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Review of Low-Clearance Early Warning Device Options for Illinois

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16. Abstract Bridge or tunnel strikes by over-height vehicles are a challenge to the transportation industry. This problem causes significant economic and social losses to the transportation industry. Low-clearance detection warning (LCDW) is one of the important technological means to address this issue. This research project was sponsored by Illinois Department of Transportation to review different LCDW systems in the current market and to collect information about their adoption in other states. The focus is on understanding the types of LCDW systems available in the market, the technology options, and their effectiveness and costs (including potential vendors).		
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- Keith Donovan, Illinois Department of Transportation
- Alan Ho, Federal Highway Administration
- Geno Koehler, Illinois Department of Transportation
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EXECUTIVE SUMMARY

Bridge or tunnel strikes by over-height vehicles are a challenge to the transportation industry. This problem causes significant economic and social losses to the transportation industry. Low-clearance detection warning (LCDW) is one of the important technological means to address this issue. This research project was sponsored by Illinois Department of Transportation (IDOT) to review different low-clearance vehicle detection and warning systems in the current market and to collect information about their adoption in other states. The focus is on understanding the types of low-clearance vehicle detection and warning systems available in the market, the technology options, and their effectiveness and costs (including potential vendors). The following are the key findings from the research.

1. The history of LCDW (including detection and warning components) can be traced back to the 1970s. The underlying technologies can be divided simply into two categories: passive/sacrificial systems and active detection and warning systems. Passive/sacrificial systems are installed above or on the sides of the road, and they utilize noise and vibration generated upon collision with vehicles to alert drivers. Although these systems have low cost and are simple to operate/maintain, they are considered risky due to physical contact with vehicles, and often fail to attract drivers' attention.

2. Active systems primarily detect over-height vehicles using infrared, laser, or visible light beams. Other types of more recent sensors include ultrasound or GPS location sensors. When the beam is interrupted, roadside signs (such as flashing signs or variable message signs) on onboard sensors inside the vehicle (such as alarms) emit warnings. As the costs for sensors and communication technologies continue to decrease, such active systems (including lidar and camera vision) have gradually become the mainstream of LCDW systems. Those using regular cameras are believed to be even more cost-effective in the future, but large-scale adoption of such new technologies has not occurred yet. As such, technologies based on lidar might be appropriate for IDOT to consider in the near future. This report includes a few popular vendor options in the current market for IDOT to consider.

3. Our survey was sent to all other states' DOTs. Among the 17 state DOTs that responded to the survey, the vast majority of them have already implemented LCDW systems or plan to use them. A few states do not use LCDW systems because cost-effectiveness studies had not been conducted or because bridge/tunnel strikes are not perceived as a problem. Regarding the types of LCDW systems used in other states, no respondents used traditional sacrificial systems. The combination of variable/static message signs and active LCDW systems has become common, with infrared-based LCDW systems being the most prevalent. Most DOTs are satisfied with their LCDW systems, finding that they reduce the number of strikes and are cost-effective, and they generally recommend IDOT to use LCDW systems. The only exception is a state using a laser-based LCDW system that seemingly generates false alarms frequently, has poor performance, and intends to replace it with a lidar-based LCDW system. We did not receive feedback on lidar- and camera-based LCDW systems, possibly because these systems are relatively new.

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CHAPTER 1: INTRODUCTION

Bridge or tunnel strikes caused by over-height vehicles, such as heavy trucks or double-decker buses, occur when these vehicles' height exceeds the clearance underneath the structure; see Figure 1 for an illustration. Research indicates that bridge strikes have been a persistent issue, as evidenced by the increasing number of reported incidents and associated costs over the years. In 2002, the Alaska Department of Transportation reported that the bridge overpass at the Eklutna Interchange on the Glenn Highway was struck frequently enough to require costly repairs (Mattingly, 2003). In 2011, a report from the New York Department of Transportation indicated that bridges in New York State were experiencing close to 200 bridge hits a year (Agrawal et al., 2011). In 2017, the Houlihan Bridge over the Savannah River in Georgia was being struck approximately 50 times per year (Maghiar et al., 2017). In the small town of Champaign, Illinois, viaducts between Washington and Green Streets in downtown Champaign experienced 41 strike accidents in 2012–2017 (Zigterman, 2017). Another historic bridge in Long Grove, Illinois, was reportedly hit by trucks 14 times in half a year, from August 2020 to April 2021 (ABC 7 Chicago, 2021), and that hit number reached 50 by June 2023 (ABC 7 Chicago, 2023).

Such strikes pose grave risks to infrastructure integrity, public safety, and societal costs. The consequences of bridge strikes can range from structural damage to severe injuries, fatalities, and even (for those involving railroad tracks) train derailments. The annual maintenance expenses to repair and service structures damaged by over-height vehicle collisions in the United Kingdom alone can amount to tens of hundreds of pounds, with the average cost per strike ranging from £5,000 to £25,000, according to Nguyen and Brilakis (2016). Strikes caused by over-height vehicles are also a costly challenge in the United States. In 1988, the Mississippi Department of Transportation reported that overweight log trucks struck the Yazoo River Bridge on US Highway 61 every two weeks, with repair costs reaching $200,000 (Hanchey & Exley, 1990). In addition to actual incidents, the fear of low-clearance collisions often forces truck or bus drivers (who are not familiar with certain tunnels or bridges) to reverse their courses or reroute their trips, which often leads to traffic disruption and delay.

Hence, there is a critical need for effective prevention measures against bridge and tunnel strikes. Yet, bridge or tunnel strike problems cannot be eliminated trivially. Measures such as driver training and formulating or revising traffic-related regulations are a big part of the long-term solution. However, on the technical side, low-clearance detection and warning (LCDW) systems can be, and have been, used to provide advanced notification to motorists about low clearances, helping to reduce the frequency of strikes by tall vehicles on these structures.

In response to the challenges posed by bridge strikes, the Illinois Department of Transportation (IDOT) has taken proactive steps to mitigate the risks associated with over-height vehicles. Senate Bill 1653, enacted into law in March 2023, mandates the establishment of a pilot program by IDOT to install early warning devices near bridges or viaducts. Specifically, Section 5 of the Illinois Highway Code is amended by adding the following requirements (605 ILCS 5/4-225 new):

Sec. 4-225. Low-clearance early warning device pilot program. The Department shall establish a pilot program to erect early warning devices on or near bridges or viaducts in this State. Early warning devices may include lidar, radar, visual signals, or additional signage. The Department may work with interested stakeholders to identify bridges and viaducts for the erection of early warning devices on roads outside of the Department's jurisdiction. The Department may work with the University of Illinois on the pilot program. The pilot program shall include, but shall not be limited to, evaluating the effectiveness of early warning devices, developing design specifications, and projecting estimated costs...

(a) A double-decker bus hitting a bridge in Manchester, UK. As a country widely adopting double-decker buses, the UK faces unique challenges of bridge/tunnel strikes.

(b) A local bus passing under a bridge in Champaign, Illinois. The lack of LCDW systems may be a larger threat to drivers that are not familiar with the town.

Figure 1. Photos. Risks of low-clearance collisions under bridges or tunnels.

Sources: Williams (2013); Google Images

The purpose of this project is to help IDOT Bureau of Operations perform a scan and survey of (i) different types of vehicle height detection and early warning devices installed throughout the United States, (ii) their level of effectiveness (if data exists) or ways to measure effectiveness, and (iii) vendors of the technologies that could be used in early warning systems in Illinois. This project will assist IDOT in developing a pilot program for installation of suitable devices on or in advance of bridge or viaduct structures.

In this project, we conducted a technology and literature review to summarize current applications of LCDW systems, their effectiveness and costs, and currently available products and technologies in the market. We then designed a survey questionnaire, which was sent by IDOT to other DOTs to gain practical experience with LCDW systems in other states. These findings are summarized into a comprehensive synthesis of the available literature, results of the state survey, and technology/device options for IDOT. The outcomes of this project will lay the foundation for future research that may develop a guide on where different kinds of early warning devices and technologies may be most effective within Illinois.

The remainder of this report is organized as follows. Chapter 2 reviews the technology and literature on LCDW systems. Chapter 3 documents similar practices in other states. Chapter 4 provides some preliminary recommendations.

CHAPTER 2: LITERATURE AND MARKET REVIEW

Bridge or tunnel strikes by over-height vehicles is not a new challenge. Research and developments on this issue have been conducted and applied for several decades. However, the rapid emergence of information and communication technologies has stimulated rapid development of LCDW technology options in the past 10–15 years, and the market has been converging into a few types of devices. This chapter provides (i) a review of existing reports and studies that are related to LCDW systems and (ii) technology options that have been historically or currently used for low-clearance warning.

LITERATURE REVIEW

An LCDW system includes two parts: (i) a detection system that first detects an approaching over-height vehicle and (ii) a warning system that alerts the driver. The warning system has relatively fewer options, which can be divided mainly into sacrificial systems (such as metal chains that trigger an alarm through vibration and sound during vehicle collision), roadside static signs (sometimes including flashlights) and variable message signs, as well as in-vehicle devices such as flashing lights and loudspeakers. Figure 2 summarizes some of these roadside warning systems. The detection system has many more options, including sacrificial systems, infrared, laser/lidar, ultrasonic, camera and computer vision, and GPS/vehicle-based systems. They will be discussed in detail in the Market Review section.

An earlier NCHRP synthesis summarized two categories of clearance warning systems: passive versus active (Bowman, 1993). Passive systems focus on simply broadcasting information, such as vertical clearance heights or the existence of a low clearance to all drivers. Active devices focus on giving vehicle-specific warnings to a driver if his or her vehicle poses a threat to low-clearance bridges or viaducts. In a 2003 survey, Alaska DOT (Mattingly, 2003) further categorized LCDW systems into three categories:

A. Rigid passive overhead devices, which “use an immovable rigid crossbeam set across the road … to warn the trucks of their over-height condition when the truck strikes the crossbeam” (Mattingly, 2003, p. 4)

B. Nonrigid passive overhead devices, which use a set of flexible items (e.g., chains) suspended from a span wire that will make warning sounds if struck by a vehicle (Hanchey & Exley, 1990)

C. Active detection and warning systems, which may utilize infrared beams, lidar, or radar for detection and audible bells, signs with flashing beacons, or in-vehicle devices for warning. The alarm will activate when the beam or sensors’ wave is discontinued by the over-height vehicle. In the newer camera + computer vision systems, computer algorithms will detect these vehicles from camera images.

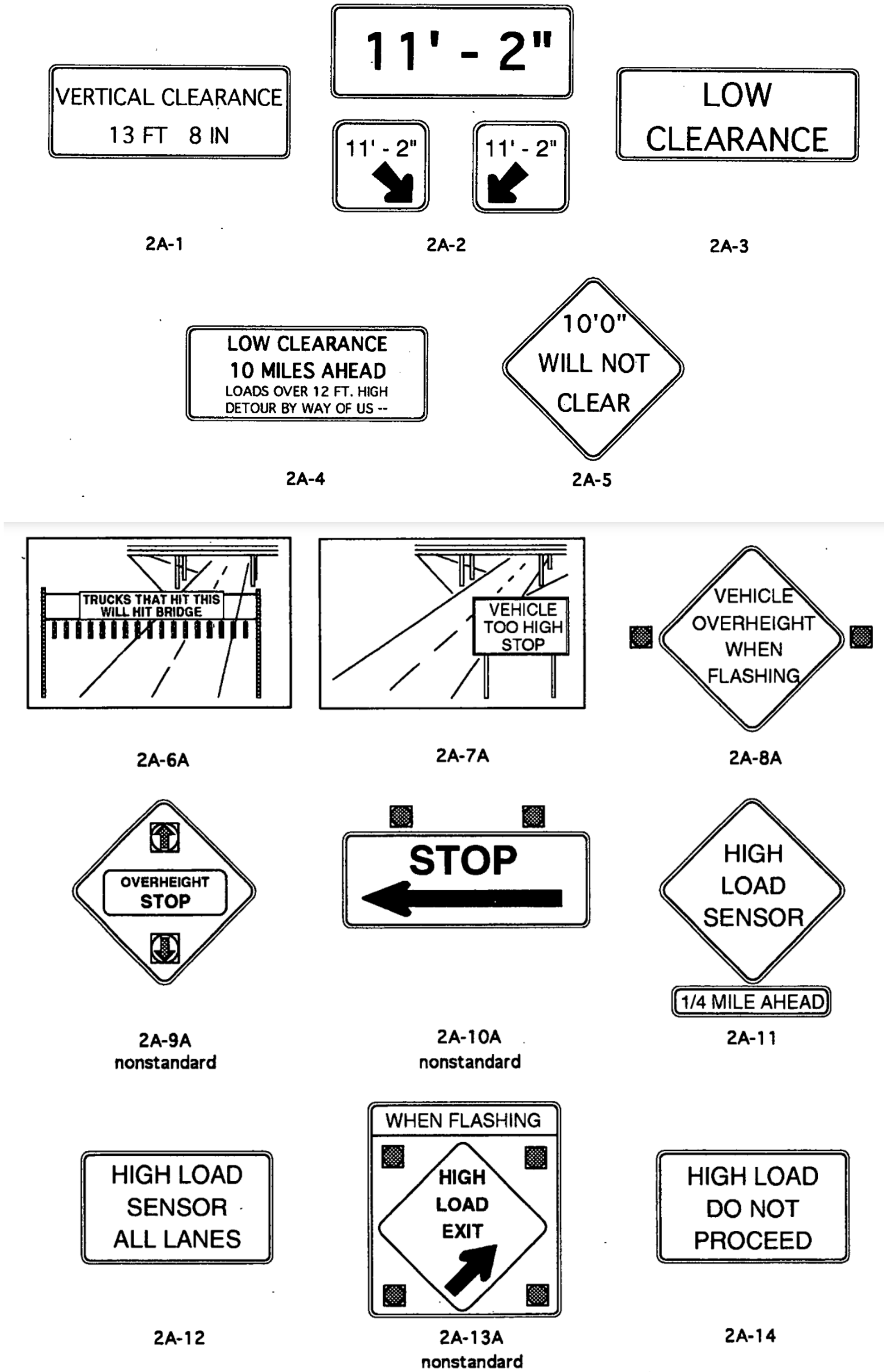


Figure 2. Illustration. Earlier roadside clearance warning devices.

Source: Bowman (1993)

The Alaska DOT survey also reported that the over-height warning systems did seem to result in fewer over-height incidents in most of the surveyed states. Table 1 summarizes some of the findings. From the survey, we know that laser/infrared systems seem most effective, but no system was perfect, and all systems face notable maintenance and operation costs.

Table 1. Strategies and Technologies to Reduce Bridge Strikes

Solution	Power Req'd	Initial Cost	Annual M&O Costs	Assessed Effectiveness	Problems
Warning signs and lights	Yes	\$0.2–3K	\$200–500	Unknown	Unknown
Passive-rigid	No	\$2–20K	\$0–500	Slight reduction	Possible damage to truck and other nearby vehicles
Passive-nonrigid	No	\$2–35K	\$0–500	Slight reduction	Inaudible over road noise for drivers
Laser/Infrared w/ signs	Yes	\$7–70K	\$0.2–1.5K	Reduction	False Positives

Source: Mattingly (2003)

Later, in 2014, Texas DOT conducted an overview of the effectiveness of warning signs near consecutive bridges (Carlson et al., 2014), but their study mainly focused on passive signs. As such, the findings from these existing studies are not conclusive because the studies were conducted many years ago, and hence (i) newer technologies, especially those related to lidar, radar, and other technologies, might have emerged into the market, and (ii) many state DOTs might have tried some of these devices and reported their effectiveness. We will begin this chapter by introducing different types of devices and providing some sample vendors for reference. In the next chapter, we will discuss the results obtained from surveys with other states.

In more recent years, New York State DOT (Agrawal et al., 2011) and Georgia DOT (Maghiar et al., 2017) published reports on their states' LCDW-related research, which not only assess the LCDW devices at those times, but also discuss (i) the status quo of bridge strikes in these states and (ii) the root reasons behind the strikes and possible policy solutions. For example, the 2011 NYSDOT report, while mainly focusing on analysis of bridge hits, summarized three types of LCDW systems that they are interested in pursuing, including HISIK 450 by SICK, Double Eye Z-Pattern by Trigg Industries, and Han-D Man & Co (passive flexible arm). The Georgia report provided a survey of the LCDW systems, including laser- and lidar-based technologies that were starting to be adopted around that time.

The literature review also found several relevant academic papers. The earlier papers, such as Hanchey and Exley (1990) and Schesser and Tanner (1980), provide historical contexts for bridge/tunnel strikes and the basic architecture of LCDW systems. These works cover the content of sacrificial/passive systems, which are considered outdated with the proliferation of active LCDW systems (especially when sensors' costs decrease), as well as early practices of active systems. The fundamental principles of active systems have remained consistent over the decades, although new types of sensors and sensor alternatives continue to be developed. A recent review by Nguyen (2016) has been particularly helpful in terms of summarizing the most recent trends in this field, including developments in lidar and camera/computer vision types of technologies. Although infrared-based active LCDW systems still dominate the market, these new technologies have demonstrated advantages in both reliability and cost.

TECHNOLOGY REVIEW

This section largely follows the three categories of LCDW devices and summarizes their current development status.

Passive/Sacrificial Detection Warning Systems

Although rarely or never used today, passive or sacrificial systems were the main types of equipment for low-clearance warning in earlier years. The so-called passive/sacrificial systems rely mainly on physical contact devices rather than sensors or even electricity. This system consists of horizontal bars (rigid, also called a "headache bar") or chains (nonrigid) suspended above the road at a height comparable to the bridge or tunnel clearance. See Figure 3 for an illustration. When an over-height vehicle hits these devices, they generate sound and vibration to make drivers aware of the risky situation.

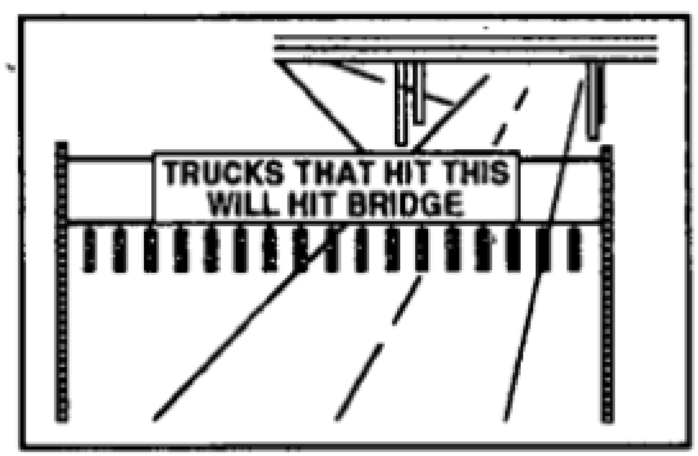


Figure 3. Illustration. A nonrigid passive system.

Source: Bowman (1993)

Traditional passive/sacrificial systems are purely mechanical, involving no electronic components or power supply. Therefore, these systems not only have lower costs, but also are straightforward to maintain and repair. However, such systems suffer from clear drawbacks, too. Henchy and Exley (1990) discussed the shortcomings of such passive systems when they were applied in Mississippi, where one of the main industries is forestry. There were a large number of logging trucks on the roads. When the rigid passive systems were used in the late 1980s, they posed an extreme danger of not only damaging the vehicles, but also dislodging the logs onboard. When they tried nonrigid passive systems, which rely on noise (from the vehicle hitting the chain) to alert drivers, they were found to be almost ineffective to a driver in a noisy cab of a logging truck.

It is particularly noteworthy that rigid passive systems pose a significant safety threat to over-height buses as well. In Wuhan, China, two double-decker buses collided with the same “headache bar” (rigid passive system) within six months, causing severe economic and safety concerns.

Active Detection and Warning Systems

The active system utilizes sensors to detect over-height vehicles and uses communication technologies to issue warnings. Compared to rigid passive/sacrificial systems, using sensors instead of the so-called “headache bar” can significantly reduce the risk of vehicle damage or cargo loss, while modern warning devices combining sound and light are more effective at capturing a driver’s attention than inaudible nonrigid systems. Active systems have been documented in reports dating back to the 1970s, but at that time, the high cost of sensors limited the adoption of such systems. With the gradual decrease in sensor costs, active systems have become increasingly popular. The types of technologies for low-clearance detection include infrared, laser, and lidar. See Figure 4 for an example. Ultrasonic sensors are mentioned in some vendors’ brochures but remain rare in the market. In recent years, some studies have started to propose using computer vision algorithms to process ordinary camera images. However, lidar and computer vision (CV) are relatively new technologies, and they are still less popular than laser and infrared in the current market. (Among our survey respondents, as discussed in Chapter 3, only Tennessee DOT adopted a CV + camera system, provided by Axis Communications.)

In addition to the cost mentioned above, the biggest challenges faced by active systems are maintenance and false active/missed detection. In addition, infrared and laser sensors exposed to outdoor environments are relatively fragile, often leading to higher maintenance costs. In the next subsection, we review a few leading systems and their vendors.

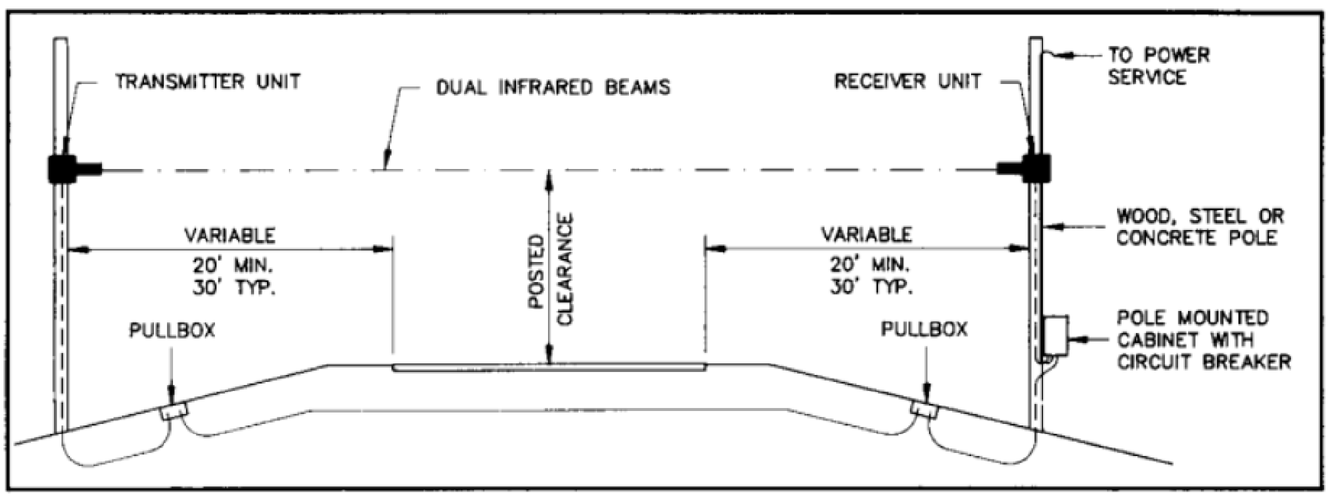


Figure 4. Schematic. An early infrared active LCDW system.

Source: Hanchey & Exley (1990)

Market Review—Sample Vendors and Products

This section briefly explains a few current LCDW systems and their vendors, which are summarized in Table 2.

Table 2. Sample of Vendors in the LCDW Market

Vendor	Technology	Link
SICK AG USA	Photoelectric (+infra-red)	https://www.sick.com/ag/en/catalog/products/analyzers/overheight-detectors/hisic450/c/g57488
Comark	Infrared	https://www.comarkud.it/wp-content/uploads/2019/03/RAM200-Altezza-EN-v2-abbondanze-.pdf
Comark	Ultrasonic	https://www.comarkud.it/wp-content/uploads/2019/01/CATALOGO-COMARK.pdf
MVIS	Ultrasonic	http://www.m-vis.co.uk/wp-content/uploads/2017/03/MVIS-SolutionSheet_IntellicomeSentryVMS.pdf
Coeval	Infrared	https://www.coeval.uk.com/wp-content/uploads/2022/05/Coeval_OVDS_Product-Brief.pdf
Trigg	Infrared/Visible Beam	https://www.triggindustries.com/wp-content/uploads/2022/09/trigg-ohvds-manual-a2z-pattern.pdf
HyPoint Solutions	Lidar	https://www.promiles.com/hawkscan/
Axis Communications	Camera + CV	https://www.axis.com/products/axis-object-analytics
GreenRoad	GPS	https://greenroad.com/
Laservision	Waterscreen	https://www.laservision.com.au/portfolio/softstop/

SICK HSIC450

SICK AG is a leading solutions provider for sensor-based applications in the industrial sector. It is a German company, and the US branch is in Minneapolis. As shown in Figure 5 and Figure 6, the SICK HISIC450 over-height detection system is available to be installed in tunnel entrances, low underpasses, or bridges with low clearance. When a vehicle triggers both photoelectric switches of the HISIC450, stop and alarm signals will activate. According to SICK, HISIC450 can detect vehicles up to 100 km/h and remain reliable under challenging weather conditions, including rain, snow, and dust clouds.

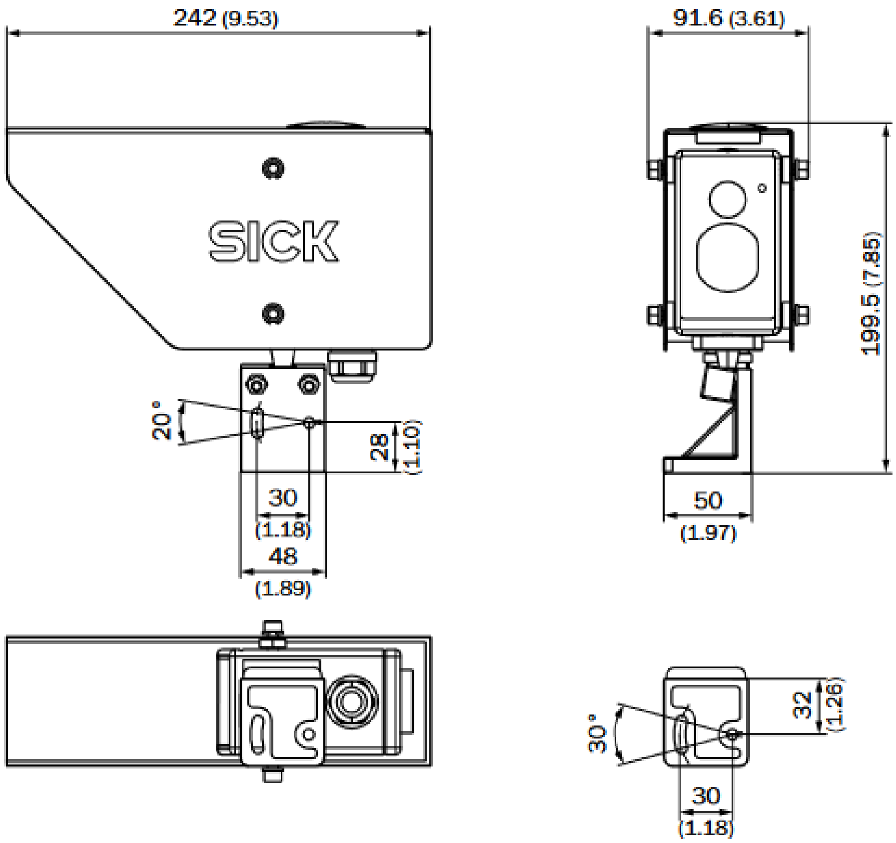


Figure 5. Schematic. Design specifications of SICK HSIC450.

Source: SICK AG USA Brochure (n.d.)

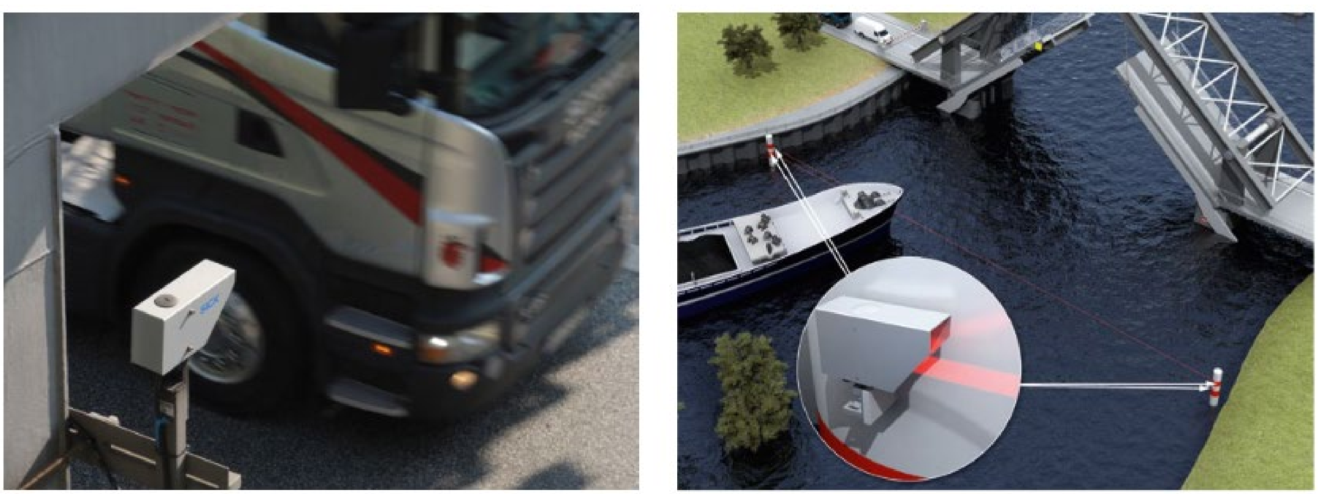
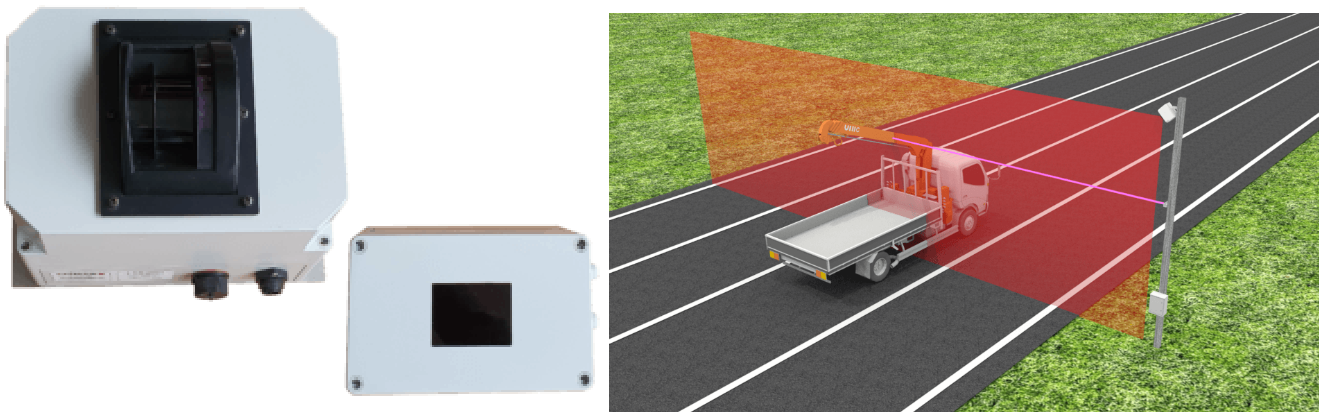


Figure 6. Photos. Application illustration of SICK HSIC450.

Source: SICK AG USA Brochure (n.d.)

Comark RAM110

Comark is an Italian company founded in 1994 and specializes in traffic monitoring and parking systems. The RAM series contains different over-height vehicle-detection solutions developed by Comark, and RAM110 is the flagship. As shown in Figure 7, Comark RAM110 is made up of a laser scanner and a single-beam laser device. The laser scanner can cover up to three lanes, detecting the presence and the height of a vehicle. The single laser beam provides accurate detection of small objects up to 20 m. To reduce the false active alarm, the system will allow small items to pass through, only activating the alarm when both the small objects and the presence of the vehicle are detected together. Compared to the infrared-based systems, according to Comark, the RAM series is easy to install, because it can be placed curbside, and there is no need of a transmitter and a receiver.



Technology	Laser Scanner + Single Beam Laser
Laser class (both)	Class 1
Opening angle	Laser scanner 96° Sinlge Beam Laser 0,5°
Detection Range	Laser Scanner 25-35 mt Single Beam Laser 50 mt
Frequency	Laser Scanner 60Hz Single Beam 500-2000Hz
Minimum width of object	50-100 mm
Maximum vehicle speed	150 km/h.
Data line	Ethernet
Alarm	Relay, D/O, software
Power supply	12 ÷ 28 Vdc
Protection	IP65
Temperature range	RAM110: -20°C ÷ +50°C RAM110T: -40°C ÷ +60°C

Figure 7. Photos. Design specifications and application illustration of Comark RAM110.

Source: Comark Brochure (n.d.)

The Ram series is modular. Both the scanner and the single-beam device can be provided and used separately or together. The customer may select the combination based on their needs. The RAM series is very likely installed on Yas Island Tunnel, UAE, as the multiple traffic detector for the project.

Comark US 6300

The US 6300 device is an entry-level ultrasonic detector developed by Comark. See Figure 8 for an illustration. According to Comark, it can be used in vehicle height detection. Like the RAM series, the US 6300 device can also be used together with other detectors, including infrared detectors, doppler radar detectors, etc.

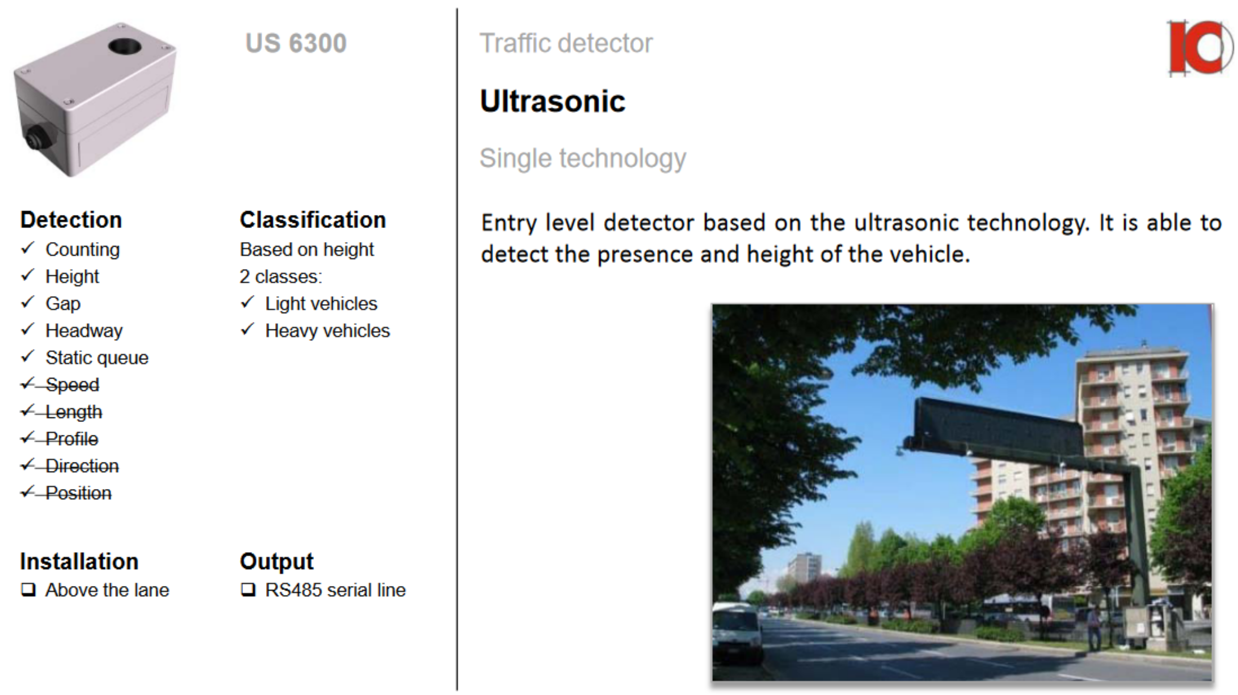


Figure 8. Illustration. Design specifications and application illustration of Comark US 6300.

Source: Comark (n.d.)

MVIS Intellicone Sentry

Intellicone Sentry is one of two ultrasonic-based systems we found for over-height vehicle detection. It has a line-of-sight range of at least 50 m. See Figure 9 for an illustration. The Sentry was adopted on UK Highways Agency's M62 and M1 J39-42 Smart Motorway project. Scaffolding built for this project increased the risk of over-height vehicle collisions and will result in road-recognized injuries and even deaths. When Sentry is activated, accompanying variable message signs will remind drivers to change routes in a timely manner. At the same time, workers on the scaffolding receive an audible alarm to escape to a safe location. According to construction contractors, Sentry is more effective than traditional solutions. In its first week of installation, Sentry successfully stopped three over-height vehicles from crashing.

Figure 9. Photos. Application illustration of Intellicone Sentry.

Source: MVIS (n.d.)

Coeval Over-Height Vehicle Detection System

The British company Coeval provides an infrared-based system for over-height vehicle warning, as shown in Figure 10. Similar to the SICK system, this product also uses beams (users may choose either two or four beams) to detect over-height vehicles and alarms the driver through variable message signs. Coeval emphasized that this product can be installed in multiple environments. It is robust and clear during all seasons, and the system can be controlled through the Cloud.

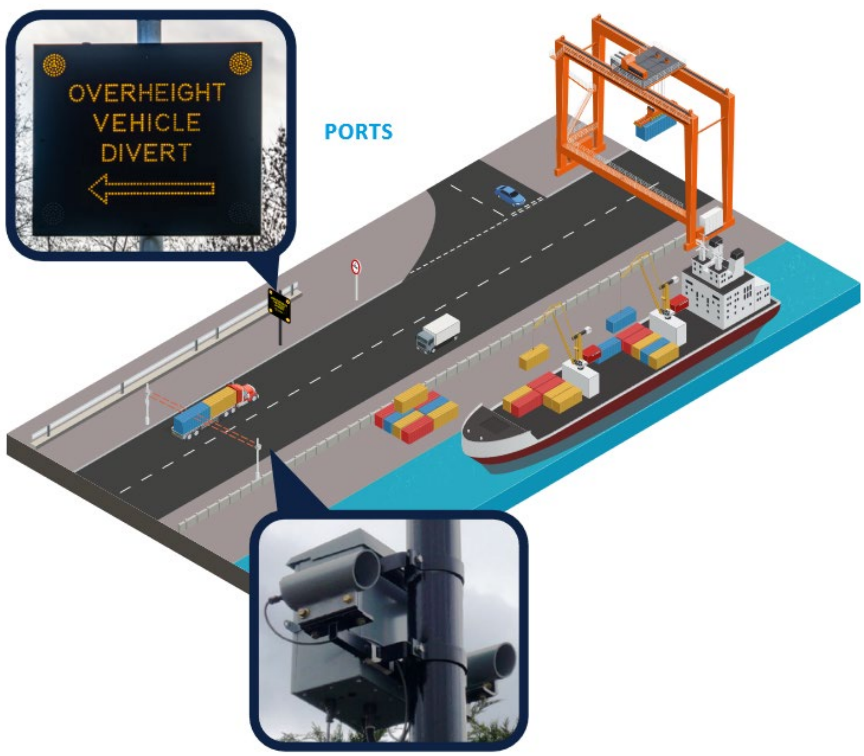


Figure 10. Illustration. Application illustration of Coeval.

Source: Coeval (n.d.)

Trigg "Z-Pattern" 340x-Z Red/Infrared

Trigg Industries is a Virginian company specializing in industry-standard over-height vehicle detection systems since 1965. It is the only vendor that specializes in this specific area. Its over-height detection system is made up of three models: 3401/2/3-Z. The 3403-Z model is the only system we found that uses a visible red beam, while the 3402/3 model uses an infrared beam. See Figure 11 for an illustration.

The "Z-Pattern" Concept is the core of these systems: "Z-Pattern Concept illustrates the detection methodology differences between models and orientation of the different eyes with respect to each cabinet. All orientation is given from the Master cabinet viewing the remote. The terms 'IR-A' and 'IR-C' refer to different modulations of the infrared source. In each model, the Master cabinet contains all control, fault detection, and alarm electronics. A two-conductor shielded wire carries the signal from the Remote cabinet detector back to the Master cabinet" (Trigg, n.d.). Trigg's product is widely adopted among many US states.

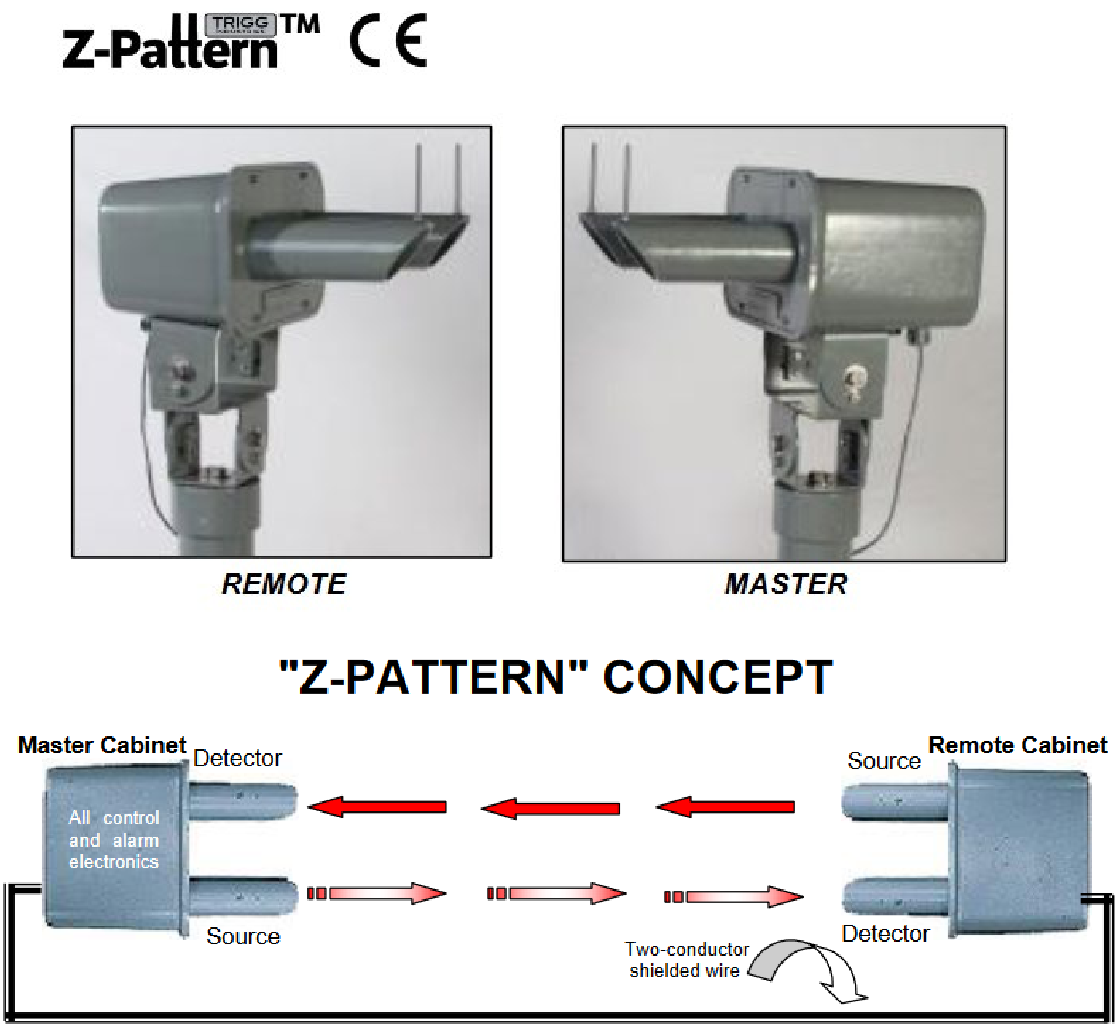


Figure 11. Illustration. Design of Trigg "Z-Pattern" 340x-Z Red/Infrared.

Source: Trigg (n.d.)

HyPoint Solutions HawkScan

The HawkScan Vehicle Classification and Measurement System is a lidar-based system. It measures and documents the length, width, and height of vehicles automatically and generates a 3D model based on the data. Also, the solution enables the counting of axles, axle spacing, and vehicle type. See Figure 12 for an illustration.

Figure 12. Illustration. HyPoint Solutions HawkScan.

Source: HyPoint Solutions (n.d.)

Lidar-based LCDW products like HawkScan can measure vehicle heights and integrate them with existing warning systems. Note that IDOT proposed procuring HawkScan in 2021 and hoped to include it as part of the FHWA State Transportation Innovation Council Incentive program. According to IDOT, one of the main purposes of procuring this system is to prevent bridge strikes. Unlike traditional LCDW systems, the HawkScan procured by IDOT appears to rely on "station operators view every passing truck's dimension in real-time" rather than using warnings to prompt drivers to stop.

AXIS Object Analysis

AXIS Object Analytics, provided by Axis Communications, is a "suite of AI-based analytics for actionable insights" (Axis, n.d.) that comprehensively analyzes and identifies humans and vehicles, suitable for various scenarios, although LCDW is not listed as one of their applications on their website. Besides providing accurate analysis through AI-trained algorithms, another highlight of this system is its low cost. Object Analytics comes pre-installed on compatible Axis network cameras, eliminating the need for additional (and expensive) servers, as well as the traditional infrared or laser sensors used in LCDW. See Figure 13 for an illustration. Furthermore, the same camera can run different detection programs simultaneously in the same scene, avoiding the purchase and use of multiple single-function detection systems.

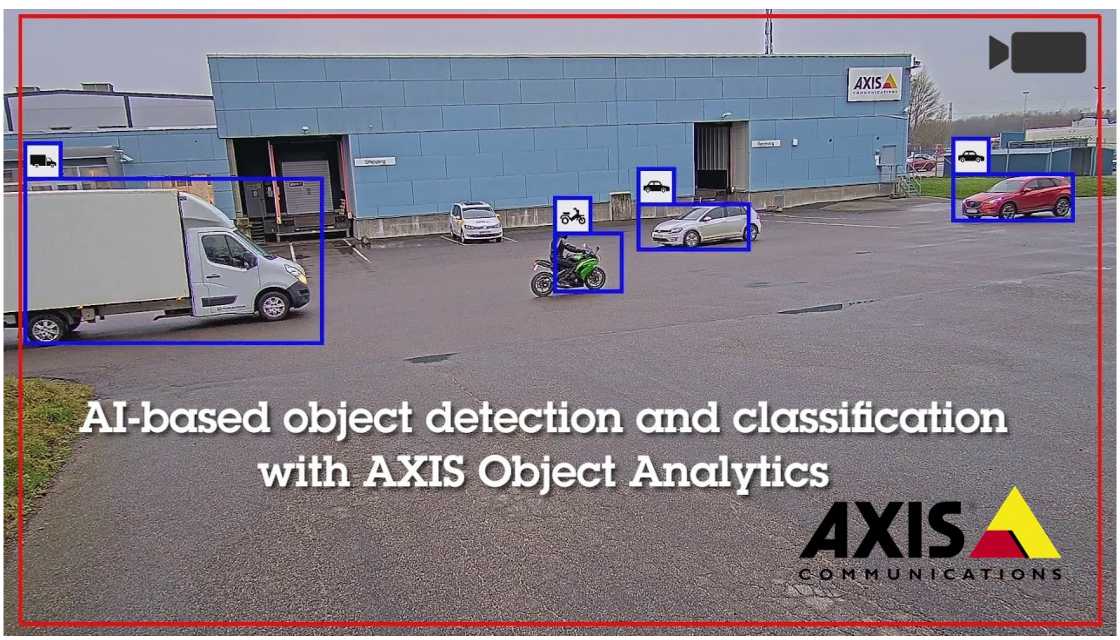


Figure 13. Illustration. AXIS Object Analysis.

Source: AXIS (n.d.)

The Tennessee DOT adopted the AXIS Object Analytics system—the only state DOT that has adopted a non-traditional active LCDW based on a computer vision + camera solution.

GreenRoad

GreenRoad is a leading global provider of digital fleet safety telematics and driver behavior management solutions. The low-clearance collision alert is an enhanced feature of the GreenRoad Edge Real-time Driver Coaching device. Serving as the trigger point for system alerts, a custom list of bridge and bridge access point locations is loaded into GreenRoad Central™ as landmarks. Information input for each bridge/access point includes the bridge name, location, hazardous direction, safety clearance, and types of voice messages. When vehicles approach hazardous bridges, the system issues audible and visual alerts while also offering alternative routes. See Figure 14 for an illustration.

Figure 14. Illustration. GreenRoad.

Source: GreenRoad, (n.d.)

Laservision's Softstop™ Barrier System

A modern variant of the passive/sacrificial system is the Softstop™ Barrier System developed by Australian company Laservision. Unlike traditional suppliers in the transportation field, Laservision is a visual effects company that has developed a unique virtual barrier system for the Sydney Harbor Tunnel (see Figure 15). When over-height vehicles approach the tunnel, the system uses a water curtain to generate a huge holographic stop sign. Laservision points out that this is the "only solution that places the warning sign directly in the driver's primary field of view rather than in the peripheral vision cone" (Laservision, n.d.). According to the tunnel manager, this holographic-based technology addresses collision issues encountered with traditional sacrificial/passive systems and is sufficiently conspicuous. However, this solution is only applicable to tunnels and not bridges. Furthermore, there is no other reported application of Softstop^{TM} Barrier System yet.

Figure 15. Photo. Softstop^{TM} Barrier System Active Systems installed in the Sydney Harbor Tunnel.

Source: Laservision

CHAPTER 3: STATE SURVEY

After completing the literature review, we designed a questionnaire to understand the current practice of using over-height vehicle-detection technologies and warning equipment in other state DOTs. The questionnaire is included in Appendix A.

The research team created the survey using Qualtrics, and IDOT sent the survey to all other state DOTs. The researchers received 20 responses from 17 states (three from different agencies in Montana and two from different agencies in Wyoming), and Figure 16 presents their geographical locations. Among the 20 responses, six responses were more detailed, as listed in Table 3. This section showcases and discusses these responses.

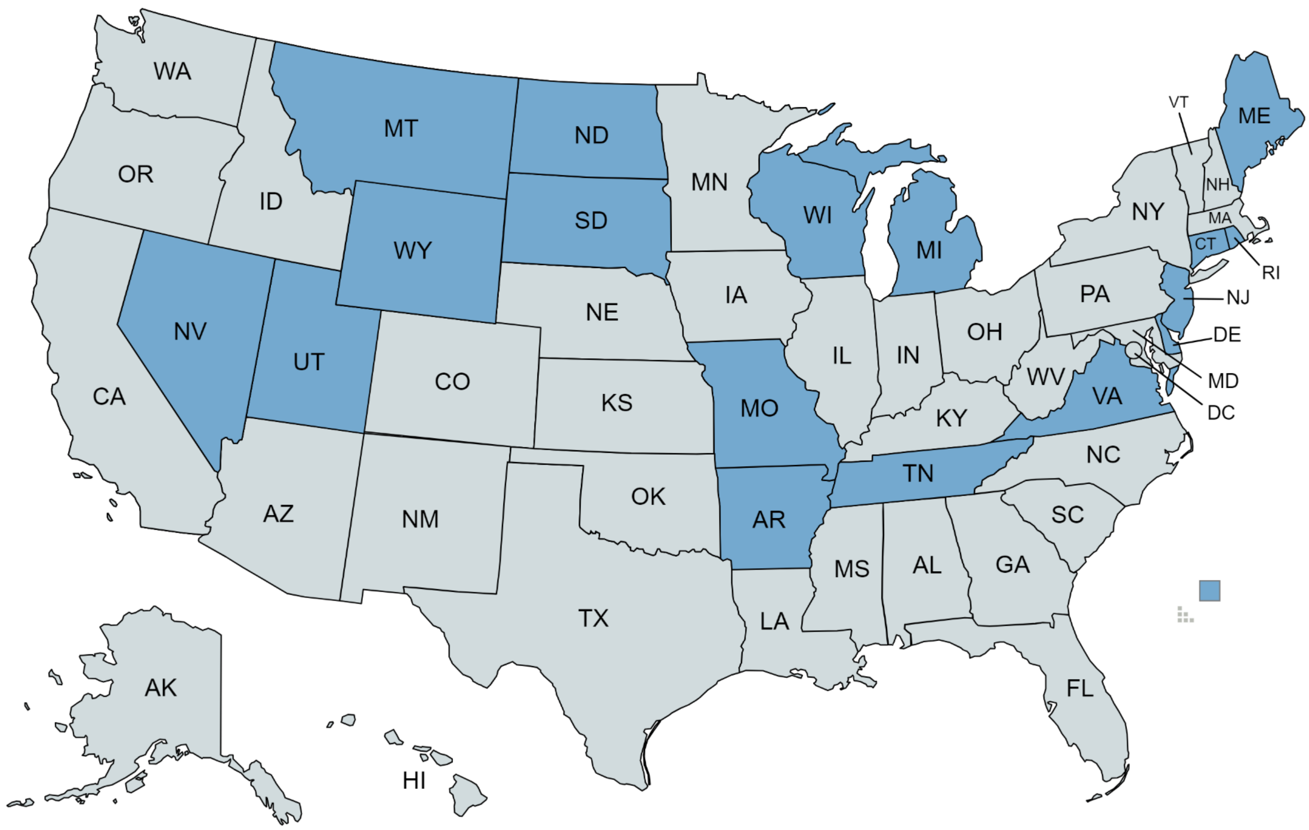


Figure 16. Map. The 17 states that responded to the survey.

Table 3. Adoption of LCDW Systems in Other States

State	Use LCDW?	If no, why not?
Arkansas	N	Cost benefit analysis has not been performed in depth. Often strikes are due to accidents, such as hauling a(n) excavator with the bucket up. It would require using a device for the majority of overpasses to prevent.
Connecticut	Y	
Delaware	Y	
Maine	Y	
Michigan	Y	
Missouri	Y	
Montana	Y	
Nevada	N	The issue has not attracted enough interest to initiate action by the Department.
New Jersey	N	Feature mounted and advance warning signs
North Dakota	Y	
Rhode Island	Y	
South Dakota	Y	
Tennessee	Y	
Utah	N	Bridge/tunnel strike is not considered as a problem
West Virginia	Y	
Wisconsin	Y	
Wyoming	Y	

From Table 3, we see that LCDW systems have been widely adopted in many states. Out of the 17 states, only four do not currently use LCDW systems. Among them, New Jersey DOT employs passive warning signs but does not use any detection systems. Arkansas DOT indicates that the state still needs to do a deeper cost-benefit analysis to justify the use of LCDW systems, even though frequent bridge strikes do occur. They agree that certain equipment is needed to prevent these accidents, but perhaps it is not necessarily LCDW systems.

The Nevada DOT and Utah DOT respondents mention that bridge/tunnel strikes are not considered a problem in their states, or the issue has not yet piqued enough interest in DOT research. These responses are intriguing because we normally would expect more strikes on bridges/tunnels from mountainous areas.

Next, Table 4 summarizes the LCDW systems adopted and their basic information. This table is divided into 10 rows and 6 columns. Each row corresponds to all answers we received regarding an LCDW device type, and each column corresponds to parameters or data related to the LCDW system.

The general findings are consistent with the development trends of LCDW systems from the literature review. None of the DOTs surveyed indicated the use of sacrificial systems. Variable message signs (VMS) and static signs are widely employed. In the realm of active systems, those based on infrared sensors remain predominant. Montana and Missouri utilize systems provided by Trigg, while Wisconsin employs the TAPCO system. Additionally, Tennessee uses the HISIC450 produced by SICK AG. Although SICK did not specify the sensor type, describing it as “photoelectric,” it is very likely to be infrared. North Dakota employs a laser-based LCDW, although the model was not specified. Tennessee has also procured the Camera+CV LCDW system from Axis Communications. No state reported the use of vehicle-based systems. For lidar systems, IDOT seems to have purchased the HawkScan system already, and North Dakota is planning to deploy them in the future.

In terms of lifespan, VMS and static signs often endure longer due to their relative simplicity. Concerns about the lifespan of LCDW systems primarily focus on active systems. Montana’s Trigg system has been in use for over 30 years, demonstrating excellent robustness. The infrared systems in Missouri and Wisconsin have also been in use for over a decade. Tennessee’s SICK HISIC450 has been in use for one year. However, as this is a well-established model that has appeared in DOT reports for many years, we assume that the durability of the HISIC450 is satisfactory. The Camera + CV systems, being a newer technology, requires observation regarding its durability. Because it relies on software rather than sensors to identify vehicles, it may have advantages in durability and maintenance.

Table 4. Types of the LCDW Systems

	Manufacturer	Initial Cost	Maintenance and Operating Cost (per year)	Number of Years in Service	Other Info
Variable Message Signs	Daktronics (TN) TAPCO (WI)	$37000 (TN)	< $1000 (TN) $1500 (WI)	10+ (WI)	New system- Bachman Tunnel in Chattanooga (TN) Will be in next deployment (ND)
Static Signs	MoDOT-Truck Tipping Warning Sign (MO) No manufacturer (TN) Decker Supply (WI)	$38 per sf (TN) $1500 (WI)	< $1000 (TN) $500 (WI)	10+ (WI)	These static signs have flashing beacons which are activated by the vehicle detection system (MO)

	Manufacturer	Initial Cost	Maintenance and Operating Cost (per year)	Number of Years in Service	Other Info
Infrared over-height vehicle sensor	Trigg Industries (MT, MO) TAPCO (WI) Unknown (MI)	-10000 (MT) -Unknown (MO)	No data available but have proven to be robust and need minimal maintenance (MO) $500 (WI)	Over 30 (MT) Over 15 (MO) 10+ (WI)	Detection system activates a beacon or blackout sign (MT) While our application is not for low clearance applications, we detect tall trucks for tipping issues. After repeated issues with radar units failing, this system was found, and it has proven very reliable (MO)
Laser	NA-Not in our region (WI) Unknown (ND)				
Lidar	NA-Not in our region (WI)				Will be in next deployment (ND)
Camera + computer vision	Axis (TN) NA-Not in our region (WI)	$4,200	< $1000 (TN)	< 1	Just for verification- no machine learning (TN)
Sacrificial	None in system (WI)				
GPS/Vehicle Based	None in system (WI)				
Other					
Photoelectric (Infrared?)	SICK HISIC450 (TN)	$94,500	< $1000 (TN)	< 1	New system- Bachman Tunnel in Chattanooga (TN)

Many DOTs did not provide cost data, and even those that have may have different statistical approaches. For example, the approaches varied by whether the total price of all equipment or the unit price is provided, whether it includes installation, spare parts, training, maintenance, and other additional options, etc. It may be challenging to make accurate assessments of the costs of these systems through simple interviews. However, based on the data we have collected, it appears that the SICK system procured by Tennessee is significantly more expensive than Axis's Camera + CV system, and cost is indeed a major advantage of the latter.

It is worth noting that the Trigg system purchased by Missouri DOT is not used to detect over-height vehicles, but to detect the risk of rollover. However, the principles are similar, and both are based on infrared sensor devices.

Next, in Table 5, we used a 1–5 scale to provide a simple assessment of state DOTs' perceptions of the effectiveness of their LCDW systems. Most DOTs selected "3: Moderately Effective" and "4: Effective." The only DOT that chose "2: Slightly Effective" was North Dakota, which is also the only DOT among the interviewees using a laser-based LCDW system. Additionally, some DOTs may not have been able to respond because their LCDW system was installed only recently.

Tennessee DOT highlighted an interesting phenomenon: even after triggering their infrared LCDW system's alert, drivers still proceeded toward tunnels because they knew the LCDW's installation position was lower than the actual over-height level. For addressing such occurrences, enhancing enforcement may be necessary and the only solution. This once again demonstrates that LCDW systems or any technological means alone cannot solve the problem of bridge/tunnel strikes.

Table 5. Effectiveness of LCDW Systems

	1 Not Effective	**2 Slightly Effective**	**3 Moderately Effective**	**4 Effective**	**5 Very Effective**	**Other Info**
Variable Message Signs			TN, WI			ND: Haven't used yet but will be in next deployment
Static Signs			TN, WI, ND	MO		
Infrared over-height vehicle sensor			WI	MT, MO		MI: Recently installed
Laser		ND				
Lidar						ND: Haven't used but will be in next deployment

	1 **Not Effective**	2 **Slightly Effective**	3 **Moderately Effective**	4 **Effective**	5 **Very Effective**	**Other Info**
Camera + CV			TN			
Sacrificial						
GPS/Vehicle Based						
Other						
TN: Photoelectric			TN			Some drivers will proceed through the tunnel even though they have tripped the over-height warning system. In many cases they know they will likely fit due to the tolerances given (sensor is put lower than the exact over-height level). (TN)

Table 6 summarizes the reported effectiveness of LCDW systems in reducing bridge/tunnel strikes. Unfortunately, none of the responding DOTs were able to provide such data. Missouri DOT believes that their Trigg system has effectively reduced rollover accidents. North Dakota DOT observed a decrease in crashes, although they do not endorse laser-based LCDWs. No DOTs indicated that LCDW systems, in any form, were not helpful. Some DOTs mentioned that they had not conducted research in this area or lacked data. Performance evaluation of LCDW systems may be an issue that DOTs need to consider.

Table 6. Reduction in Crashes

	Percent or Number of Crash Reduction	Note
Variable Message Signs		
Static Signs	We used the signs with flashers, activated by the infrared detection. The first application was on a 20-foot narrow truss bridge which had a sever camber where trucks couldn't see the other end, truck routinely sideswiped mirrors. We installed these devices on either end of the bridge to meter truck traffic and eliminate opposing trucks on the bridge, eliminating the collisions until a new bridge was constructed. The other two systems we have are used to activate flasher on truck tipping signs at two different curves where we had multiple role overs, these systems are still in place. In all three cases the Trigg system proved to be very reliable and in all cases, we had yet to have any additional roll overs. (MO)	When this system was active, we did see a reduction in crashes. I don't have a percentage. We did add a camera to this location so we could monitor it when the system was triggered and did notice those over height loads turning around. We also noticed a great number of false alarms triggered by birds, exhaust and hay loads. (ND)
Infrared over-height vehicle sensor		
Laser		When this system was active, we did see a reduction in crashes. I don't have a percentage. We did add a camera to this location so we could monitor it when the system was triggered and did notice those over height loads turning around. We also noticed a great deal of false alarms triggered by birds, exhaust and hay loads.
Lidar		
Camera + CV		
Sacrificial		
GPS/Vehicle Based		
Other		

Table 7. DOT's Responses on Effect of LCDW

Has your state experienced a reduction in crashes?	
Response	**State**
Yes	MO, ND
Maybe	MT: Haven't investigated data yet. TN: Unknown at this time MI: Recently installed. WI: Still get hits but reduced some
No	

In the next four tables, we collect information about the accuracy of LCDW systems. When an LCDW system malfunctions, there are two possible scenarios: failing to successfully alert to over-height vehicles (i.e., missed detection) or being triggered when no over-height vehicles are present (i.e., false alarm). Table 8 summarizes the reported missed detection from LCDWs, while Table 10 concludes the reported false positive alarms.

Like the previous section, many DOTs still indicate that they have not conducted research in this area or lack data. Wisconsin DOT and Missouri DOT believe that such errors have never occurred. Tennessee DOT defines the behavior of ignoring alerts for over-height vehicles, mentioned earlier, as false positives and notes that this occurs frequently. Once again, North Dakota DOT, which uses laser-based LCDW systems, gives the poorest evaluation, stating that both missed detections and false positives occur "often."

We also inquired about specific weather conditions such as rain, snow, fog, etc., and whether they would increase the probability of misses/false positives. Missouri did not observe this phenomenon with their Trigger system, although their previous radar system was highly unreliable. North Dakota DOT believes that cold, exhaust, birds, and even hay are reasons for triggering false positives. It is not yet clear if this is related to the characteristics of laser sensors.

Table 8. LCDW Systems' Misses of Detection/Warning

	1 Never	2 Occasional	3 Sometimes	4 Often	5 Very Frequent	Other
Variable Message Signs						
Static Signs	WI					
Infrared over-height vehicle sensor	MO, WI		MT			MT: We don't have good data on misses, but assume it happens sometimes. MI: Recently installed
Laser				ND		
Lidar						
Camera+CV / Machine Learning						
Sacrificial						
GPS/Vehicle Based						
Other						
TN: Photoelectric	TN					

Table 9. DOT's Responses on Missed Detection

Does missed detection happen more under certain conditions, such as heavy rain, fog or snow?	
State	**Response**
MO	To our knowledge, the devices have been very accurate and are easily adjusted and they do not appear to be impacted by environmental conditions that we have seen
TN	Further research required
ND	Cold causes exhaust to trigger the system.

Table 10. LCDW Systems' False Positive Alarms

	1 Never	2 Occasional	3 Sometimes	4 Often	5 Very Frequent	Other
Variable Message Signs	WI					
Static Signs	WI					
Infrared over-height vehicle sensor	MO, WI		MT			MT: No data, but assumed to happen sometime. MI: Recently installed
Laser				ND		
Lidar						
Camera+CV / Machine Learning						
Sacrificial						
GPS/Vehicle Based						
Other						
TN: Photoelectric				TN		Mostly locals that know they will trip system but can still barely fit in the tunnel (TN)

Table 11. DOT's Responses on False Alarms

Q15. Do false alarms happen more under certain conditions, such as heavy rain, fog, or snow?	
State	**Response**
MT	Unknown
MO	We have not seen false positives, the infrared beam seems to be very precise, if the beam is broken the system is triggered, if it is not broken the system doesn't activate. This was not the case with the radar system we used initially that had constant issues and was very difficult to dial in for accuracy.
TN	Unknown
ND	Cold conditions and certain seasons. During hay hauling it would get triggered often.

Finally, recall that in our literature and market review, durability and ease of maintenance are emphasized in the literature. Because most active LCDW systems involve electronic components including sensors and are exposed to open space almost throughout their lifetime, the importance of robustness and cost for maintenance is critical. Thus, in our survey, we asked other DOTs to evaluate the durability and maintainability of these systems. The results are summarized in Table 12. Furthermore, these systems may erroneously issue or miss alerts, causing traffic disruptions and even failing to prevent accidents. We want to understand if DOTs encounter these issues, and whether they are triggered more frequently under certain circumstances, like snow, rain, or fog.

All DOTs gave positive comments on the LCDW systems' reliability and ease of maintenance, and none complained about maintenance issues. In fact, Missouri's Trigg system has been in use for more than 30 years. At least as far as traditional LCDW systems are concerned, repair does not seem to be an issue. Of course, this will depend on the state in which they are placed, the maintenance capabilities of that state's DOT, etc. Further research is necessary for LCDW systems with newer technologies such as lidar and Camera + CV.

Table 12. Durability and Ease of Maintenance

	1 Vulnerable and Hard to Maintain	**2 Slightly Durable and Easy to Maintain**	**3 Moderately Durable and Easy to Maintain**	**4 Durable and Easy to Maintain**	**5 Very Durable and Easy to Maintain**	**Other**
Variable Message Signs			WI	WI		
Static Signs			WI	WI		
Infrared over-height vehicle sensor			MT	WI	MO	MT: The basic IR has been relatively easy to maintain, as long as poles aren't struck and underground wiring doesn't fail. MI: Recently installed
Laser				ND		
Lidar						
Camera + CV						

	1 Vulnerable and Hard to Maintain	2 Slightly Durable and Easy to Maintain	3 Moderately Durable and Easy to Maintain	4 Durable and Easy to Maintain	5 Very Durable and Easy to Maintain	Other
Sacrificial						
GPS/Vehicle Based						
Other						
TN: Photoelectric				TN		TN: No complaints about maintenance as of now

Table 13. DOT's Responses on Maintenance Challenges

Q16. Has your state experienced maintenance challenges? If yes, please list some.	
State	**Response**
MT	Yes, but our maintenance challenges have much more often been due to aged warning devices (blackout signs), and not necessarily the detection systems.
MO	The only maintenance issues I know of is if the support poles are hit and moves the TRIGG detectors out of alignment
TN	No

At the end of the survey, we asked the states to provide any additional comments or questions. Their responses are summarized below.

- Please describe the cost-effectiveness of your system.
  - MT: Most likely, they're cost effective, considering minor installation and maintenance cost. But without crash reduction info, we don't have quantitative cost effectiveness.
  - MO: Give the low maintenance aspects, and the fact these installations appeared to solve our issues for over 15 years they would appear to be very reliable
  - TN: None
  - MI: None

- WI: They are cost effective.
- ND: Our site was solar and that drove the cost very high. Other components of the system were reasonable.

- Plan to upgrade your system?
  - MT: No plans to upgrade, so we expect our IR systems to last until the "next project" necessitates replacement.
  - MO: There are no plans to upgrade this system as it has proven very reliable
  - TN: No, expect to last at least 10 years
  - MI: Recently Installed
  - WI: No, we are hoping to replace the bridge that get hits
  - ND: Our new system will be lidar. We anticipate 5–7 years for the sensors.
- Improvements you want to see in your LCDW?
  - MT: We don't know of necessary improvement needed to the LCDW systems, but we've added vehicle detection to some to conditionally warn turning traffic that's overheight.
  - MO: No
  - TN: None
  - MI: None
  - WI: No
  - ND: New systems will also be using DMS to alert drivers instead of flashing beacons.
- Would you recommend your LCDW?
  - MT: Yes
  - MO: We have had great luck with the TRIGG vehicle height detection system, so yes we would recommend it.
  - TN: yes
  - MI: None

- WI: They do help some
- ND: I don’t recommend laser. We will see how lidar works.

- Anything Else?
  - MT: None
  - MO: This is a link to the TRIGG Industries equipment https://www.triggindustries.com/overheight-systems/dual-beam/
  - TN: None
  - MI: None
  - WI: None
  - ND: None

From these responses, we find that most DOTs recommend their LCDW system. Missouri DOT believes they “had great luck with the TRIGG.”

Regarding the cost-effectiveness and durability of LCDW systems, most DOTs seem satisfied, although Montana DOT feels they lack accurate data to assess the cost-effectiveness. North Dakota DOT believes that their “solar site” (possibly the solar panels that supply power) “drove the cost very high,” but other aspects are reasonable.

North Dakota DOT is the only one planning to upgrade their LCDW system. They are the sole user of laser-based LCDW systems (although they are not totally satisfied with this technology), and their new system will employ more advanced lidar sensors. The expected lifespan of the new LCDW is 5–7 years, shorter than traditional LCDW systems. Other DOTs either believe their current LCDW systems are sufficiently reliable or have recently updated them, with no reason for further updates.

Two DOTs provided their expectations on next-generation LCDW systems. Montana DOT would like to have vehicle detection/classification to warn over-height turning traffic conditionally. North Dakota DOT’s next-generation LCDW system will use variable message signs instead of flashing beacons to warn drivers.

CHAPTER 4: CONCLUSION

This research project conducted a literature review and state survey to assist the Illinois Department of Transportation (IDOT) in understanding the types of LCDW systems available in the market, the technology options and their effectiveness and costs (including potential vendors), and their current adoption in those states. The following are the key findings from the research:

1. Bridge/tunnel strikes by over-height vehicles have increasingly become a serious issue in the transportation industry worldwide. Such strikes cause significant economic and social losses. Low-clearance detection warning is one of the important technological means to address this issue, but long-term social and educational measures should also be considered in order to reduce over-height vehicle bridge/tunnel strikes.

2. The history of LCDW (including detection and warning components) can be traced back to the 1970s. The underlying technologies can be divided simply into two categories: passive/sacrificial systems and active detection and warning systems. Passive/sacrificial systems are installed above or on the sides of the road, and they utilize noise and vibration generated upon collision with vehicles to alert drivers. Although these systems have low cost and are simple to operate/maintain, they are considered risky due to physical contact with vehicles, and often fail to attract drivers' attention.

3. Active systems primarily detect over-height vehicles using infrared, laser, or visible light beams. Other types of more recent sensors include ultrasound or GPS location sensors. When the beam is interrupted, roadside signs (such as flashing signs or variable message signs) on onboard sensors inside the vehicle (such as alarms) emit warnings. As the costs for sensors and communication technologies continue to decrease, such active systems (including lidar and camera vision) have gradually become the mainstream of LCDW systems. Those using regular cameras are believed to be even more cost-effective in the future, but large-scale adoption of such new technologies has not occurred yet. As such, technologies based on lidar might be appropriate for IDOT to consider in the near future. This report includes a few popular vendor options in the current market for IDOT to consider.

4. Among the 17 state DOTs that responded to our survey, the vast majority have already implemented or plan to use LCDW systems. Most DOTs are satisfied with their LCDW systems, finding that they reduce the number of strikes and are cost-effective, and they generally recommend IDOT to use LCDWs. The only exception is a state using a laser-based LCDW system that seemingly generates false alarms frequently, has poor performance, and intends to replace it with a lidar-based LCDW. We did not receive feedback on lidar- and camera-based LCDW systems, possibly because these systems are relatively new.

Based on these findings, the research team proposes the following opportunities for further research beyond the scope of this short project:

1. Conduct experiments with a few types of LCDW systems, and document the performance of different LCDWs. Existing literature in this area is very limited, and none of the literature seems to have considered newer technologies such as lidar. In the longer term, field tests of the most promising devices may be carried out to prove their effectiveness for the State of Illinois.

2. This project primarily relies on secondary data and qualitative findings from the existing literature. More data is necessary to conduct a comprehensive examination of the state of the practice for oversized vehicle warning devices so as to create a guide for selecting over-height detection and warning solutions in future designs or retrofits. Such quantitative before-and-after studies should be carried out with primary data collected either in the field (e.g., from other states) or from simulation experiments (e.g., from a driving simulator).

3. Maintain close contact with other DOTs and research institutions to obtain the latest developments and experiences in this area.

4. Conduct further research on bridge/tunnel strike issues and formulate a comprehensive plan that involves education and training. While LCDW systems are an important part of the solution, they are not the sole solution. For instance, one of our responding states mentioned that due to the margin of error in their LCDW systems, some over-height vehicle drivers may take a chance and continue moving forward even after seeing the alert. Such compliance and enforcement issues cannot be entirely addressed through technological devices alone; they require policy interventions and other complementary measures that can engage all interested parties to contribute to maximum effectiveness of installed devices. Further research could also look into better truck route design, incentives/penalties (especially those related to oversize truck permits), and police enforcement.

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APPENDIX A

ICT PROJECT R27-SP65 QUESTIONNAIRE

LOW-CLEARANCE DETECTION AND WARNING SYSTEMS IN PEER STATES

The Illinois Department of Transportation (IDOT) is sponsoring an ongoing research project to study the use of low-clearance detection and warning (LCDW) systems to increase safety and mobility in peer states. This online survey is designed to take less than **15 minutes** to complete. Your valuable feedback will assist IDOT in evaluating the current use and effectiveness of LCDW systems. We would really appreciate it if you completed the survey by **Friday, March 08, 2024**.

The research team will be glad to share the findings of this survey with you upon completion. If you have any questions or comments, please contact the Principal Investigator (PI) and/or the Steering Committee Chair of this project:

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Thank you in advance for your time.

1. What is your name? (Optional) ____________________

2. What state do you represent? (Required) ____________________

3. What is your current job title? (Optional) ____________________

Use of LCDW Systems

The LCDW systems can be roughly categorized into the following types:

- Variable message signs (VMS), dynamic message signs (DMS), portable changeable message signs (PCMS), or dynamic message boards;
- Static roadway signs;
- Vehicle/GPS-based systems, which are integrated with bridge and tunnel database to provide alerts or other measures as soon as vehicles approach impassable tunnels;
- Infrared over-height vehicle sensors;
- Laser over-height vehicle sensors;
- Ultrasonic over-height vehicle sensors;
- Camera + computer vision/machine learning systems;
- Sacrificial systems (physical notification structures such as crash breams, hanging chains, portal frames and road narrowing techniques).

4. Which of the following LCDW systems have been used by your state DOT? If not, does your state have plans to consider any of them in the future? (Select all that apply)

[ ] No LCDW systems have ever been used, and there is no plan for future deployment;

[ ] Yes, the following LCDW systems have been or will be used (check all that apply):

Type of Device	**Manufacturer /Model**	**Initial Cost (per unit)**	**Maintenance and Operating Cost (per unit-year)**	**Number of Years in Service**
[ ] Variable message signs				
[ ] Static signs				
[ ] Infrared over-height vehicle sensor				
[ ] Laser over-height vehicle sensor				

Type of Device	Manufacturer /Model	Initial Cost (per unit)	Maintenance and Operating Cost (per unit-year)	Number of Years in Service
[ ] Ultrasonic over-height vehicle sensor				
[ ] Camera + computer vision /machine learning				
[ ] Sacrificial systems				
[ ] GPS/Vehicle based systems				
[ ] Other—Please specify				

5. If your state does not use (or plan to use) LCDW systems, what are some reasons or challenges?

[] Cost

[] Bridge/tunnel strike is not considered as a problem;

[] Current technologies do not meet requirements or other solutions are adopted for bridge/tunnel strike (Please specify) ___________________________

[] Other—Please specify and provide a brief description ______________________

Effectiveness of LCDW Systems in Reducing Crashes

6. Please rank the effectiveness of each LCDW system in **reducing over-height vehicle crashes** at the specific installation locations, on a scale from 1 to 5. (1 Not Effective, 2 Slightly Effective, 3 Moderately Effective, 4 Effective, and 5 Very Effective)

LCDW Systems	1 Not Effective	2 Slightly Effective	3 Moderately Effective	4 Effective	5 Very Effective	Inadequate Information
Variable message signs						
Static signs						
Infrared over-height vehicle sensor						
Laser over-height vehicle sensor						
Ultrasonic over-height vehicle sensor						
Camera + computer vision/machine learning						
Sacrificial systems						
GPS/Vehicle based systems						
Other—Please specify						

7. Has your state experienced a reduction in roadway crashes at the specific installation locations through utilizing LCDW systems?

[ ] Yes

[ ] No

8. If yes, please report experienced reduction in crashes (in percentage or annual number) of unauthorized vehicles (please specify which one, or both) at the specific installation locations, and provide web links to documented crash reduction records if available.

LCDW Systems	Percent or Number of Crash Reduction (and documentation)
Variable message signs	
Static signs	
Infrared over-height vehicle sensor	
Laser over-height vehicle sensor	
Ultrasonic over-height vehicle sensor	
Camera + computer vision/machine learning	
Sacrificial systems	
GPS/Vehicle based systems	
Other—Please specify	

Accuracy of LCDW Systems

9. Are your state's LCDW systems accurate? How many times do they miss detection? Please indicate the frequencies on a scale from 1 to 5. (1 Never, 2 Occasional, 3 Sometimes, 4 Often, and 5 Very frequent)

LCDW Systems	1 Never	2 Occasional	3 Sometimes	4 Often	5 Very Frequent	Inadequate Information
Variable message signs						
Static signs						
Infrared over-height vehicle sensor						
Laser over-height vehicle sensor						
Ultrasonic over-height vehicle sensor						
Camera + computer vision/machine learning						
Sacrificial systems						
GPS/Vehicle based systems						
Other – Please specify						

Does missed detection happen more under certain conditions, such as heavy rain, fog, or snow?

____

10. How frequent are false positives? Please indicate the frequencies on a scale from 1 to 5. (1 Never, 2 Occasional, 3 Sometimes, 4 Often, and 5 Very frequent)

LCDW Systems	1 Never	2 Occasional	3 Sometimes	4 Often	5 Very Frequent	Inadequate Information
Variable message signs						
Static signs						
Infrared over-height vehicle sensor						
Laser over-height vehicle sensor						
Ultrasonic over-height vehicle sensor						
Camera + computer vision/machine learning						
Sacrificial systems						
GPS/Vehicle based systems						
Other – Please specify						

Do false alarms happen more under certain conditions, such as heavy rain, fog, or snow?

____

Maintenance of LCDW Systems

11. Has your state experienced maintenance challenges? If yes, please list some.

12. Please rate the durability and ease of maintenance of your LCDW systems on a scale from 1 to 5.

LCDW Systems	1 Vulnerable and Hard to Maintain	2 Slightly Durable and Easy to Maintain	3 Moderately Durable and Easy to Maintain	4 Durable and Easy to Maintain	5 Very Durable and Easy to Maintain	Inadequate Information
Variable message signs						
Static signs						
Infrared over-height vehicle sensor						
Laser over-height vehicle sensor						
Ultrasonic over-height vehicle sensor						
Camera + computer vision/machine learning						
Sacrificial systems						
GPS/Vehicle based systems						
Other – Please specify						

13. How would you rate the cost-effectives of the equipment/systems used in your state? Is it too expensive, or does the cost not justify the effectiveness?

14. Do you have plans to upgrade your system? How long do you expect your LCDW systems to last?

15. Are there any improvements you want to see in the next-generation LCDW systems?

16. Will you recommend your LCDW systems to other states?

17. Anything else you want to share but not covered by the previous questions?

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