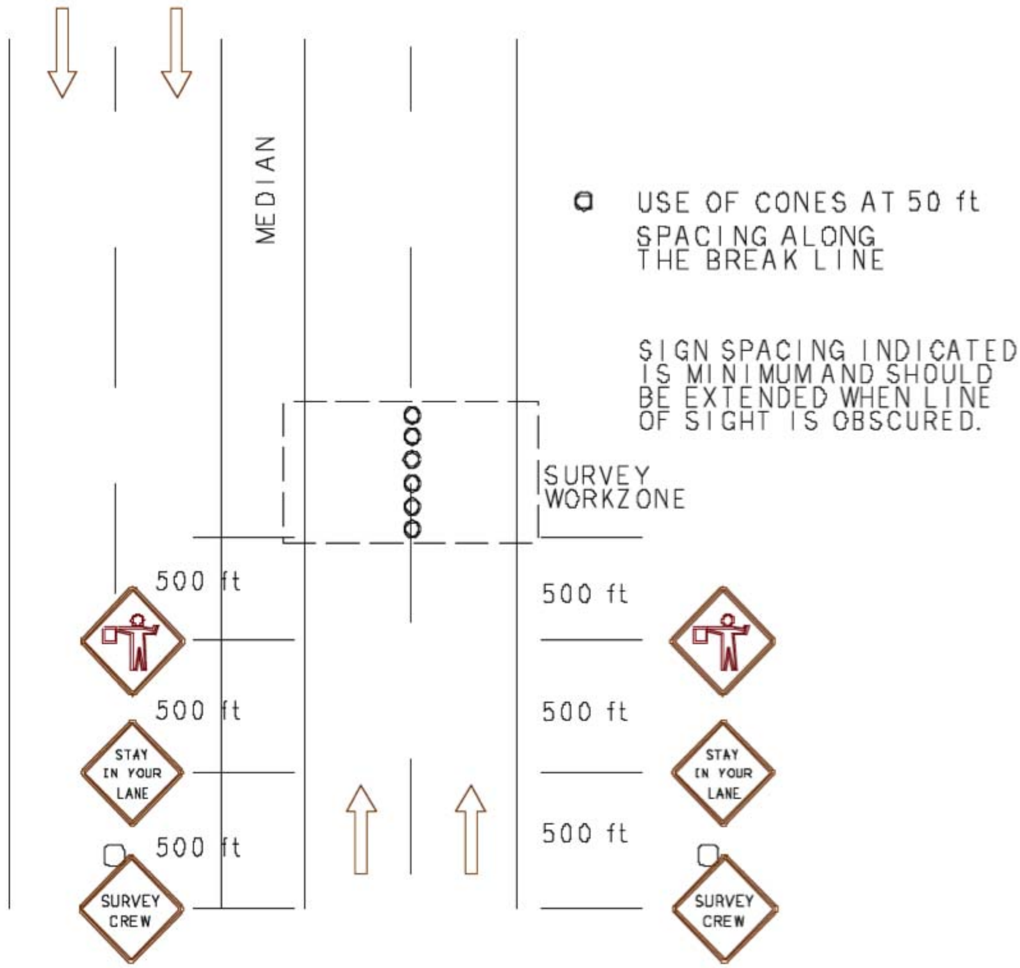


Figure 28. Set up guideline for multi-lane roadway [54]

(Adopted with slight modifications from the surveyor safety guidelines of Florida State DOT)

Multi-Lane Roadway with Shared Turn Lane

For land surveying crew who work in a shared turn lane of a multi-lane roadway, and the speed limit is less than 45 mph.

As shown in Figure 29, which is adopted from the surveyor safety guidelines of Florida DOT [54], land surveying crews are advised to use a flagger. PPRS and advance warning lights may be used as additional safety devices. Similar set up should be followed when land surveying crew works between active lanes and on the right shoulder.

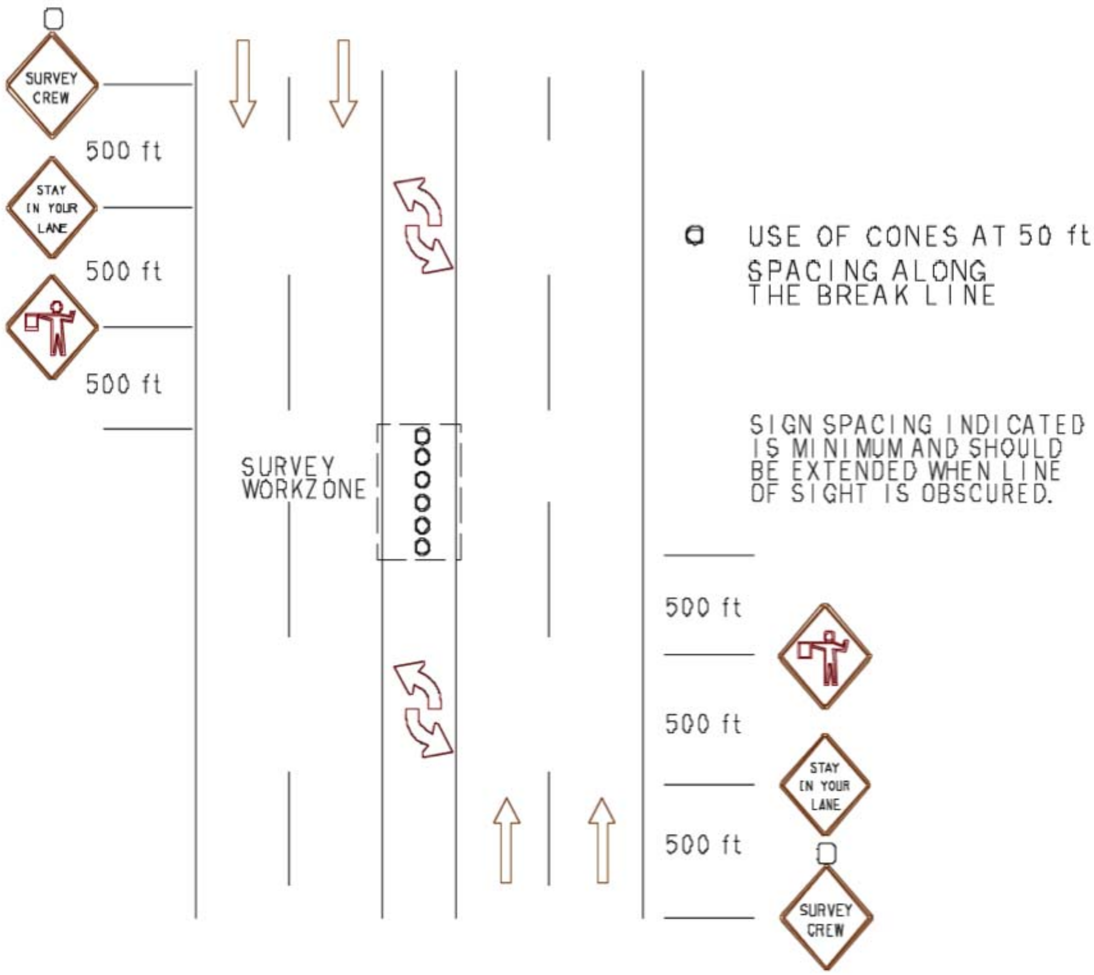


Figure 29. Set up guideline for multi-lane roadway with shared turn lane [54]

(Adopted with slight modifications from the surveyor safety guidelines of Florida State DOT)

CONCLUSIONS

Surveyors who often work on or near roadways encounter unique safety risks, as only limited, temporary traffic control devices are available to warn motorists of the presence of a work zone. Surveyors usually cover a large area within predetermined limits, which restricts the use of widely accepted TCD specific to stationary work zones for maintenance and construction activities.

To enhance the safety of surveyors, additional TCD that are easy to deploy, effective, and inexpensive are needed. Among the various potential TCD that the research team identified, two were selected for further analysis: PPRSs and warning lights. These two selected devices are deployed and tested at multiple urban roadway surveying sites with the help of NJDOT land surveying crews. A total of 18 field tests were conducted: 10 two-way two-lane roadways and eight two-way four-lane roadways in New Jersey, as listed in Table 14 and Table 15.

The effectiveness of PPRSs and warning lights on alerting motorists of short-term surveying sites were examined by using a set of surrogate safety measures extracted from the video data. These measures are:

- Change in speed variance;
- Reduction in speed;
- Change in speed distribution;
- Reduction in speeding proportion; and
- Increase in braking proportion.

Overall, comparative analysis demonstrated positive effects for PPRSs and warning lights in enhancing safety at surveying sites. Specifically, the deployment of the warning lights and/or PPRSs did not deteriorate the stability of traffic, because the speed variance did not statistically change compared to the scenario with an advanced warning sign only.

In addition, the relationship between driver actions and the deployment of TCD was modeled using binary regression. Two categories of driver actions were analyzed: (1) speeding action and (2) braking action, given the presence of TCD. The variables considered for speeding and braking analysis are listed in Table 17. The estimated statistical model showed that deployment of additional TCD overall positively affects driver behavior (i.e., speeding and braking) at land surveying sites.

The results of field tests are summarized as follows:

Warning lights:

- The use of warning lights resulted in a 6.6 percent reduction in mean speed at two-lane sites and a 4.4 percent reduction in the right lane and 7.2 percent reduction in the left lane at four-lane sites, respectively.
- The 85th percentile speed was reduced by 7.0 percent at two-lane sites and by 1.2 percent in the right lane and 8.5 percent in the left lane at four-lane sites, respectively.
- Speed distributions for some of the tests were significantly shifted to a lower level.
- The effect on speed limit compliance was not clear, as only about half of the field tests showed a significant reduction in the proportion of speeding vehicles.
- The use of warning lights did not show a clear effect on braking behavior for the two-lane sites. However, the braking rate increased at the four-lane sites.

PPRSs:

- Deployment of PPRSs resulted in a 15.2 percent reduction in mean speed at two-lane sites and 10.1 percent reduction in the right lane and 13.8 percent reduction in the left lane at four-lane sites, respectively.
- The 85th percentile speed was reduced by 12.6 percent at two lane sites and by 8.3 percent in the right lane and 14.5 percent in the left lane at four-lane sites.
- Speed distributions for most of the tests were significantly shifted to a lower level.
- The proportion of speeding vehicles was significantly reduced for both the two-lane test sites and the four-lane test sites.

- Similarly, the use of PPRSs significantly increased the proportion of braking vehicles compared with baseline (scenario with an advanced warning sign only).

Warning lights + PPRSs:

- Deployment of the two devices together further reduced the mean speed at the surveying sites. The use of these devices reduced the mean speed by 19.7 percent at two-lane sites and by 14.9 percent in the right lane and 15.1 percent in the left lane at four-lane sites, respectively.
- The 85th percentile speed was reduced by 17.0 percent at two lane sites and by 11.6 percent in the right lane and 15.4 percent in the left lane at four-lane sites.
- Speed distributions for most of the tests were significantly shifted to a lower level.
- The proportion of speeding vehicles was significantly reduced for both the two-lane test sites and the four-lane test sites. The magnitude of reduction was larger when each device was deployed separately.
- Similarly, the combined use of PPRSs and advance warning lights significantly increased the proportion of braking vehicles when compared with baseline (scenario with the advanced warning sign only). The magnitude of increase was larger when each device was deployed separately.

To sum up, the decrease in operating speed coupled with the increase in speed compliance rate and braking vehicles shows that the additional TCD increased driver awareness. The combination of the two devices further enhanced their positive effect on alerting motorists.

Unlike other traffic control devices, PPRSs and warning lights both can be easily installed and removed in minutes, which makes them more practical for short-term surveying operations. The tests in the present study were conducted on several urban roadways under different traffic conditions. The positive effects of these TCD shown in different test conditions suggest that traditional traffic control plans at surveying sites can be improved.

The research team also investigated the possibility of using some novel ideas such as deploying laser intrusion alarm systems, and broadcasting a brief message to vehicles'

FM radios by installing a device before the work zone. However, none of these technologies are readily available as off-the-shelf products and they do not satisfy several operational, legal and cost related criteria. Thus, they were not studied further by the research team.

In addition, as mentioned in the Recommended Traffic Control Devices section, NJDOT should investigate the possibility of assigning a Truck with Attached Attenuator for the sole use of the surveying department to eliminate scheduling issues between the maintenance department and the surveying department.

Aside from traffic safety devices, based on the review of existing safety technologies and the feedback from field personnel, it is recommended that having additional surveyors / lookout personnel present in the field can benefit the whole crew significantly in terms of safety. Therefore NJDOT should internally seek possibilities of allocating a minimum number of surveyors at any giving surveying job so that one person is always assigned specifically for flagging / lookout purposes.

In addition to traffic control devices evaluated in this study, the use of advanced surveying technologies offer opportunities for surveyors to collect vast amount of data very fast, thereby reducing the amount of time they spent in the field and thus their exposure to traffic. This reduced exposure to traffic will clearly enhance their safety.

Although at this point LiDAR technology might not be the best fit for all surveying needs or might not meet the required surveying accuracy standards of many DOTs, with increasing interest in the technology, it is highly likely that the accuracy level and the capital cost of LiDAR technology will meet the expectations of the department in the near future. LiDAR technology can be used in aiding the traditional surveying methods, which will reduce the number of site visits by surveyors, and will therefore enhance their safety. It is recommended that NJDOT take an initiative to start investigating the feasibility of this technology to stay ahead of the curve.

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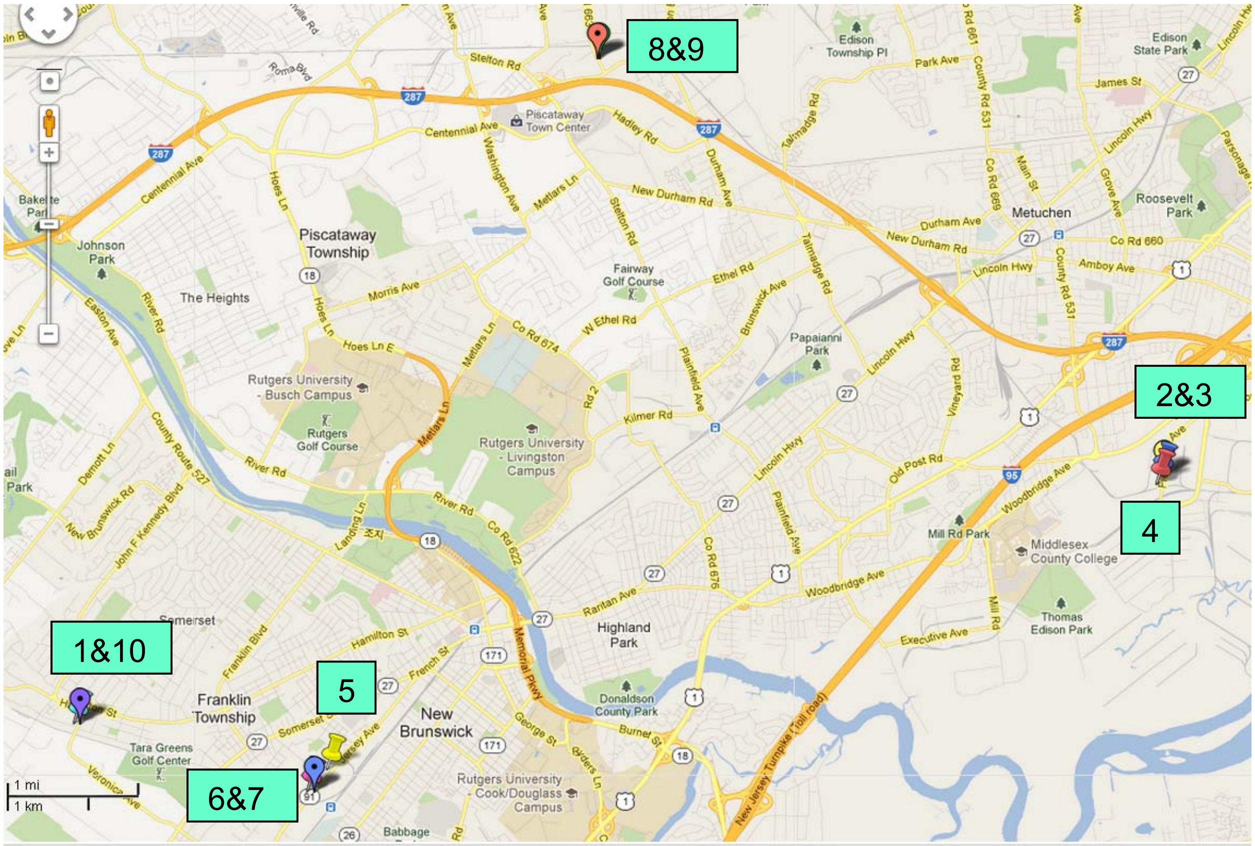
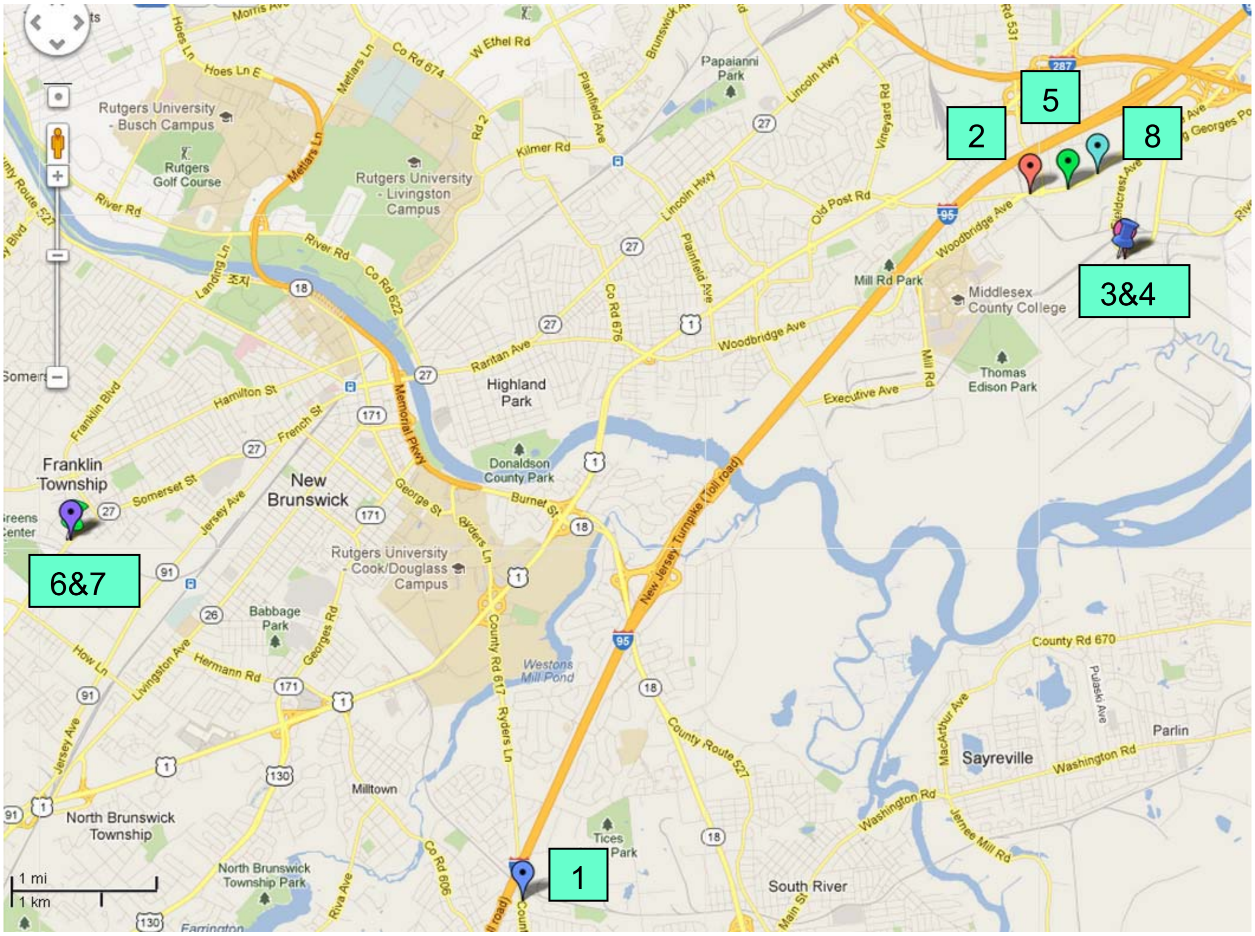
APPENDIX A: LOCATIONS OF FIELD TEST SITES

The following map shows the locations of 10 tests at different two-lane roadways.



Test	Name	Direction	Shoulder	Lanes	Speed Limit	Date	Time	Total Volume (veh)
1	Veronica Ave.	SB	No	1	40 mph	10/05/2011	09:30–11:30	480
2	Fieldcrest Ave.	SB	No	1	25 mph	03/14/2012	09:30–11:30	367
3	Fieldcrest Ave.	SB	No	1	25 mph	03/19/2012	09:30–11:30	416
4	Fieldcrest Ave.	SB	No	1	25 mph	03/20/2012	09:30–11:30	366
5	Jersey Ave.	NB	No	1	25 mph	10/21/2011	09:30–11:30	638
6	Jersey Ave.	SB	Yes	1	40 mph	11/01/2011	09:30–11:30	603
7	Jersey Ave.	SB	Yes	1	40 mph	11/02/2011	09:30–11:30	576
8	South Clinton Ave.	NB	Yes	1	40 mph	11/04/2011	09:30–11:30	642
9	South Clinton Ave.	NB	Yes	1	40 mph	11/09/2011	09:30–11:30	724
10	Veronica Ave.	SB	No	1	40 mph	10/07/2011	09:30–11:30	533

The following map shows the locations of eight tests at different four-lane roadways.

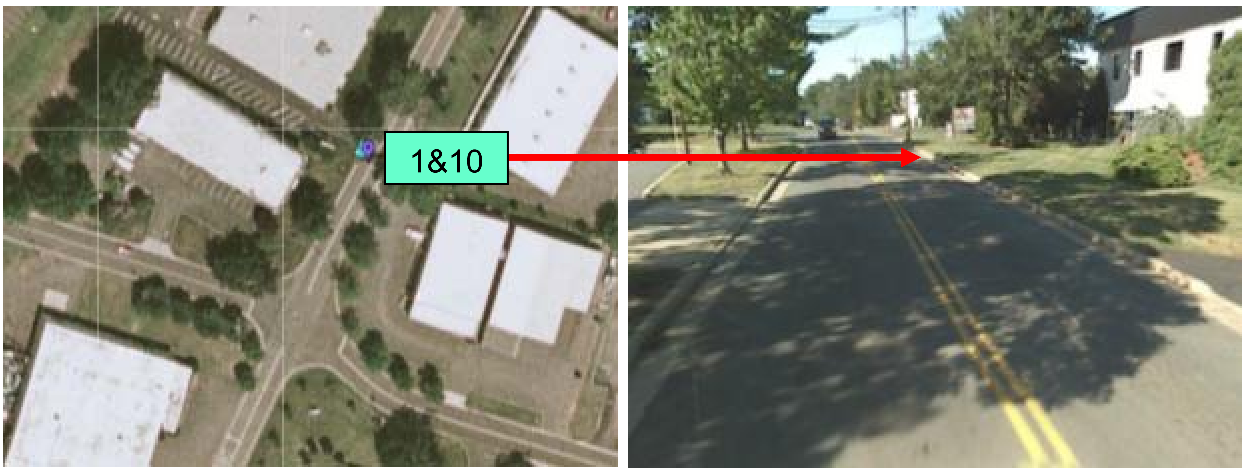


Test	Name	Direction	Shoulder	Lanes	Speed Limit	Date	Time	Total Volume (veh)
1	Ryders Ln.	NB	No	2	45 mph	09/30/2011	09:30–11:30	1,545
2	Woodbridge Ave.	WB	Yes	2	40 mph	11/21/2011	09:30–11:30	1,779
3	Raritan Center Pkwy.	SB	No	2	25 mph	02/28/2012	09:30–11:30	688
4	Raritan Center Pkwy.	SB	No	2	25 mph	03/02/2012	09:30–11:30	624
5	Woodbridge Ave.	EB	Yes	2	50 mph	01/11/2012	09:30–11:30	1,653
6	Route 27	SB	No	2	40 mph	10/11/2011	09:30–11:30	1,366
7	Route 27	SB	No	2	40 mph	10/17/2011	09:30–11:30	1,364
8	Woodbridge Ave.	WB	Yes	2	50 mph	01/17/2012	09:30–11:30	1,518

APPENDIX B: DESCRIPTIONS OF FIELD TEST SITES

Two-lane test sites:

Veronica Ave. This avenue has one lane in each direction. The posted speed limit for the section is 40 mph. There is no shoulder on either side. Field tests 1 and 10 for the two-lane test were conducted on the southbound lane of this site. The following figures show the aerial map of the roadway and lane configuration.



Jersey Ave. The section for test 5 has no shoulder, and the speed limit is 25 mph. The section for tests 6 and 7 has a shoulder, and the speed limit is 40 mph.

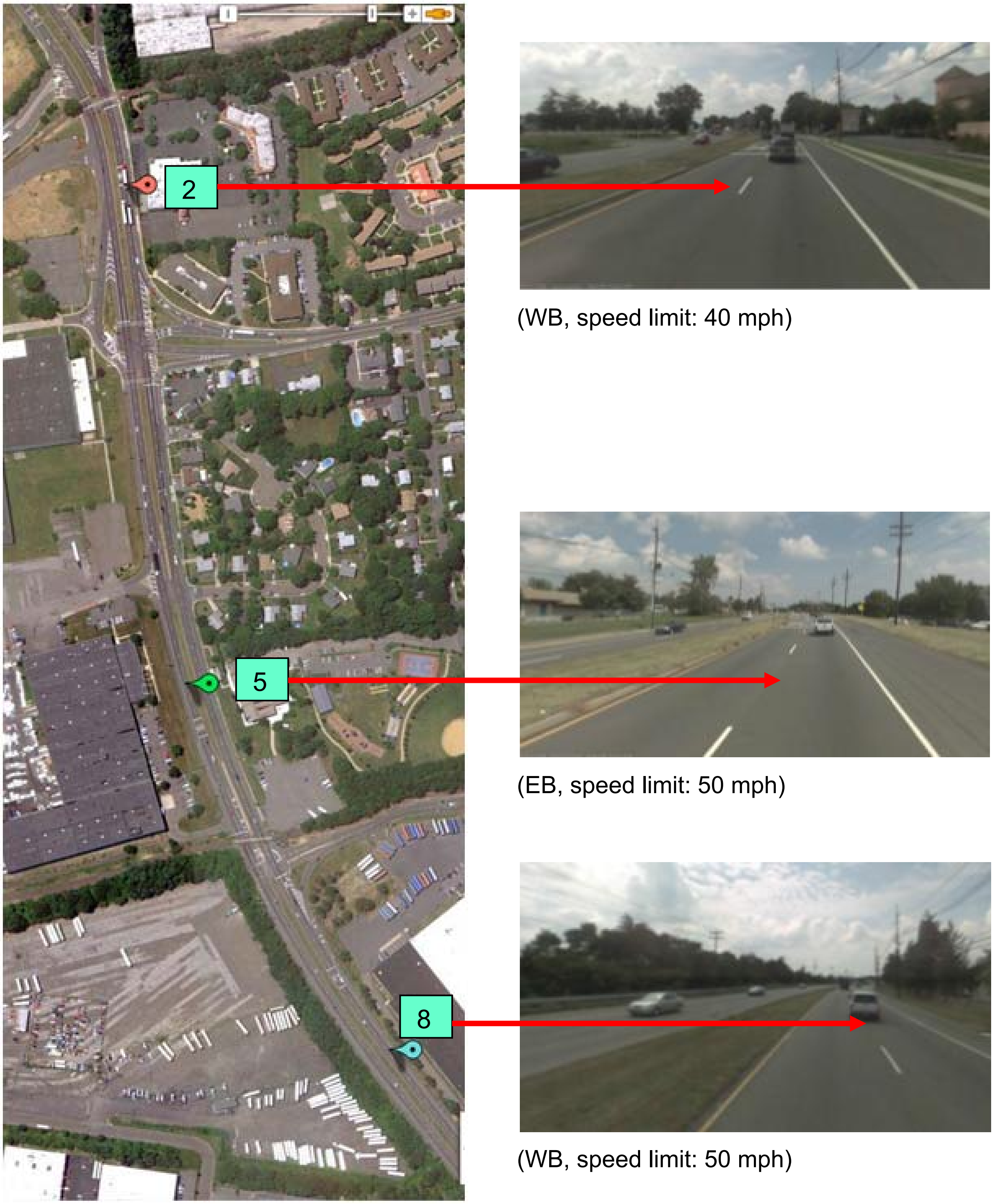
Fieldcrest Ave. This avenue has one lane in each direction. The posted speed limit for the section is 25 mph. There is no shoulder on either side. Field tests 2, 3, and 4 for the two-lane test were conducted on the southbound lane of this site. The following figures show the aerial map of the roadway and lane configurations at each section.

South Clinton Ave. This avenue has one lane in each direction, with a speed limit of 40 mph. Tests 8 and 9 were conducted on the northbound lane of this site. The northbound lane of this section has a shoulder. The following figures show the aerial map of the roadway and lane configurations of the section.

Four-lane test sites:

Ryders Ln. This lane has two lanes in each direction, with a speed limit of 45 mph. There is no shoulder. The first test for deploying control devices on the four-lane roads was conducted at this site. The following figures show the aerial map of the roadway and lane configurations at each section.

Woodbridge Ave. This avenue has two lanes in each direction. There is no shoulder. Tests 2, 5, and 8 were conducted at different sections of the road. The following figures show the aerial map of the roadway and lane configurations at each section.



(WB, speed limit: 40 mph)

(EB, speed limit: 50 mph)

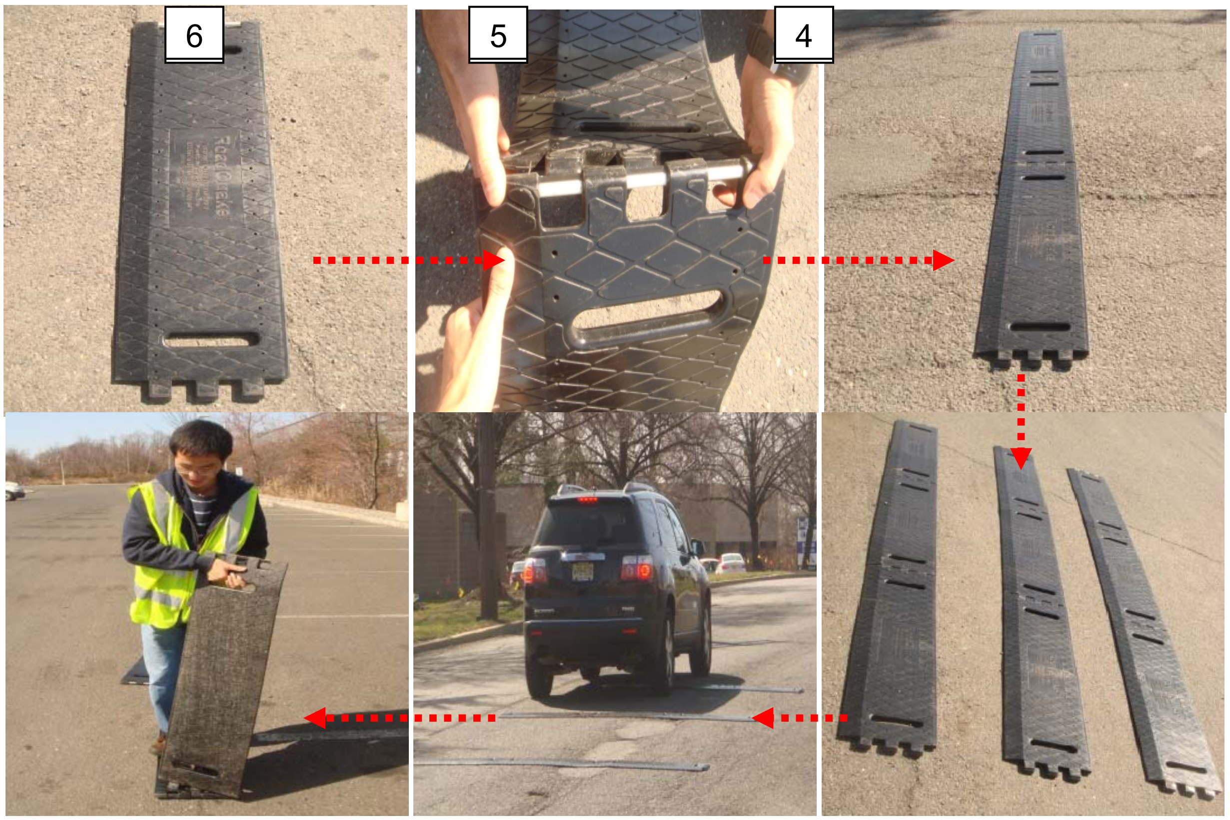
(WB, speed limit: 50 mph)

Raritan Center Pkwy. This parkway has two lanes in each direction, with a speed limit of 25 mph. There is no shoulder. Tests 3 and 4 were conducted on the southbound lane of the road. The following figures show the aerial map of the roadway and lane configurations at each section.

Route 27 (Somerset St). This road has two lanes in each direction. The speed limit is 40 mph. Tests 6 and 7 were conducted on the southbound lane of the section near Somerset St. and School Ave. The following figures show the aerial map of the roadway and lane configurations at each section.

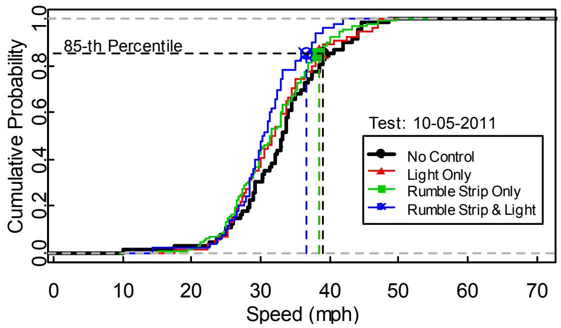
APPENDIX C: ILLUSTRATION OF DEPLOYING TCD

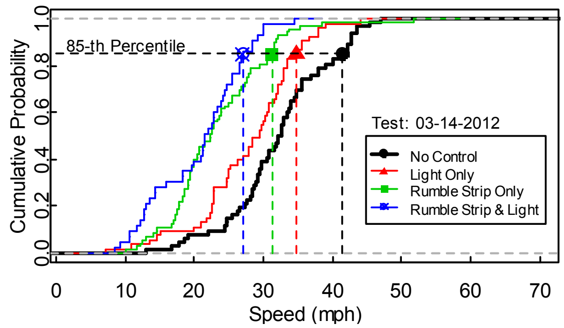
Example of deploying temporary rumble strips. The rumble strips can be easily assembled or disassembled:

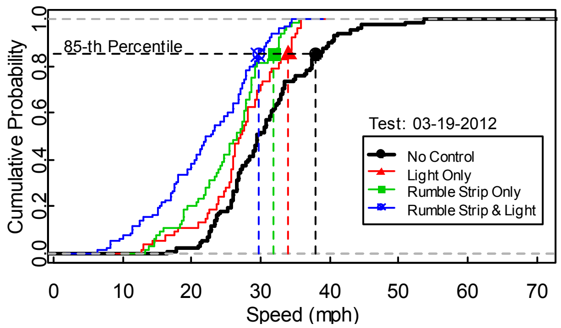


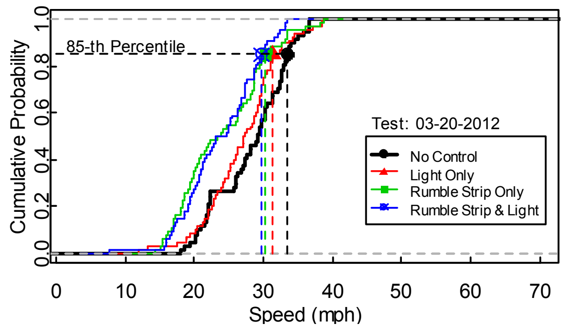
Example of deploying warning lights. The warning lights can be easily deployed on shoulders or curbs:

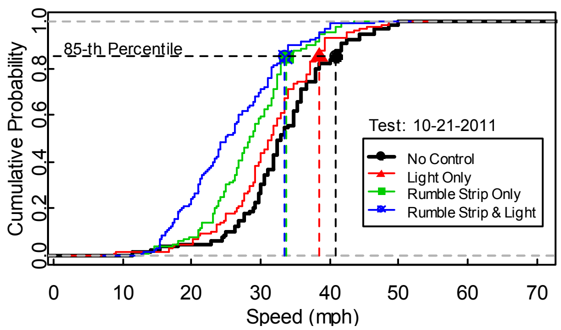
APPENDIX D: SPEED DISTRIBUTIONS FOR TWO-LANE SITES

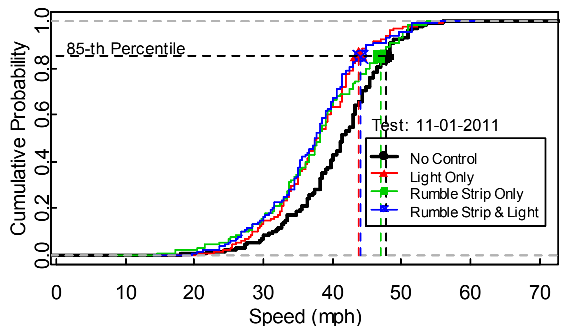


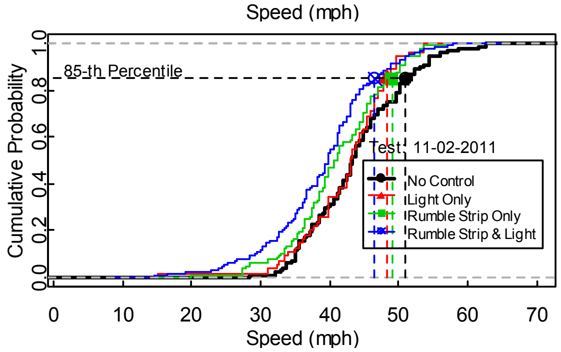


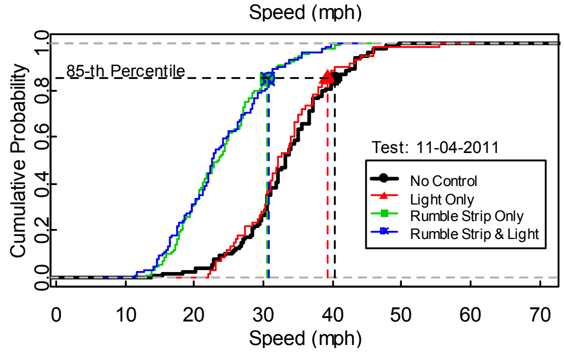


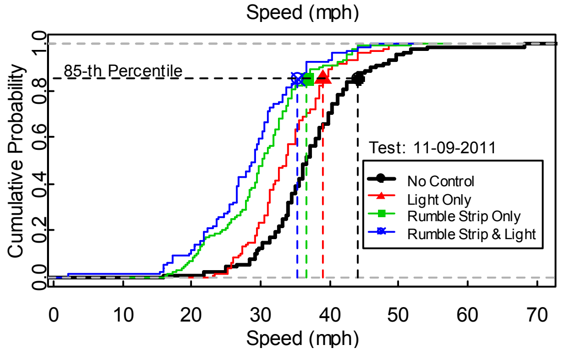


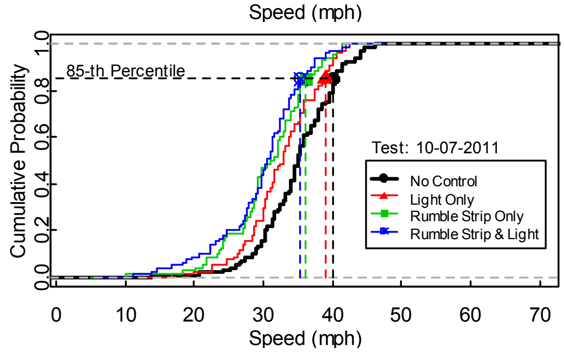






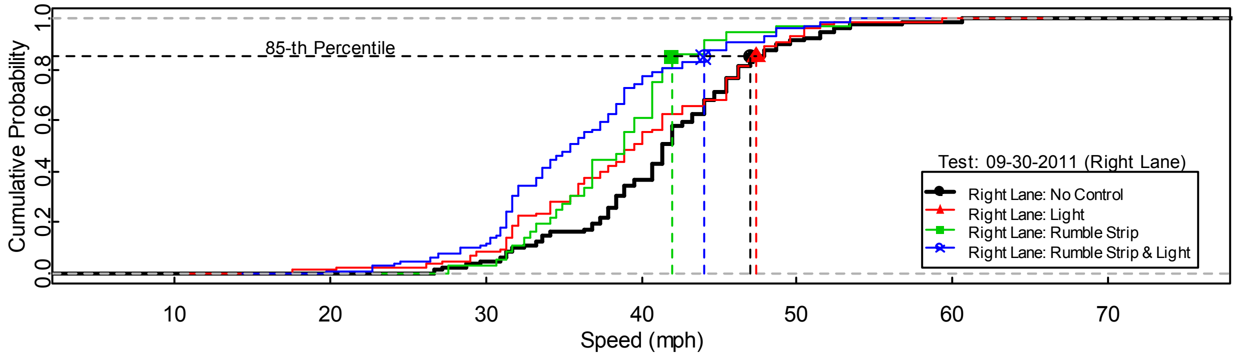


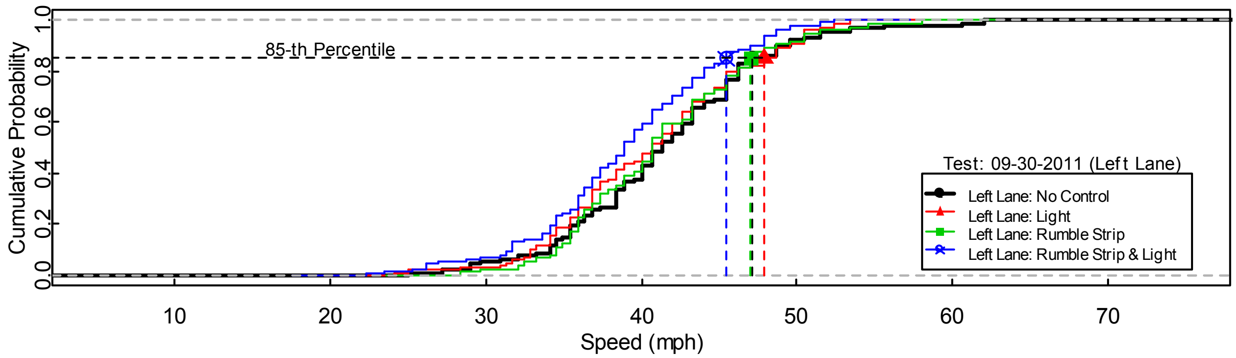




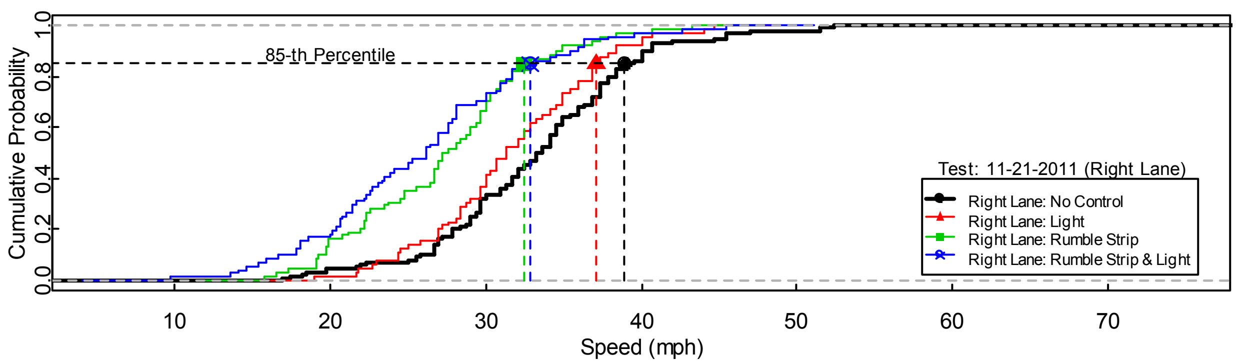
APPENDIX E: SPEED DISTRIBUTIONS FOR FOUR-LANE SITES

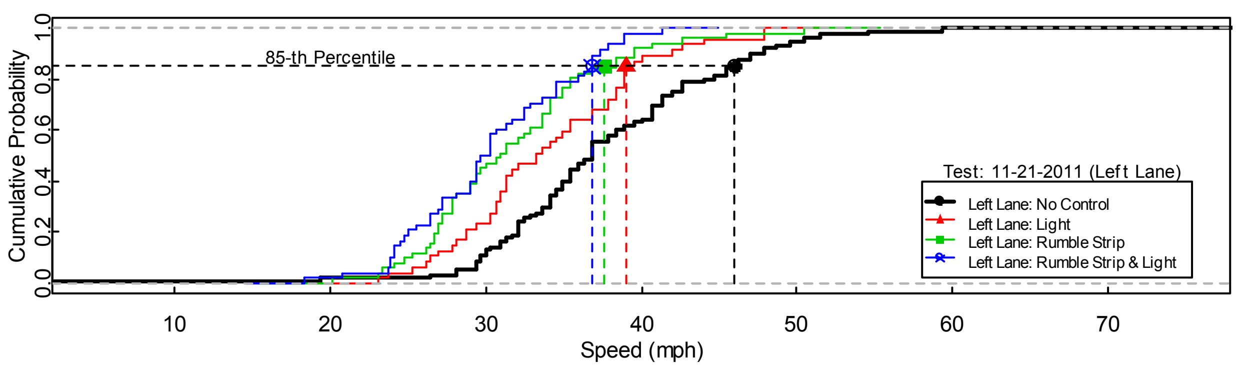
Test 1:



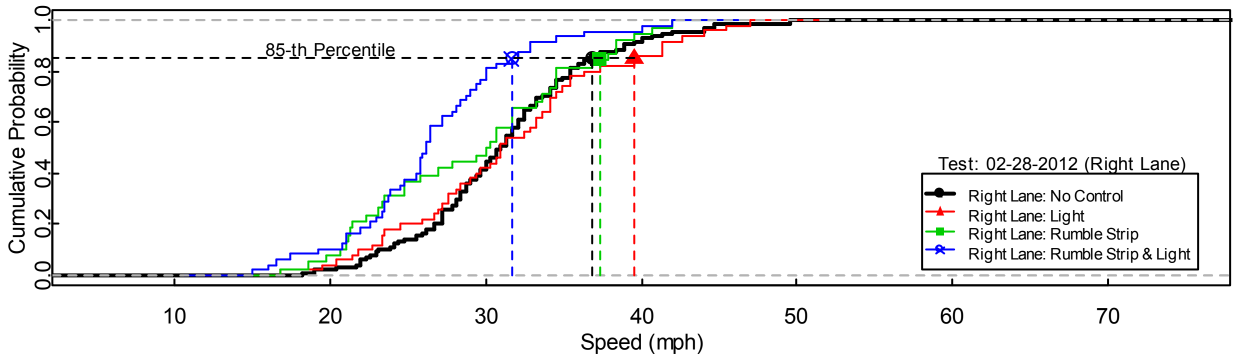


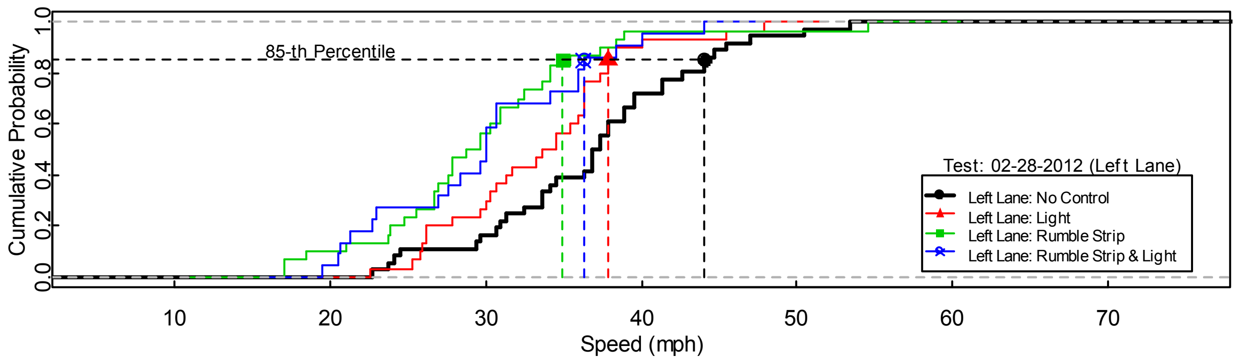
Test 2:



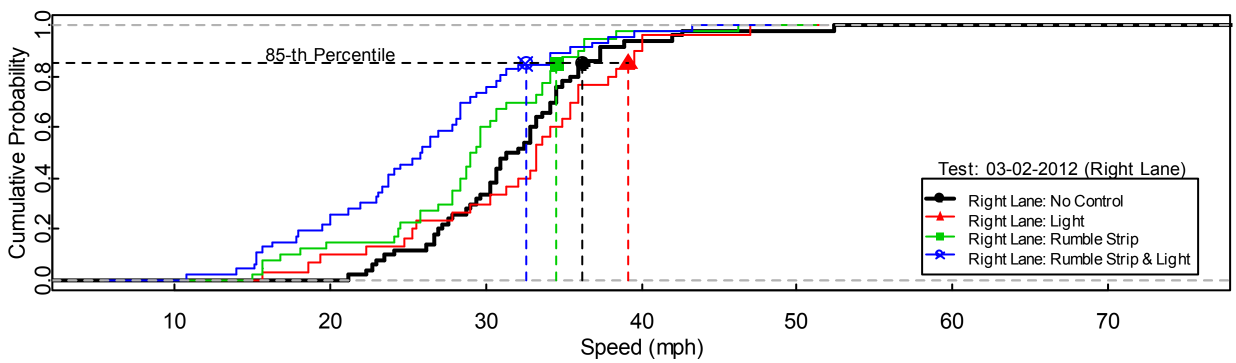


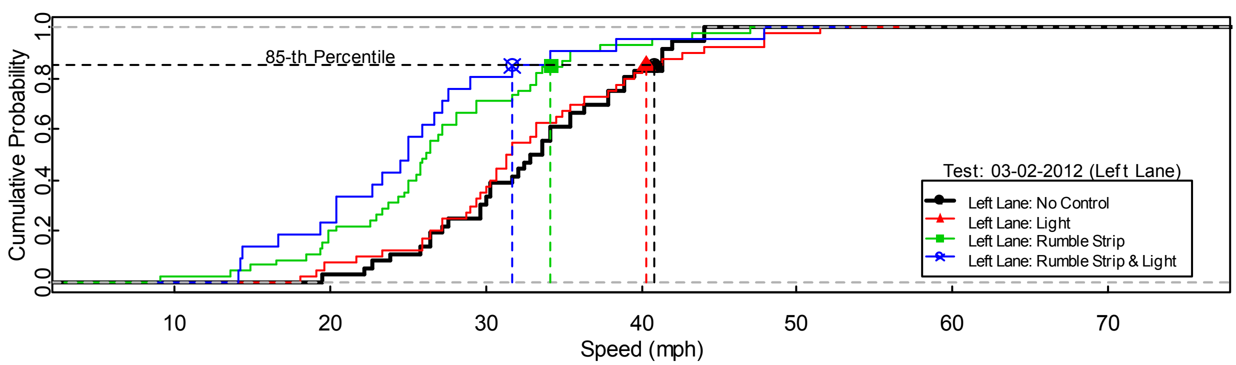
Test 3:


85-th Percentile
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)
Test: 02-28-2012 (Right Lane)
Right Lane: No Control
Right Lane: Light
Right Lane: Rumble Strip
Right Lane: Rumble Strip & Light

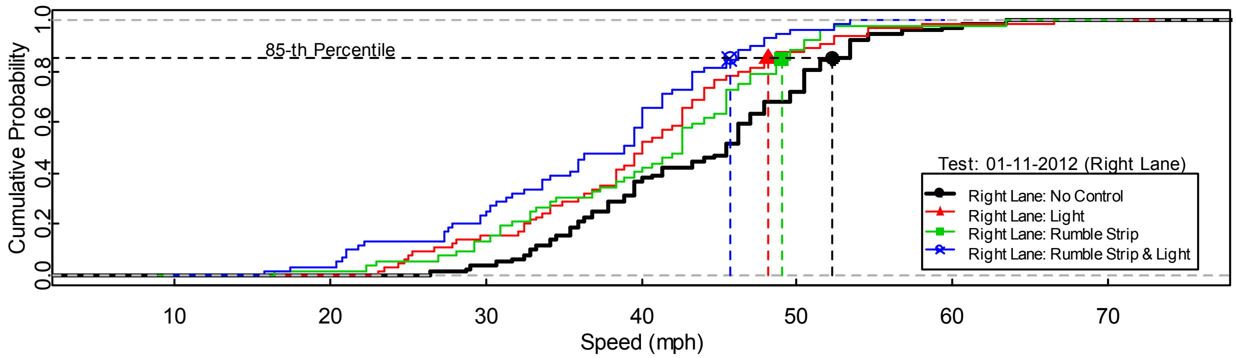

85-th Percentile
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)
Test: 02-28-2012 (Left Lane)
Left Lane: No Control
Left Lane: Light
Left Lane: Rumble Strip
Left Lane: Rumble Strip & Light

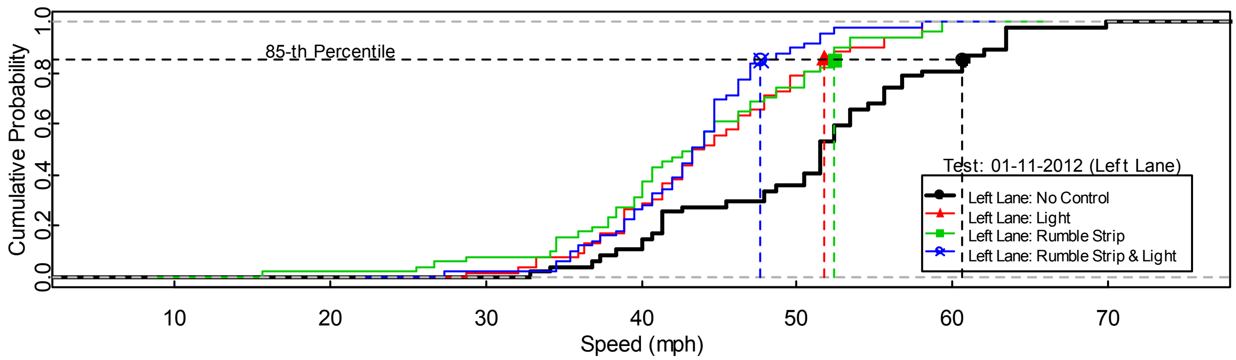
Test 4:


85-th Percentile
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)
Test: 03-02-2012 (Right Lane)
Right Lane: No Control
Right Lane: Light
Right Lane: Rumble Strip
Right Lane: Rumble Strip & Light

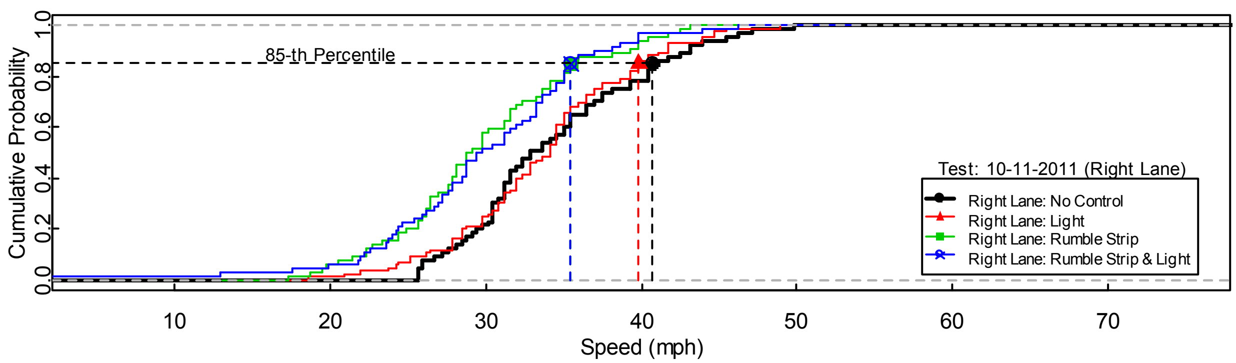

85-th Percentile
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)
Test: 03-02-2012 (Left Lane)
Left Lane: No Control
Left Lane: Light
Left Lane: Rumble Strip
Left Lane: Rumble Strip & Light

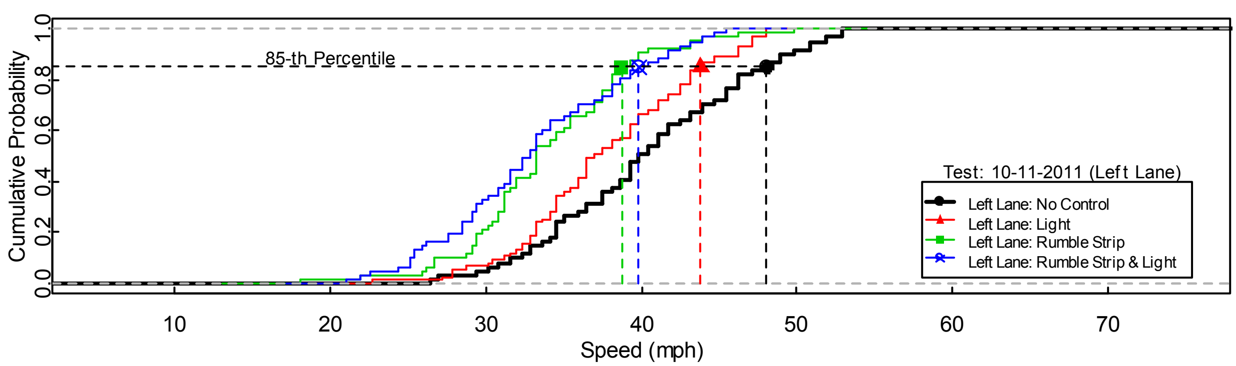
Test 5:


85-th Percentile
Test: 01-11-2012 (Right Lane)
Right Lane: No Control
Right Lane: Light
Right Lane: Rumble Strip
Right Lane: Rumble Strip & Light
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)

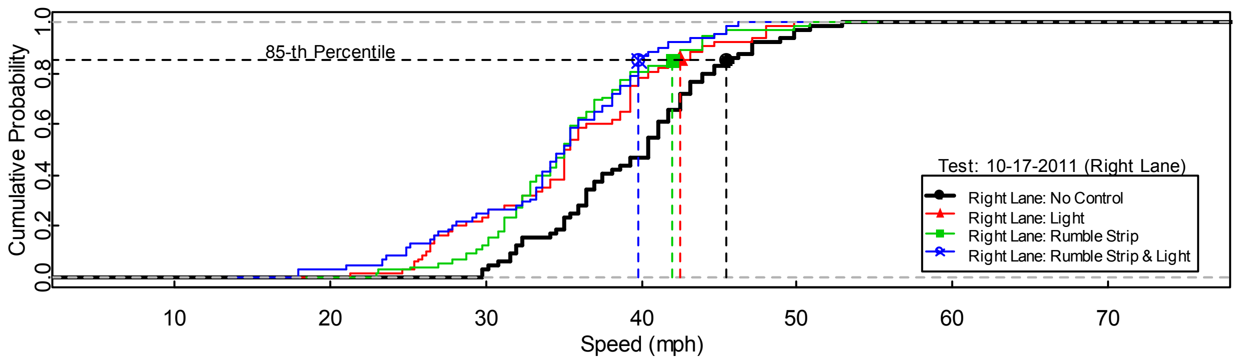

85-th Percentile
Test: 01-11-2012 (Left Lane)
Left Lane: No Control
Left Lane: Light
Left Lane: Rumble Strip
Left Lane: Rumble Strip & Light
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)

Test 6:

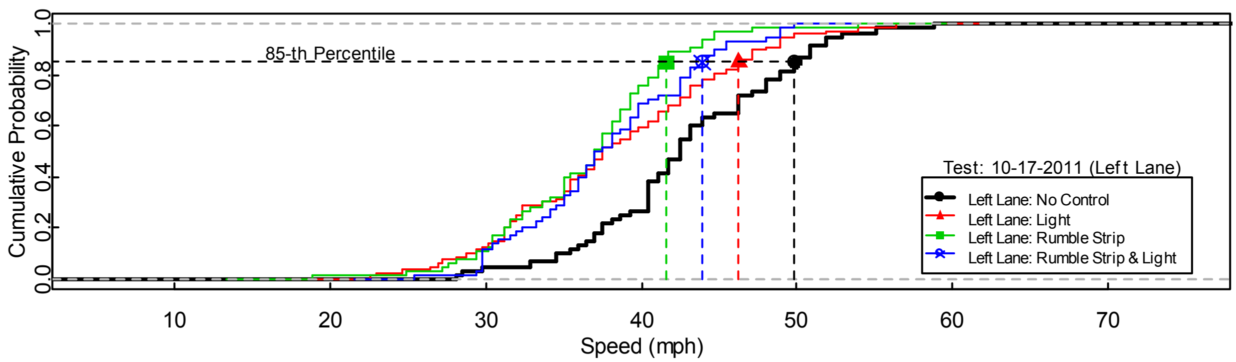

85-th Percentile
Test: 10-11-2011 (Right Lane)
Right Lane: No Control
Right Lane: Light
Right Lane: Rumble Strip
Right Lane: Rumble Strip & Light
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)


85-th Percentile
Test: 10-11-2011 (Left Lane)
Left Lane: No Control
Left Lane: Light
Left Lane: Rumble Strip
Left Lane: Rumble Strip & Light
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)

Test 7:

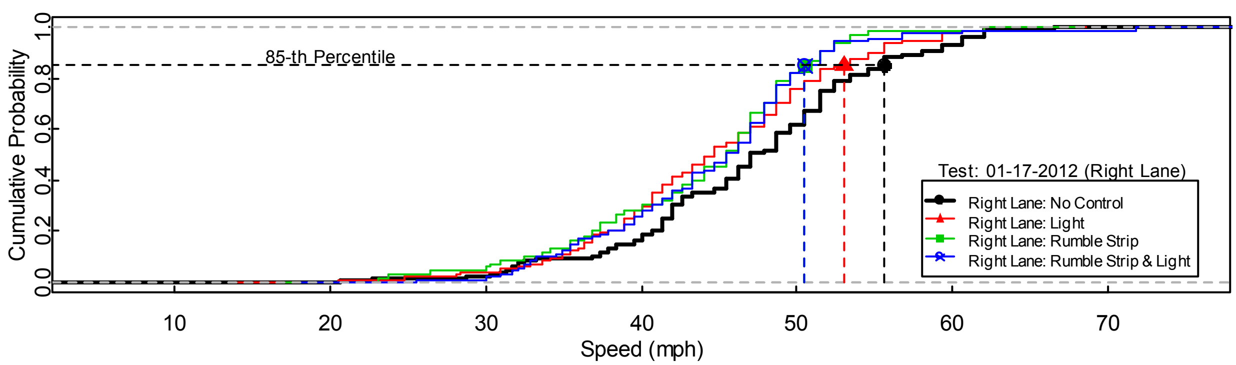


85-th Percentile
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)
Test: 10-17-2011 (Right Lane)
Right Lane: No Control
Right Lane: Light
Right Lane: Rumble Strip
Right Lane: Rumble Strip & Light

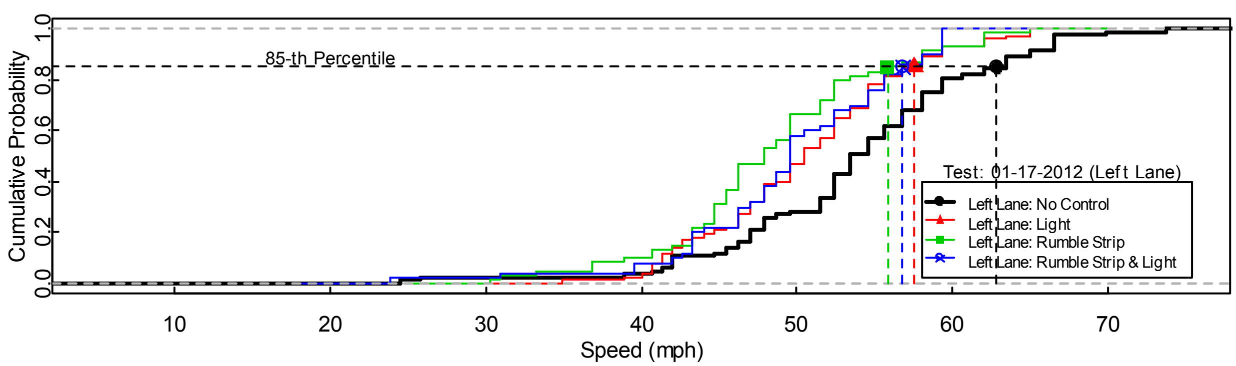


85-th Percentile
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)
Test: 10-17-2011 (Left Lane)
Left Lane: No Control
Left Lane: Light
Left Lane: Rumble Strip
Left Lane: Rumble Strip & Light

Test 8:



85-th Percentile
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)
Test: 01-17-2012 (Right Lane)
Right Lane: No Control
Right Lane: Light
Right Lane: Rumble Strip
Right Lane: Rumble Strip & Light



85-th Percentile
Cumulative Probability
0.0
0.2
0.4
0.6
0.8
1.0
10
20
30
40
50
60
70
Speed (mph)
Test: 01-17-2012 (Left Lane)
Left Lane: No Control
Left Lane: Light
Left Lane: Rumble Strip
Left Lane: Rumble Strip & Light