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Title: **Vehicle-width Measurement Technology Development: Phase I Technical Memorandum**

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Abstract:

The Virginia Tech Transportation Institute (VTTI) was tasked with investigating the feasibility of developing a vehicle-width measurement and alert system to reduce over-width violations in Virginia Department of Transportation's (VDOT) work zones. A two-phase approach was developed to investigate the measurement system feasibility. During Phase I, the focus of the current report, VTTI first generated design criteria with support from stakeholders (i.e., the Virginia Center for Transportation Innovation and Research [VCTIR] and VDOT). Next, researchers and engineers assessed existing vehicle-width measurement systems against these criteria to determine design gaps, and then explored solutions (e.g., new technologies) to these design gaps. Identified potential solutions were then tested on the Virginia Smart Road. In the end, VTTI developed a preliminary system architecture for a vehicle-width measurement system. Based on the findings of this research effort three recommendations are offered to guide future development of a vehicle-width measurement system.

FINAL CONTRACT REPORT

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DISCLAIMER

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INTRODUCTION

The focus of this project was to investigate the feasibility of developing a vehicle-width measurement and alert system to reduce over-width vehicle violations in Virginia Department of Transportation's (VDOT) work zones. These over-width vehicle violations often result in traffic congestion and work disruptions while the offending vehicle is being turned around by law enforcement officers. The objective of the Vehicle-Width Measurement Technology Development project was to explore existing systems and potential technologies that are able to successfully measure vehicle widths at highway speeds while remaining cost-effective and portable.

Background

Measuring maximum vehicle width at highway speeds from a portable platform creates several design challenges (e.g., sampling rate, measurement quality, power, and weather) that must be systematically addressed using a systems engineering approach. A two-phase approach was developed to investigate the measurement system feasibility. During Phase I, the focus of the current report, the Virginia Tech Transportation Institute (VTTI) research team: 1) generated design criteria with support from stakeholders (i.e., the Virginia Center for Transportation Innovation and Research [VCTIR] and VDOT), 2) assessed existing vehicle-width measurement systems against these criteria to determine design gaps, 3) explored solutions (e.g., new technologies) to meet these design gaps, 4) assessed initial performance of promising solutions, and 5) generated and provided the system architecture for a promising vehicle-width measurement system. During Phase II, it is recommended that VTTI: 1) further the development of the prototype vehicle-width measurement system, 2) assess its performance under near-operational conditions (i.e., on the Virginia Smart Road), and 3) assess its performance under operational conditions (i.e., within VDOT's roadway system).

Organization of Current Report

The current report details all steps completed during Phase I. Key project tasks are briefly described below.

Design Criteria

Design criteria were developed through a collaborative effort between VCTIR, VDOT, and VTTI personnel. The purpose of the design criteria was to guide the project during the evaluation of existing vehicle-width measurement technologies, identify existing system design gaps, identify potential technology solutions, and, finally, develop a recommended system architecture.

Over-width Notification/Warning Guidelines

The purpose of this task was to develop a set of guidelines towards the development of an over-width vehicle notification/warning system to accompany the vehicle-width measurement system. Current best practices, standards, and regulations associated with temporary traffic control work zone devices were examined, especially those related to temporary lane restrictions.

Commercial vehicle (CV) drivers and escort drivers (also referred to as pilot drivers) were interviewed for their input into the notification/warning system guidelines design. A final set of notification/warning system guidelines was generated and presented in this section.

Vehicle-width Measurement Technology

The objective for the vehicle-width measurement technology portion of this project was to evaluate existing vehicle dimension measurement systems, identify design gaps, and examine promising sensor technologies to address these design gaps. Design gaps were identified by comparing existing vehicle dimension measurement systems (Fontaine, 2010) to the vehicle-width measurement design criteria developed early in the project through collaboration with project stakeholders. Finally, a vehicle-width measurement system architecture was developed.

DESIGN CRITERIA

The design criteria were used to evaluate existing technologies, investigate potential solutions, perform component testing, and develop recommendations for system architecture. There are 12 criteria defined below, and specified in Table 1.

- Operational duration – The amount of time the system is functional in the field (measured in months).
- Deployment time – The amount of time required to set up the system (measured in hours).
- Distance from roadside – The distance from the system deployment location to the edge of the outermost lane (measured in feet).
- Lane count – The number of unidirectional lanes present at system deployment.
- System performance – System Performance is defined as the system’s ability to detect and provide notification of an over-width vehicle. Distance will be the metric to assess the system’s performance, where a shorter distance between the detection system and the last remaining exit available will indicate a higher level performance. Therefore, the objective is to minimize this distance to allow greater flexibility in installation locations.
- Detection resolution – The smallest object measurable on a vehicle traveling at highway speeds (measured in inches).
- Overhead mounting height – The height at which an overhead system can be mounted during installation, from road surface to the system (measured in feet).
- Power supply – The source of the electrical energy required.
- Power type – The system’s voltage and current specifications (measured in volts direct current (VDC) or volts alternating current (VAC).
- Detection accuracy – The probability of that the system correctly detects an over-width vehicle.
- Vehicle speed requirements – The maximum and minimum velocities of vehicles that can be evaluated by the system (measured in miles per hour [mph]).
- Notification/warning priority – The order of in which people are notified when a violation occurs.

The criteria set forth in Table 1 provide a summary of both the *objective* and *allowable* values for the over-width detection and notification/warning system success.

Table 1. System design criteria summary.

Criterion	Objective	Allowable
Operational duration	12 months	3 months
Deployment time	1/2 day setup	1 day setup
Distance from roadside	> 12 ft.	4 ft.
Lane count	2 Lanes	1 Lane
System performance	4 miles prior to last exit	6 miles prior to last exit
Detection resolution	2 in.	12 in.
Overhead mounting height	>20 ft.	>14 ft.
Power supply	Battery or external power	External power only
Power type	12VDC and 120VAC	12VDC, 120VAC, or other
Detection accuracy	100%	75%
Vehicle speed requirements	5-75 mph	5-60 mph
Notification/warning priority	Driver, Work zone, VDOT	Driver

OVER-WIDTH NOTIFICATION/WARNING GUIDELINES

To successfully reduce over-width violations in work zones, the driver (and/or escort) of the over-width vehicle must be properly notified of the occurrence of lane width restrictions and if their vehicle is in violation. This section will cover current best practices, standards, and regulations associated with temporary traffic control work zone devices with an emphasis on those related to temporary lane restrictions. In addition, over-the-phone interviews were performed with drivers that transport and/or escort over-width loads in Virginia. The purpose of these interviews was to gather information from drivers and escorts regarding their perspective on the most effective and least effective over-width signage and how they think current signage could be improved. A detailed description of the interview method and results obtained will be provided. Finally, a set of guidelines towards the development of an over-width vehicle notification/warning system to accompany the vehicle-width measurement system will be presented.

Relevant Guidelines, Restrictions, and Standards

Federal Standards

The Research and Innovative Technology Administration's (RITA) Intelligent Transportation Systems (ITS) characterizes over-height/over-width warning systems as systems using roadside detectors and electronic warning signs to warn drivers that are too tall or wide to pass under bridges (RITA, n.d.). While many states have implemented over-height warning systems and strategies (e.g., routing strategies for permitted vehicles), redundancies are necessary to address potential failures within such systems (e.g., when drivers disregard routing instructions, or when drivers fail to follow routing instructions due to errors; Mattingly, 2003). The need to warn drivers of impending roadway width constraints within temporary traffic control (TTC) zones is of great importance. TTC zones are those where highway construction, utility work, maintenance operations, or the management of traffic incidents change road user conditions (FHWA, 2009).

This section focuses on federal guidelines and standards regarding the use of TTC zone devices. As this report focuses on the development of an over-width measurement and notification system, the review of best practices is limited to those with specific applicability for use in such a system. Several sources exist to provide guidance on the use of TTC devices. Design standards are included in the Manual on Uniform Traffic Control Devices (MUTCD; Federal Highway Administration [FHWA], 2009), the Standard Highway Signs and Markings (SHSM) book, and the Temporary Traffic Control Devices Final Rule 23 CFR 630 Subpart K. These sources are supplemented by the *NCHRP Report 350, Recommended Procedures for the Safety and Performance Evaluation of Highway Features* (Ross, Sicking, and Zimmer, 1993) and the American Traffic Safety Association's (ATSA) *Quality Guidelines for Work Zone Devices (n.d.)*. Additionally, the American Association of State Highway Transportation Officials (AASHTO) provides guidance in the form of the Highway Safety Manual (2010), Roadside Design Guide, and Manual for Assessing Safety Hardware (MASH; AASHTO, 2009). MASH is an update to and supersedes the *NCHRP Report 350* (see: http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/policy_memo/memo112009/). Relevant design standards and guidelines provided within these documents are presented.

MUTCD and SHSM Book

The MUTCD defines the standards used by road managers to install and maintain traffic control devices on all public streets, highways, bikeways, and private roads open to public traffic. The MUTCD is the law governing all traffic control devices and non-compliance can result in the loss of federal funds. The MUTCD is approved by the Federal Highway Administrator as the National Standard in accordance with Title 23 U.S. Code, Sections 109(d), 114(a), 217, 315, and 402(a), 23 CFR 655, and 49 CFR 1.48(b)(8), 1.48(b)(33), and 1.48(c)(2) (FHWA, 2009). The current official version of the MUTCD is the 2009 Edition, dated December 16, 2009. States are required to adopt the MUTCD by January 15, 2012, or have a state MUTCD/supplement that is in substantial conformance with the federal MUTCD (23 CCFR 655.603(b)).

FHWA also publishes the SHSM book. The SHSM provides design details of the signs and markings in the MUTCD. Currently, FHWA is working to incorporate the changes in the 2009 MUTCD in order to update the 2004 SHSM to reflect the new signs and markings as well as the modifications to current signs and markings.

Chapter 6F, Temporary Traffic Control Zone Devices, of the SHSM provides guidance for those devices used in TTC zones. As noted in Section 6B.01 Fundamental Principles of TTC, "advanced warning, delineation, and channelization should be provided to assist in guiding road users in advance of and through the TTC zone or incident site by using proper pavement markings, signing, or other devices that are effective under varying conditions" (FHWA, 2009). The following sections provide an overview of TTC zone warning locations and distances, detour and diversion standards, crashworthiness standards, TTC devices, and portable changeable message signs.

Warning Location and Distance

The MUTCD (FHWA, 2009) notes that most TTC zones are divided into four areas: the advanced warning area, the transition, the activity area, and the termination area (See Appendix A, MUTCD Figure 6C-1, Component Parts of a TTC Zone). Of note, advanced warning areas (i.e., the section of the highway where road users are informed about the upcoming work zone or incident area) may vary from a single sign or high-intensity rotating, flashing, oscillating, or strobe lights on a vehicle to a series of signs in advance of the TTC zone activity area. This advanced warning area is the most critical for the measurement and notification of over-width vehicles and will be the primary focus for the warning/notification guidelines section as well as the vehicle-width measurement system design section.

The recommended spacing for advanced warning signs is presented in MUTCD Section 6C.04 as Table 6C-1 (Table 2). Section 6F.17 further notes that where a series of two or more advanced warning signs is used, the closest sign to the TTC zone should be placed approximately 100 ft ahead for low-speed urban streets to 1,000 ft ahead – or more – for freeways and expressways (Table 3). Additionally, where multiple advance warning signs are needed on the approach to a TTC zone, the ROAD WORK AHEAD (W20-1) sign should be the first advance warning sign encountered by road users. The ROAD NARROWS (W5-1) sign is also applicable in this case (Figure 1and Figure 2). An optional fifth area, a taper, may be used in both the transition and termination areas. Tapers are used to move traffic out of or into the normal path using a series of channelizing devices and/or pavement markings. Types of tapers are shown in Appendix B, MUTCD Figure 6C-2, Types of Tapers and Buffer Space.

Table 2. MUTCD Table 6C-1: Recommended Advance Warning Sign Minimum Spacing
(Source: Adapted from FHWA, 2009, p. 554)

Road Type	**Distance Between Signs****		
	A	**B**	**C**
Urban (low speed)*	100 ft.	100 ft.	100 ft.
Urban (high speed)*	350 ft.	350 ft.	350 ft.
Rural	500 ft.	500 ft.	500 ft.
Expressway/Freeway	1,000 ft.	1,500 ft.	2, 640 ft.

*Speed category to be determined by the highway agency

**The column headings A, B, and C are the dimensions shown in Figures 6H-1through 6H-46 (see FHWA, 2009, pages 635-725). The A dimension is the distance from the transition or point of restriction to the first sign. The B dimension is the distance between the first and second signs. The C dimension is the distance between the second and third signs. (The "first sign" is the sign in a three-sign series that is closest to the TTC zone. The "third sign" is the sign furthest upstream from the TTC zone.)

Table 3. FHWA Table 6E-1: Stopping Distance as a Function of Speed
(Source: Adapted from FHWA, 2009, p, 575)

Speed*	Distance
20 mph	115 ft.
25 mph	155 ft.
30 mph	200 ft.
35 mph	250 ft.
40 mph	305 ft.
45 mph	360 ft.
50 mph	425 ft.
55 mph	495 ft.
60 mph	570 ft.
65 mph	645 ft.
70 mph	730 ft.
75 mph	820 ft.

*Posted speed, off-peak 85th percentile speed prior to work starting, or the anticipated operating speed

Figure 1. Sign W20-1 road work ahead sign.
(Source: FHWA, 2009, p. 590)

Figure 2. Sign W5-1 road narrows sign.
(Source: FHWA, 2009, p. 589)

Channelizing Devices

The MUTCD provides clear guidance for the use of channelizing devices (FHWA, 2009). Channelizing devices function to guide road users and to warn them of conditions created by work activities in or near the roadway. These devices provide for smooth and gradual vehicular traffic flow from one lane to another, onto a bypass or detour, into a narrower traveled way, or away from the work space.

Warning lights may be placed on channelizing devices in areas with frequent fog, snow, or severe roadway curvature, or where visual distractions are present. Warning lights placed on channelizing devices used along or in a cluster will flash to warn of a condition and warning lights placed on channelizing devices used in a series will be steady-burn to channelize road users. However, a series of sequential flashing warning lights may be placed on those channelizing devices that form a merging taper in order to increase driver detection and recognition of the merging taper (FHWA, 2009, pp. 604, 614-615). Examples of channelizing devices, including size and optional warning lights, are presented in Appendix C. Specific instructions regarding warning lights follow (FHWA, 2009, pp. 614-615):

1) The warning lights used in TTC zones are Type A, Type B, Type C, and Type D 360-degree warning lights. These lights are portable, powered, yellow, lens-directed, enclosed

lights. Warning lights must be in accordance with the current ITE "Purchase Specification for Flashing and Steady Burn Warning Lights (See Section 1A.11 of the MUTCD).

a. Type A Low-Intensity Flashing warning lights are used to warn road users during nighttime hours that they are approaching or proceeding in a potentially hazardous area. Type A warning lights may be mounted on channelizing devices.
b. Type B High-Intensity Flashing warning lights are used to warn road users during both daylight and nighttime hours that they are approaching a potentially hazardous area. Type B warning lights are designed to operate 24 hours per day and may be mounted on advance warning signs or on independent supports.
c. Type C Steady-Burn warning lights and Type D 360-degree Steady-Burn warning lights may be used during nighttime hours to delineate the edge of the traveled way. When used to delineate a curve, Type C and Type D 360-degree warning lights should only be used on devices on the outside of the curve, and not on the inside of the curve.

2) When a series of sequential flashing lights are used (for example on channelizing devices that form a merging taper to increase driver detection and recognition of the merging taper), the successive flashing of lights is to occur from the upstream end of the merging taper to the downstream end of the merging taper in order to identify the desired vehicle path. Each warning light in the sequence is to be flashed at a rate of not less than 55 or more than 75 times per minute.
3) Type A Low-Intensity Flashing warning lights, Type C Steady-Burn warning lights, and Type D 360-degree Steady-Burn warning lights shall be maintained so as to be capable of being visible on a clear night from a distance of 3,000 feet. Type B High-Intensity Flashing warning lights shall be maintained so as to be capable of being visible on a sunny day when viewed without the sun directly on or behind the device from a distance of 1,000 feet.
4) Warning lights shall have a minimum mounting height of 30 inches to the bottom of the lens.

TTC Zone Devices

The MUTCD specifies that TTC zone signs convey both general and specific messages through words, symbols, and/or arrows and have the same three categories as all road user signs: regulatory, warning, and guide. TTC warning signs are used to notify road users of specific situations or conditions on or adjacent to a roadway that might not otherwise be apparent. Special warning signs also may be used based upon engineering judgment. Special warning sign messages should be brief, legible, and clear (FHWA, 2009, 596).

Sign Color

Section 6F.02 of the MUTCD notes that generally, in regard to warning signs, the standard is as follows (see MUTCD, Section 6F.02, p. 576-577):

> The colors for regulatory signs shall follow the Standards for regulatory signs in Table 2A-5 and Chapter 2B. Warning signs in TTC zones shall have a black legend and border on an orange background, except for the Grade Crossing Advance Warning (W10-1) sign which shall have a black legend and border on a yellow background, and except for signs

that are required or recommended in Parts 2 or 7 to have fluorescent yellow-green backgrounds. Colors for guide signs shall follow the Standards in Table 2A-5 and Chapter 2D, except or guide signs as otherwise provided in Section 6F.55 (FHWA, 2009, p. 576-577).

Sign Illumination

According to the MUTCD, signs that will be used at night need to be either retroreflective with a material that has a smooth, sealed outer surface or illuminated to show the same shape and similar color both night and day. Sign illumination requirements are not considered satisfied by street, highway, or strobe lighting. Therefore, sign illumination may be internal or external. The standards for retroreflectivity and illumination are provided in Table 2A-1 and Table 2A-2 of Section 2A.07 of the MUTCD (Figure 3; FHWA, 2009; p. 29).

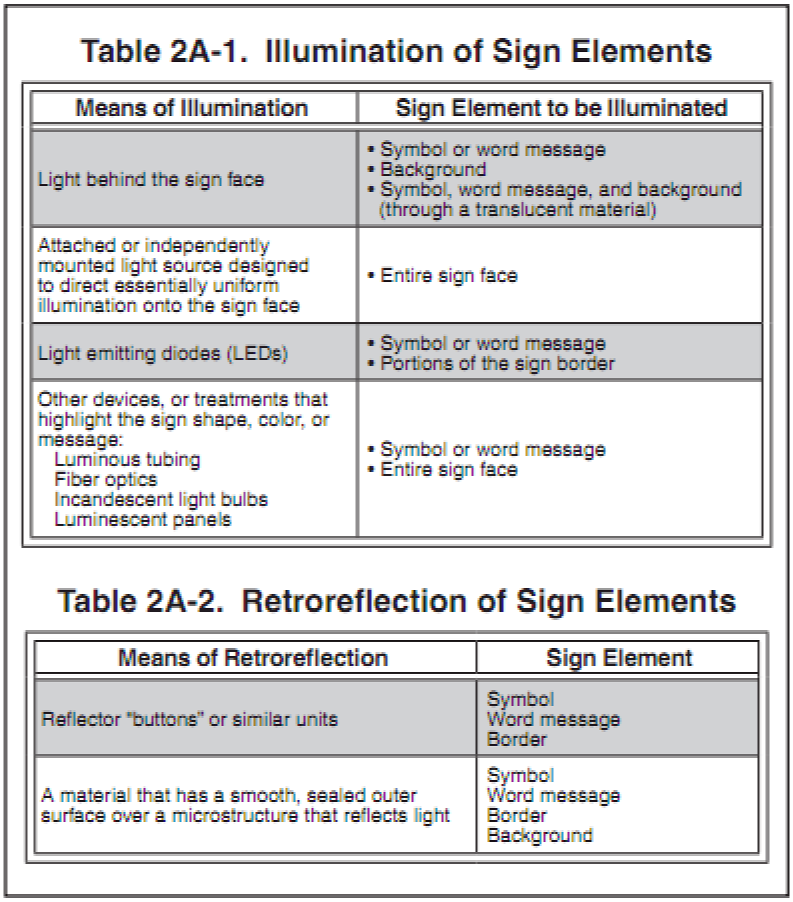


Table 2A-1. Illumination of Sign Elements

Means of Illumination	Sign Element to be Illuminated
Light behind the sign face	• Symbol or word message • Background • Symbol, word message, and background (through a translucent material)
Attached or independently mounted light source designed to direct essentially uniform illumination onto the sign face	• Entire sign face
Light emitting diodes (LEDs)	• Symbol or word message • Portions of the sign border
Other devices, or treatments that highlight the sign shape, color, or message: Luminous tubing Fiber optics Incandescent light bulbs Luminescent panels	• Symbol or word message • Entire sign face

Table 2A-2. Retroreflection of Sign Elements

Means of Retroreflection	Sign Element
Reflector "buttons" or similar units	Symbol Word message Border
A material that has a smooth, sealed outer surface over a microstructure that reflects light	Symbol Word message Border Background

Figure 3. Standards for illumination and retroreflection of sign elements.
(Source: FHWA, 2009, p. 29)

The MUTCD notes that, if used, the light-emitting diodes (LEDs) shall have a maximum diameter of 1/4 inch and shall be the following colors based on the type of sign:

- White or red, if used with STOP or YIELD signs.
- White, if used with regulatory signs other than STOP or YIELD signs.
- White or yellow, if used with warning signs.

- White, if used with guide signs.
- White, yellow, or orange, if used with temporary traffic control signs.
- White or yellow, if used with school area signs.

Additionally, if flashed, all LED units are to flash simultaneously at a rate of more than 50 and less than 60 times per minute (FHWA, 2009, p.30).

Sign Size

Sizes for TTC signs and plaques are shown in Table 6F-1 of the MUTCD (FHWA, 2009; except as provided in Section 2A.11; see Appendix D). The minimum sizes are only for use on local streets or roadways where the 85th-percentile speed or posted speed limit is less than 35 mph. When necessary for greater legibility or emphasis, alterations to the dimensions of signs and plaques can be made in 6-inch increments. Further information regarding specific sign details is contained in the SHSM book.

Standardization of Location

While the standardization of sign locations is not always possible, Section 6F.03 of the MUTCD provides guidance for sign placement. Generally, signs should be located on the right-hand side of the roadway. Signs requiring separate decisions by the road user are to be spaced sufficiently far apart for the appropriate decisions to be made.

One of the factors to consider when determining the appropriate spacing is the posted or 85th-percentile speed. Signs in other locations are to be considered only as supplementary to signs in the normal locations, except as otherwise provided in the MUTCD. For example, when special emphasis is needed, signs may be placed on both the left-hand and right-hand sides of the roadway. Signs mounted on portable supports may be placed within the roadway itself. According FHWA, 2009 (pp. 40-41), signs should be located so that they:

A. Are outside the clear zone unless placed on a breakaway or yielding support (see Section 2A.19),
B. Optimize nighttime visibility,
C. Minimize the effects of mud splatter and debris,
D. Do not obscure each other,
E. Do not obscure the sight distance to approaching vehicles on the major street for drivers who are stopped on minor-street approaches, and
F. Are not hidden from view.

Furthermore, the MUTCD (FHWA, 2009) notes that all sign supports must be crashworthy. Large signs exceeding 50 square ft are to be installed on multiple breakaway posts that have a clearance from the ground to the bottom of the sign of at least 7 ft. Signs may also be mounted on or above barricades. The bottom of signs mounted on barricades or portable supports must be at least 1 foot above the traveled way. Sign height measurements are as follows (FHWA, 2009, p. 577; See Appendix E and F):

> The minimum height, measured vertically from the bottom of the sign to the elevation of the near edge of the pavement, of signs installed at the side of the road in rural areas shall be 5 ft (see Figure 6F-1). The minimum height, measured vertically from the bottom of

the sign to the top of the curb, or in the absence of curb, measured vertically from the bottom of the sign to the elevation of the near edge of the traveled way, of signs installed at the side of the road in business, commercial, or residential areas where parking or pedestrian movements are likely to occur, or where the view of the sign might be obstructed, shall be 7 ft (see Figure 6F-1). The minimum height, measured vertically from the bottom of the sign to the sidewalk, of signs installed above sidewalks shall be 7 ft.

Portable Changeable Message Signs

The MUTCD notes that portable changeable message signs (PCMSs) are TTC devices installed for temporary use which have the flexibility to display a variety of messages (FHWA, 2009). In most cases, PCMSs follow the same guidelines for design and application as those provided for changeable message signs in Section 2L of MUTCD. MUTCD Section 6F.60 discusses situations where the provisions for PCMSs differ from those of changeable message signs (FHWA, 2009).

The MUTCD notes that PCMSs have a wide variety of applications in TTC zones, including: roadway, lane, or ramp closures; incident management; width restriction information; speed control or reductions; advisories on work scheduling; road user management and diversion; warning of adverse conditions or special events; and other operational control. Further, as indicated in the MUTCD, the primary purpose of MUTCD in TTC zones is to advise the road user of unexpected situations. The MUTCD indicates that PCMSs are useful as they are capable of conveying complex messages, displaying real-time information about conditions ahead, and providing information to assist road users in making decisions prior to the point where actions must be taken (FHWA, 2009, p. 599). PCMSs’ typical applications include:

- Where the speed of vehicular traffic is expected to drop substantially;
- Where significant queuing and delays are expected;
- Where adverse environmental conditions are present;
- Where there are changes in alignment or surface conditions;
- Where advance notice of ramp, lane, or roadway closures is needed;
- Where crash or incident management is needed; and/or
- Where changes in the road user pattern occur.

PCMS components include: a message sign, control systems, a power source, and mounting and transporting equipment. In addition, the front face of the sign should be covered with a protective material. PCMSs in TTC zones are required to meet the design and application principles as non-portable changeable message signs. PCMSs are only to be used for the display of traffic operational, regulatory, warning, and guidance information. Table 1A-2 of the MUTCD provides a listing of the abbreviations that are to be used only on PCMS (2009, p.25). Table 1A-3 of the MUTCD (FHWA, 2009, p. 26) lists unacceptable abbreviations. Both tables have been included as Appendix G.

The MUTCD notes that the PCMS must have a control system that includes a display screen upon which messages can be reviewed before being displayed on the message sign. Additionally, PCMSs need to be equipped with a power source and a battery back-up to provide continuous operation in the event of a failure of the primary power source. Similarly, the control system needs to be capable of maintaining memory when power is unavailable (FHWA, 2009, p. 600).

Visibility and Legibility

The MUTCD indicates that the maximum distance at which a driver can first correctly identify letters and words on a sign is called the legibility distance of the sign, which is affected by the characteristics of the sign design and the visual capabilities of drivers (2009, p.326). Additionally, legibility distances are much shorter when the sun is behind the sign face, when the sun is on the horizon and shining on the sign face, or at night (FHWA, 2009). Visibility is the characteristic that enables a PCMS to be seen. Visibility is associated with the point where the PCMS is first detected, whereas legibility is the point where the message on the PCMS can be read. Environmental conditions such as rain, fog, and snow impact the visibility of changeable message signs and can reduce the legibility distances. The guideline for visibility and legibility is as follows:

> Changeable message signs used on roadways with speed limits of 55 mph or higher should be visible from ½ mile under both day and night conditions. The message should be designed to be legible from a minimum distance of 600 ft for nighttime conditions and 800 ft for normal daylight conditions. When environmental conditions that reduce visibility and legibility are present, or when the legibility distances stated in the previous sentences in this paragraph cannot be practically achieved, messages composed of fewer units of information should be used and consideration should be given to limiting the message to a single phase. (FHWA, 2009, p. 326)

PCMS Placement

According to the MUTCD, PCMSs should be visible from ½ mile under both day and night conditions. Additionally, PCMSs need to automatically adjust their brightness under varying light conditions. When mounting the PCMS on a trailer, a large truck, or a service patrol truck, it should be mounted so that the bottom of the message sign shall be a minimum of 7 ft above the roadway in urban areas and 5 ft above the roadway in rural areas when it is in operating mode. The MUTCD's further guidance regarding the placement of PCMS includes (FHWA, 2009, pp. 600-601):

- When PCMSs are used for route diversion, they should be placed far enough in advance of the diversion to allow road users ample opportunity to perform necessary lane changes, to adjust their speed, or to exit the affected highway.
- PCMSs should be sited and aligned to provide maximum legibility and to allow time for road users to respond appropriately to the PCMS message.
- PCMSs should be placed off the shoulder of the roadway and behind a traffic barrier, if practical. Where a traffic barrier is not available to shield the PCMS, it should be placed off the shoulder and outside of the clear zone. If a PCMS has to be placed on the shoulder of the roadway or within the clear zone, it should be delineated with retroreflective TTC devices.
- When PCMSs are used in TTC zones, they should display only TTC messages. When PCMSs are not being used to display TTC messages, they should be relocated such

that they are outside of the clear zone or shielded behind a traffic barrier and turned away from traffic. If relocation or shielding is not practical, they should be delineated with retroreflective TTC devices.

PCMS Message Design

As previously noted, in most cases, PCMSs follow the same guidelines for design and application as those provided for changeable message signs in Section 2L, Changeable Message Signs, of MUTCD. Section 6F.60 of the MUTCD discusses situations where the provisions for PCMSs differ from those of changeable message signs. Colors used for legends on PCMSs must comply with those shown in Table 2A-5 (FHWA, 2009; Appendix H). Generally, TTC devices are to have black backgrounds with orange writing. In regard to message length and units of information, "the maximum length of a message should be dictated by the number of units of information contained in the message, in addition to the size of the CMS. A unit of information, which is a single answer to a single question that a driver can use to make a decision, should not be more than four words." Word messages should be as brief as possible and the lettering should be large enough to provide the necessary legibility distance (a minimum specific ratio of 1 inch of letter height per 30 ft of legibility distance should be used; FHWA, 2009, p. 35). Because road users have difficulty reading messages displayed in more than two phases on a typical three-line PCMS, PCMS messages should consist of no more than two phases, and a phase should consist of no more than three lines of text. Each phase should be capable of being understood by itself, regardless of the order in which it is read. Therefore, the message should be as brief as possible and should contain three thoughts (with each thought preferably shown on its own line) that convey (see Section 2L.05 of the MUTCD; FHWA, 2009):

a. The problem or situation that the road user will encounter ahead,
b. The location of or distance to the problem or situation, and
c. The recommended driver action.

When displaying messages on changeable message signs, the following principles relative to message display should be used (See Sections 2L.04 and 2L.05 of the MUTCD; FHWA, 2009, p. 325 - 328):

1) The minimum time that an individual phase is displayed should be based on 1 second per word or seconds per unit of information, whichever produces a lesser value. The display time for a phase should never be less than 2 seconds.
2) The maximum cycle time of a two-phase message should be 8 seconds.
3) The duration between the display of two phases should not exceed 0.3 seconds.
4) No more than three units of information should be displayed on a phase of a message.
5) No more than four units of information should be in a message when the traffic operating speeds are 35 mph or more.
6) No more than five units of information should be in a message when the traffic operating speeds are less than 35 mph.
7) Only one unit of information should appear on each line of the CMS.
8) Compatible units of information should be displayed on the same message phase.
9) The following formatting rules apply:
    a. Messages should be centered within each line of legend.

b. Techniques of message display such as animation, rapid flashing, dissolving, exploding, scrolling, travelling horizontally or vertically across the face of the sign, or other dynamic elements shall not be used.
c. Word messages should not contain period, apostrophes, question marks, ampersands, or other punctuation or characters that are not letters, numerals, or hyphens unless necessary to avoid confusion.
d. The solidus (slanted line or forward slash) is intended to be used for fractions only and should not be used to separate words on the same line of legend. Instead, a hyphen should be used for this purpose, such as “TRUCKS - BUSES.”
e. Fractions shall be displayed with the numerator and denominator diagonally arranged about the solidus (slanted line or forward slash). The overall height of the fraction is measured from the top of the numerator to the bottom of the denominator, each of which is vertically aligned with the upper and lower ends of the solidus. The overall height of the fraction shall be determined by the height of the numerals within the fraction, and shall be 1.5 times the height of an individual numeral within the fraction.
f. All sign lettering shall be in upper-case letters as provided in SHSM book unless otherwise provided for. Specific examples of exceptions include: the sign lettering for names of places, streets, and highways shall be composed of a combination of lower-case letters with initial upper-case letters;
g. When a mixed-case legend is used, the height of the lower-case letters shall be 3/4 of the height of the initial upper-case letter. The unique letter forms for each of the Standard Alphabet series shall not be stretched, compressed, warped, or otherwise manipulated.

Additional guidance is as follows (FHWA, 2009 p. 35 and 600):

1) A portable changeable message sign should be limited to three lines of eight characters per line or should consist of a full matrix display. Except as noted below, the letter height used for portable changeable message sign messages should be a minimum of 18 inches.
    a. For portable changeable message signs mounted on service patrol trucks or other incident response vehicles, a letter height as short as 10 inches may be used.
    b. Shorter letter sizes may also be used on a portable changeable message sign used on low speed facilities provided that the message is legible from at least 650 feet.
2) If more than two phases are needed to display a message, additional portable changeable message signs should be used. When a message is divided into two phases, the display time for each phase should be at least 2 seconds, and the sum of the display times for both of the phases should be a maximum of 8 seconds.
3) When multiple portable changeable message signs are needed, they should be placed on the same side of the roadway and they should be separated from each other by a distance of at least 1,000 feet on freeways and expressways, and by a distance of at least 500 feet on other types of highways.

Virginia Standards

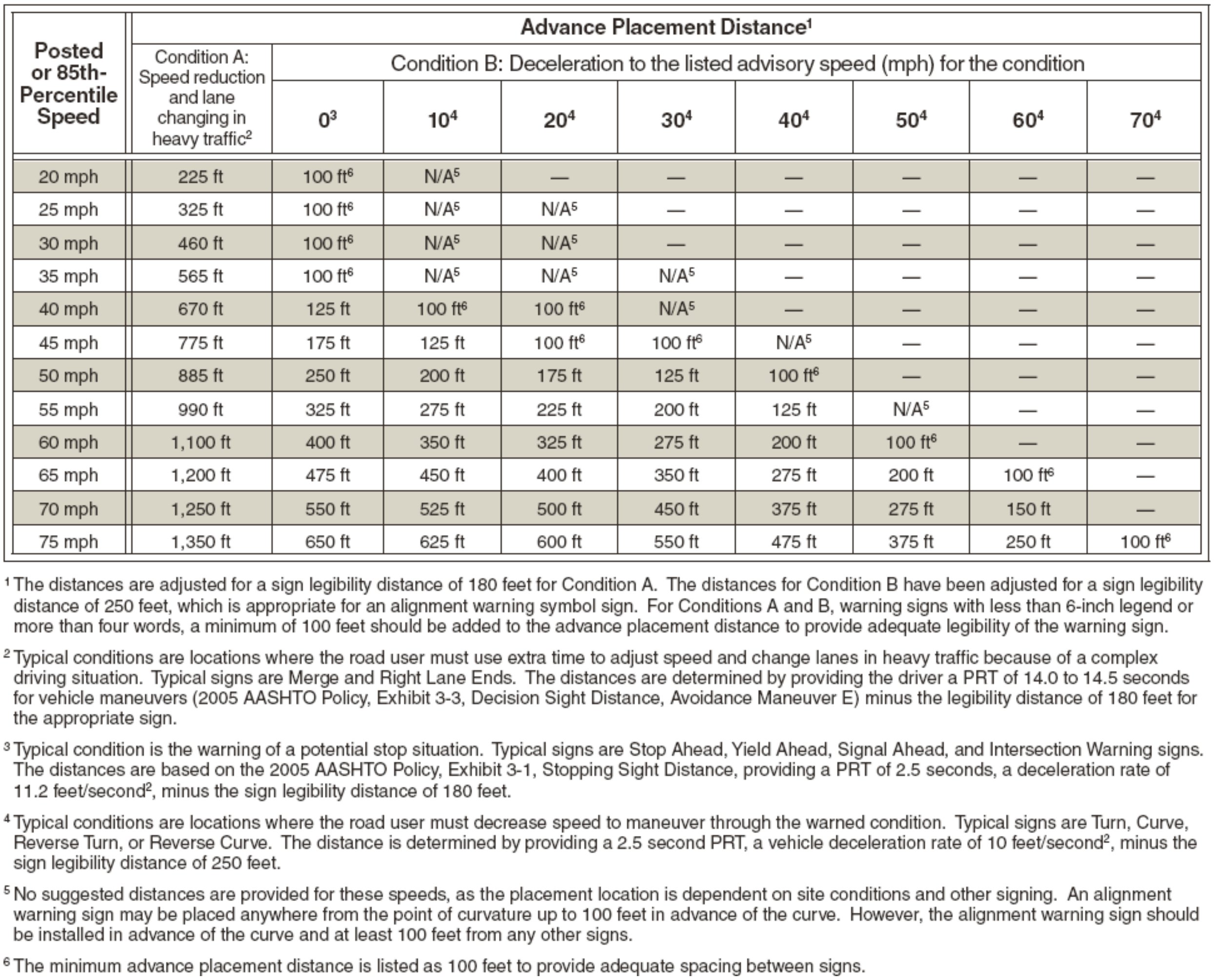
Virginia standards regarding over-width vehicles are presented in the VDOT Traffic Engineering Memorandum TE-339, Restricted Width Route Sign. VDOT has created a restricted width route sign for use in situations where construction/maintenance activities create roadway width restrictions that are less than 14 ft. These signs are intended to warn operators of vehicles with blanket width permits that the roadway may be insufficient for their passage.

Sign Installation

Restricted route signs are to be installed on roadways where construction/maintenance activities exist with physical barriers on both sides of a single lane and the clear distance between edge lines is less than 14 ft (Khoury, 2006).

Signs are to be installed in advance of the location where the clear width is less than 14 ft and also in advance of the last alternative route. VDOT instructs that the signs are installed according to the MUTCD Table 2C-4, Guidelines for Advance Placement of Warning Signs (Table 4). Signs are also to be installed on the approaches of the alternate route to alert traffic intending to turn onto the restricted route. For placement on highways where the intersection of the last alternate route is via an interchange, VDOT instructs that signs should be installed on the alternate route for both directions. When advance signs are installed on the alternate routes, a third sign consisting of the appropriate M6 directional arrow panel to indicate the direction of the restriction is to be installed below the main sign (Figure 4). Additionally, when other roadways exist between the last route and the restricted location, which may generate traffic having blanket width permits, VDOT recommends considering posting additional signs at those intersecting locations (Khoury, 2006). Appendix I provides the design details for Virginia's restricted width route signs.

Table 4. MUTCD Table 2C-4. Guidelines for advance placement of warning signs.
(Source: FHWA, 2009, p. 108)



Posted or 85th-Percentile Speed	Advance Placement Distance[1]								
	Condition A: Speed reduction and lane changing in heavy traffic[2]	Condition B: Deceleration to the listed advisory speed (mph) for the condition							
		0[3]	10[4]	20[4]	30[4]	40[4]	50[4]	60[4]	70[4]
20 mph	225 ft	100 ft[6]	N/A[5]	—	—	—	—	—	—
25 mph	325 ft	100 ft[6]	N/A[5]	N/A[5]	—	—	—	—	—
30 mph	460 ft	100 ft[6]	N/A[5]	N/A[5]	—	—	—	—	—
35 mph	565 ft	100 ft[6]	N/A[5]	N/A[5]	N/A[5]	—	—	—	—
40 mph	670 ft	125 ft	100 ft[6]	100 ft[6]	N/A[5]	—	—	—	—
45 mph	775 ft	175 ft	125 ft	100 ft[6]	100 ft[6]	N/A[5]	—	—	—
50 mph	885 ft	250 ft	200 ft	175 ft	125 ft	100 ft[6]	—	—	—
55 mph	990 ft	325 ft	275 ft	225 ft	200 ft	125 ft	N/A[5]	—	—
60 mph	1,100 ft	400 ft	350 ft	325 ft	275 ft	200 ft	100 ft[6]	—	—
65 mph	1,200 ft	475 ft	450 ft	400 ft	350 ft	275 ft	200 ft	100 ft[6]	—
70 mph	1,250 ft	550 ft	525 ft	500 ft	450 ft	375 ft	275 ft	150 ft	—
75 mph	1,350 ft	650 ft	625 ft	600 ft	550 ft	475 ft	375 ft	250 ft	100 ft[6]

[1] The distances are adjusted for a sign legibility distance of 180 feet for Condition A. The distances for Condition B have been adjusted for a sign legibility distance of 250 feet, which is appropriate for an alignment warning symbol sign. For Conditions A and B, warning signs with less than 6-inch legend or more than four words, a minimum of 100 feet should be added to the advance placement distance to provide adequate legibility of the warning sign.

[2] Typical conditions are locations where the road user must use extra time to adjust speed and change lanes in heavy traffic because of a complex driving situation. Typical signs are Merge and Right Lane Ends. The distances are determined by providing the driver a PRT of 14.0 to 14.5 seconds for vehicle maneuvers (2005 AASHTO Policy, Exhibit 3-3, Decision Sight Distance, Avoidance Maneuver E) minus the legibility distance of 180 feet for the appropriate sign.

[3] Typical condition is the warning of a potential stop situation. Typical signs are Stop Ahead, Yield Ahead, Signal Ahead, and Intersection Warning signs. The distances are based on the 2005 AASHTO Policy, Exhibit 3-1, Stopping Sight Distance, providing a PRT of 2.5 seconds, a deceleration rate of 11.2 feet/second^2, minus the sign legibility distance of 180 feet.

[4] Typical conditions are locations where the road user must decrease speed to maneuver through the warned condition. Typical signs are Turn, Curve, Reverse Turn, or Reverse Curve. The distance is determined by providing a 2.5 second PRT, a vehicle deceleration rate of 10 feet/second^2, minus the sign legibility distance of 250 feet.

[5] No suggested distances are provided for these speeds, as the placement location is dependent on site conditions and other signing. An alignment warning sign may be placed anywhere from the point of curvature up to 100 feet in advance of the curve. However, the alignment warning sign should be installed in advance of the curve and at least 100 feet from any other signs.

[6] The minimum advance placement distance is listed as 100 feet to provide adequate spacing between signs.

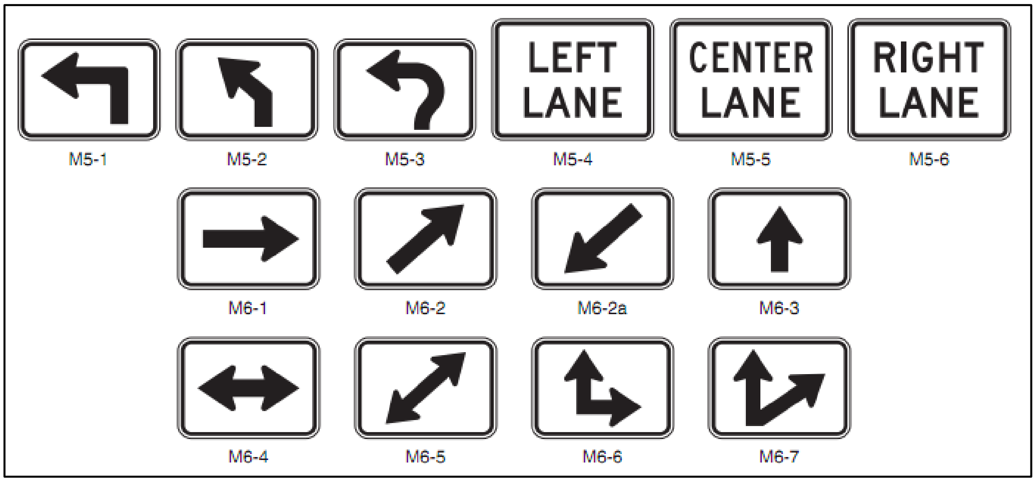


Figure 4. MUTCD Figure 2D-5, Advance Turn and Directional Arrow Auxiliary Signs
(Source: Adapted from FHWA, 2009, p. 147)

Additional Over-Size Detection Practices and Procedures

RITA ITS Deployment Statistics indicate that 23 states (of the 43 returned state surveys) have deployed an automated over-height or over-width warning system that uses roadside detectors and electronic warning signs to warn drivers of vehicles that are too tall or wide to pass under bridges or tunnels (Carson, 2008). "However, while preliminary research would suggest that both over-width and over-height detections are employed, further research indicates that over-size alert systems tend to be targeted to over-height detection with potential application for over-width notification." (Carson, 2008, p.2) Additionally, the installation of a warning system will not guarantee a 100% reduction in incidents. For example, an over-size notification warning system was installed on a tunnel outside of Pittsburgh, Pennsylvania. Yet, in 2001, a driver ignored the system's warnings and in 2006 another driver assumed that his truck would fit in the tunnel at a time when the system was inactive due to mechanical problems (Drakopoulos, 2006). Hanchey and Exley (1990) discussed three basic bridge protection schemes used to warn drivers of over-height conditions (i.e., a rigid passive overhead device, a non-rigid passive overhead device, and an active detection and warning system). From their research they concluded that neither non-rigid passive overhead devices (e.g., a set of chains suspended from a span wire) nor audible alarms installed as part of an active detection and warning system provided drivers with adequate warning because of the loudness of truck engines. Additionally, they concluded that bridge strikes could not be fully eliminated due to driver error. In 2002, Michigan's DOT examined strategies used to mitigate bridge hit incidents and corollary damage costs (Cawley, 2002). Through this study, three groups of countermeasures were identified along with corresponding issues (Table 5).

Table 5. Cost comparisons for over-height warning action alternatives.
(Source: Adapted from Cawley, 2002)

	Description	Estimated Cost	Estimated Effectiveness	Issues
Passive Signing and Permitting	Signing, continued permit process, possible increased promotion and outreach	$9,000	10% – 20%	Requires increased permit awareness
Sacrificial Structure	Physical notification or sacrificial structure (e.g., chains/metal foil strips hanging as a target or false structure used to warn drivers)	$62,000	30% - 50%	Can create liability for agency
Active Detection and Warning System	ITS-based warning utilizing electronics to detect the vehicle and provides a visible/audible warning. Consists of infrared transmitter, receiver, warning sign with alternating flashers and optional audible alarms.	$110,000	50% - 80%	Will not eliminate all collisions

Bridge Over-Height Detection System Practices

An example over-height sign layout with potential applicability for over-width detection can be found within the Minnesota Department of Transportation's Intelligent Work Zone Systems Toolbox (Minnesota Department of Transportation Office of Traffic, Safety, and

Operations, 2008, p. 18). The Toolbox includes the plans for a vehicle responsive over-dimension warning system for use in work zones where minimal clearance conditions exist. In accordance with the MUTCD, this Minnesota system includes a multiple alert approach:

1) A warning sign that adheres to the principles presented in the MUTCD:
    a) The problem or situation that the road user will encounter ahead,
    b) The location of or distance to the problem or situation, and
    c) The recommended driver action.
2) Non-intrusive detection placed along the roadway as needed to measure for over-dimensions in vehicles.
3) An alert to the driver that the vehicle is over-dimension and the use of an escape route is required. The alert can either be vehicle-specific and presented on PCMS or may include option signage, such as a sign with warning lights.
4) A non-intrusive detection system to determine whether an over-dimension vehicle missed the exit. Drivers who have missed the exit are to be alerted of their route mistake and should be provided sufficient time to conduct the escape maneuver.
5) Audible alerts to warn vehicle drivers and roadway workers of vehicle intrusion in the restricted area combined with room to stop and pull over before restriction.

An illustration of this approach is provided in Appendix J. It is important to note that these guidelines were last revised in 2008, which pre-dates the current MUTCD.

Agrawal (2010) surveyed states to determine current procedures for addressing over-size concerns in relation to bridge hits. As part of this effort, participants were asked to rate on a scale of 0 to 100 the three causes of bridge hits identified on the basis of analysis of the New York State DOT bridge hits database: over-height trucks, accidental equipment storage, and reckless drivers, Over-height trucks (59%) were identified as the prime cause of bridge hits followed by accidental equipment storage (21%) and reckless drivers (13%). The low percentage attributed to reckless drivers should be considered concomitantly with another survey finding regarding driver knowledge. Agrawal (2010) noted that a United Kingdom study found that truck drivers who were aware of the height of their truck/cargo were more likely to react to low-clearance warning signs. Therefore, states were asked if they required truck drivers to know the height of their truck/cargo. Forty-three of the 44 responding states required truck drivers to know the height of their truck/cargo. Agrawal (2010) also identified bridge vertical under-clearance requirements, under-reporting of actual vertical under-clearance (i.e., posting legal vertical clearance as less than the actual clearance), and placement of warning signs (Figure 5 and Figure 6). Further, Agrawal explored messages posted on signs near bridges. He found that a majority of states use messages such as “Low Clearance Ahead,” “No Vehicles Over xx Ft xx inches,” etc. (Agrawal, 2010, p. 13). Finally, Agrawal determined that 14 states had passive over-height systems (e.g., chains, headache bars, etc.) and 15 had automated vehicle height measurement systems. Those with automated vehicle height systems were: Maryland, Virginia, Maine, South Dakota, Texas, South Carolina, Massachusetts, Idaho, Hawaii, Montana, Wyoming, Minnesota, Missouri, Wisconsin, and Alaska. For example, the Maryland Department of Transportation’s State Highway Administration’s over-height warning detection system alerts CV drivers of a low clearance bridge on MD 75 near Baldwin Road (Maryland Department of Transportation’s State Highway Administration, 2010). Of the states with automated systems, no further data were obtained from Idaho, Montana, and Wisconsin. South Dakota, Massachusetts, and South

Carolina stated that they used automated vehicle height detection systems several years ago and didn't have information on the systems (Agrawal, 2010). A summary of Agrawal's second stage survey of the automated vehicle over-height measurement systems is presented in Appendix K. These findings include system-specific details, opinions of the system, and additional notable approaches that have been effective in reducing the frequency of bridge hits (Agrawal, 2010, pp. 16-18).

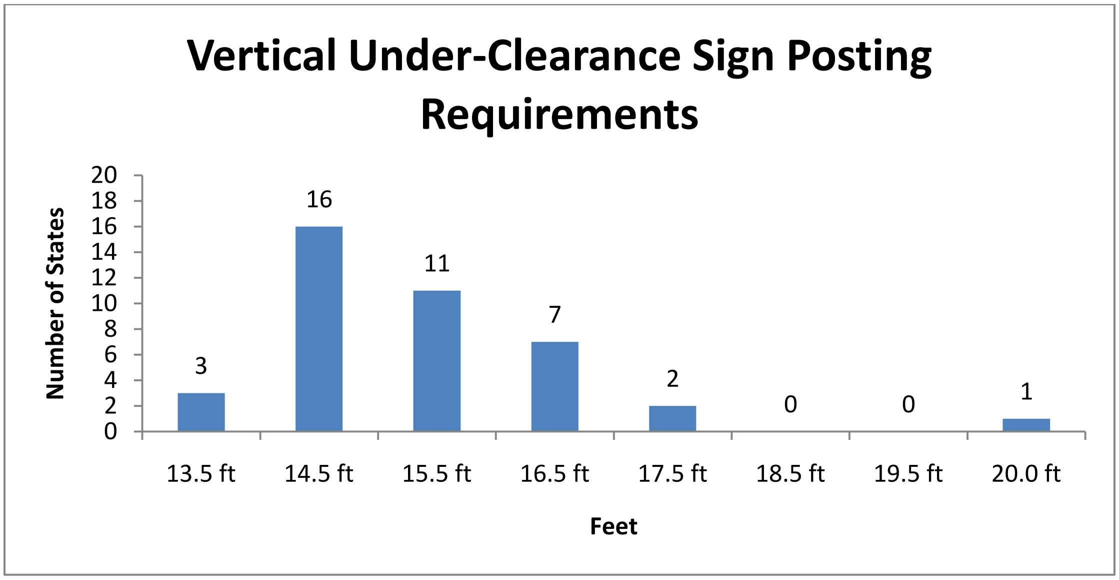


Figure 5. Bridge vertical under-clearance requiring sign posting.
(Source: Adapted from Agrawal, 2010a)

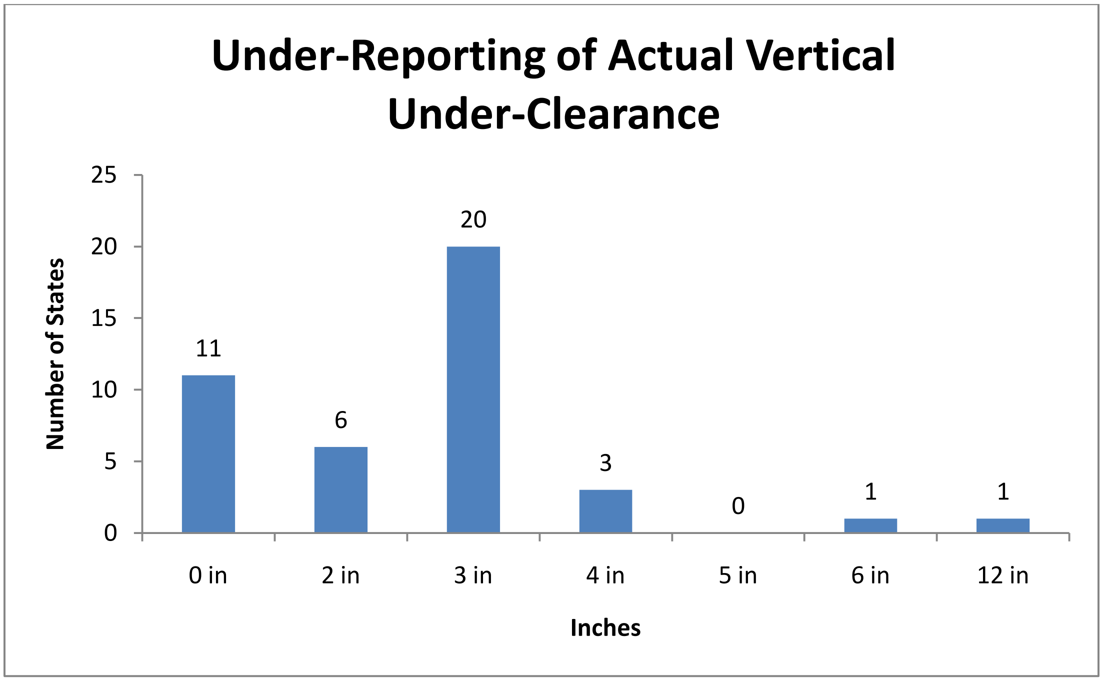


Figure 6. Under-reporting of actual vertical under-clearance.
(Source: Adapted from Agrawal, 2010a)

Over-width Vehicle Driver and Escort Interviews

A key part of this study involved interviews with drivers that transport and/or escort over-width loads in Virginia. Interviews were used to gather information from drivers regarding their perspective on what is most effective and least effective about current over-width signage, how they think current signage can be improved, and experiences they have had entering lane-restricted areas while transporting or escorting over-width loads.

Method

Participants

The subject pool for this study consisted of drivers that transport and/or escort over-width loads in Virginia. These drivers were recruited because of their unique understanding and experience regarding the signage currently used in Virginia to alert over-width vehicle drivers/escorts to lane restrictions such as work zones. Seven drivers (four escort drivers and three over-width drivers) were involved in the study. Two participants mentioned that they had worked as both escort and over-width drivers.

Participants for this study were identified via the World Wide Web. The websites used for recruitment included:

- Drivers that Transport Over-width Loads
    - Mobile Home Park Store (http://www.mobilehomeparkstore.com)
    - Fleet Directory (http://www.fleetdirectory.com)
- Drivers that Escort Over-width Loads
    - Oversize Load Escorts (http://www.oversizeloadescorts.com)
    - US and Canada Pilot Cars (http://www.uspilotcars.com)

During the recruitment process, VTTI contacted over-width transport and escort companies via phone and/or e-mail. Participant privacy and confidentiality information was presented to each participant in an informed consent form (ICF) sent via email or fax. The informed consent form (Appendix L) described the purpose of the study, study procedures, general risks of the study, confidentiality procedures, and participant rights and responsibilities. At the start of the phone interview, participants were reminded through a verbal consent process (Appendix M) of the key sections of the ICF (i.e., time required, confidentiality, etc.) and asked to voice any concerns or questions that he/she had to a researcher. Once any questions and concerns were addressed, researchers asked participants to provide their verbal consent to participate in the interview rather than providing a hand written signature. One person chose to have the ICF read verbally to him prior to the interview instead of receiving a fax/e-mail.

During data reduction and analysis participant privacy was protected. All audio files were transcribed without the use of personal names so that no participant comments could be connected with names. The audio files and transcripts are kept on password-protected computers that are only accessible to researchers working on the project.

Data Collection and Transcription

As part of the system development process, the VTTI team used interviews to gather opinions from drivers about current over-width signage in Virginia. The purpose of the interviews was to understand what over-width signage is most effective, what over-width signage is least effective, what causes a driver/escort to enter a lane-restricted area, and how over-width signage can be improved from the perspective of those who experience it regularly as part of their job transporting and/or escorting over-width loads. The interview script (Appendix N) varied slightly by driver type (i.e., escort driver versus over-width driver). The interview script was general in format to allow researchers to cover key topic areas while allowing for flexibility to delve into issues of interest with each participant. The duration of the interviews varied but all were kept to less than 15 minutes in length.

All seven interviews were audio-recorded and transcription of the discussions was completed for data reduction purposes. The transcription process involved initial transcription of audio files and then a complete review of the transcript for quality control purposes by a member of the research team. The seven interviews resulted in more than an hour of discussion. After transcription was completed, researchers conducted a brief content analysis on the interview results.

Data Analysis

The approach used to analyze the results of the interviews was an adaptation of framework analysis, a methodology developed in the 1980s at the National Centre for Social Research in Britain (Ritchie et al., 2003). The steps that were taken to carry out the framework analysis were as follows:

1) **Determining Analysis/Thematic Focus:** Researchers determined that the focus of the framework analysis would be on driver opinions related to four key areas or themes of importance to the development of an advanced vehicle measurement and warning system: most effective signage, least effective signage, reasons for entering width-restricted area, and sign suggestions.
2) **Transcribing:** Each interview was transcribed in full and then reviewed for quality control purposes by a member of the research team.
3) **Familiarization:** A researcher read over each of the transcripts to become familiar with the data set.
4) **Indexing Themes:** A researcher conducted a review of the data set and comments were identified and marked in the transcripts by theme (e.g., Most Effective Signage). Multiple themes were assigned to the statements if necessary.
5) **Charting Themes:** A researcher arranged indexed comments into Microsoft® Excel® spreadsheets. Individual spreadsheets were created for each theme.
6) **Identifying Sub-Thematic Framework:** A researcher conducted a review of the thematic spreadsheets and identified for each theme (e.g., Most Effective Signage, Least Effective Signage, Reasons for Entering Restricted Area, Sign Suggestions) a list of subthemes. A subtheme was considered to be an idea or concept mentioned by at least two participants in response to a particular question. For instance, under the theme Most Effective Signage were the subthemes Detour Information, Restriction Information, and Electronic Signs. Once the subthemes were identified, the spreadsheets or thematic charts

were further sorted by subtheme (e.g., Most Effective Signage: Detour Information) and arranged in a logical order for interpretation.

7) **Interpretation:** As a last step in the framework analysis process, the themes and subthemes detailed in the charts were used by the research team to better understand driver perspectives related to the themes. A summary of the results of the content analysis are found in the following results section.

Results

During the interviews, information was collected regarding the key themes of interest for the study (i.e., Most Effective Signage, Least Effective Signage, Reasons for Entering Lane-Restricted Area, and Suggestions for Signage). Participants were also asked about their years of experience escorting and/or driving over-width loads, their experience entering width-restricted areas, and other general suggestions related to over-width signage in Virginia.

Years Experience

In terms of experience, over-width drivers had a range of 36 to 52 years of experience (mean of 43) transporting over-width loads. Escort drivers had a range of 1 to 30 years experience (mean of 12) of escorting over-width loads. In total, participants brought 176 years of experience to bear on the discussion of over-width signage in Virginia.

Most Effective Signage

Participants were asked in the interview about the most effective signage they had experienced while transporting or escorting an over-width load. An effective over-width warning sign was described as one that is electronic and provides specific restriction and detour/alternate routing information. As one participant said, effective signs were “lighted signs and they gave you warning.” Another participant described how signs in West Virginia that include wide load restrictions and dimensions are effective. In terms of alternative routing, one participant said “I personally think everything was well with re-routing us over a different way, you know, ‘Get off this exit ramp because it is restricted to wide loads you can’t cross, come through.’ I’ve seen that being effective.”

Least Effective Signage

Interview participants were asked about the least effective signage they had experienced while transporting or escorting an over-width load. Three participants did not answer this question, saying they didn’t know or had not experienced ineffective signage. Of those who answered the question, the least effective signage was described as a sign that was unspecified and/or unreadable. Unspecified signage was described by one participant as signage that provides generic wording such as “road narrows” versus specific information. The participant said “I mean, yeah, it is helpful information but it is not really effective if we don’t know how narrow it is, if it is not specified.” Unreadable signage was described as signage with wording that is too small or that is flashing too fast to be read. One participant said: “a lot of times with their flashing, the writing is on but by the time you get through the writing is gone and you go by before you see what it says.”

Width-Restricted Area Entry

Of the seven participants interviewed, five (i.e., three escort drivers and two over-width drivers) said they had entered a width-restricted area while transporting/escorting an over-width load. While one participant said "oh yeah, we always do that" another participant said that he had never entered a width-restricted area because "I always go ahead and check my routes before I pull the over-width. And then I change my route if I see there is a restriction."

Reasons for Entering Width-Restricted Area

Participants who had entered a lane-restricted area cited two main reasons. The first reason was permit-related. Participants said they entered a lane-restricted area because their permit information was incorrect or they were directed by the DOT to travel on a route that ended up having paving or other road work underway. One participant said she entered a lane-restricted area because "we have to stay on route, we have to obey what Virginia, what DOT tells us to, you know, the directions that they tell us to go." The participant added that it is a problem if the DOT is "not connected with where they are doing construction, paving or what have you." Another participant indicated that he cannot re-route because he escorts superloads, and if he runs into a night paving activity when he is escorting a superload he has nowhere to go.

The other issue a few participants cited for why they ended up in a lane-restricted area was unawareness of the lane width. One participant said "personally, I didn't realize it was going to be so narrow." Another participant said, "There was no specific signage there that said how wide the area was and we just had to deal with it when we got there. If there was signage that was specific then I guess it would be helpful even a couple minutes in advance to see that signage."

Suggestions for Signage

Participants made a few suggestions for improving signage for over-width loads. Suggestions included more signage and better positioned signs. As one participant said, signage is needed "more often and set back further from the construction zone or whatever is going on up ahead to let not only the wide loads know, but also the other drivers on the road."

Other General Suggestions

A suggestion was made by a few participants that was not directly related to the issue of signage but was important input nonetheless. Two of the seven participants brought up the issue of the need for light-vehicle drivers to be trained on how to share the road with over-width vehicles. Both participants mentioned adding training information to the light-vehicle driver manual as a way to deal with this problem. As one participant said, "To be honest with you I'd like to see them put something in the driver's manual when you go to take your test for your driver's license, especially the younger people. Just making a small section in there on oversize just to let people be aware of what is going on. There has to be some changes or something because, like I said, the public is our biggest enemy out there."

Notification/Warning System

As previously identified in the Design Criteria section of this document, the main priority of the notification/warning system is to the driver transporting (and/or escorting) the over-width load. The purpose is to notify/warn the drivers or escorts when the measurement system detects a vehicle width that is unacceptable for the work zone ahead. Based on these criteria, in addition to interviews with drivers and escorts, the use of a PCMS with slight modifications is recommended for the notification/warning system. Recommended guidelines for the design of an Over-width Notification/Warning PCMS are to follow.

Over-width Notification/Warning PCMS Guidelines

Type

A PCMS is traditionally used to advise the road user of unexpected situations (e.g., width-restriction information) (FHWA, 2009, p. 599). They are typically used to convey complex messages in real time with the goal of assisting road users in making decisions prior to some roadway event ahead. The standard components of a PCMS include:

- Message Sign
- Control System (with message preview display)
- Power Source (including a back-up in case of main power failure)
- Mounting/Transportation Equipment

It is recommended that the PCMS have the capability of automatically adjusting its message brightness under varying lighting conditions (e.g., nighttime, daytime, etc.). Modifications to a standard PCMS will be required for successful operation as an Over-width Notification/Warning PCMS. These modifications would include communication capabilities with other systems: 1) one-way communication with the Vehicle-width Measurement System (signal reception capabilities), and 2) if applicable, one-way communication with work zone and/or enforcement personnel (signal transmission capabilities).

Driver Detection and Recognition

The PCMS should be aimed/aligned to provide maximum legibility and to allow time for road users to respond appropriately to the message. Flashing lights are used in other TTC systems for increasing driver detection and recognition of objects as well as signage. Channelizing Type B High-Intensity Flashing warning lights are an example of use of lighting for increasing driver detection in both daytime and nighttime conditions. Recommendations for these channelizing flashing warning lights range from 55 to 75 flashes per minute (equivalent to approximately 1 to 1.5 Hz). However, recent research by VTTI on enhanced rear lighting for light and heavy vehicles has indicated that flashing rates of 4 to 5 Hz (upwards of 300 times per minute) provide ideal driver detection capabilities (depending on whether incandescent lights or LEDs are used) (Wierwille et al., 2003; Lee et al., 2005; Wierwille et al., 2005; Wierwille et al., 2009; Schaudt et al., in press). It is recommended that flashing be utilized in the Over-width Notification/Warning PCMS whether it be LEDs presented within the message sign itself, or additional units mounted to the top. The Over-width Notification/Warning PCMS should use white or yellow lighting (preferably LEDs) to meet FHWA recommendations. If LEDs within a message sign are used and flash, the rate must be 50 to 60 times per minute. Any flashing used should not provide an unacceptable rating of discomfort glare that affects a driver's ability to read the message sign. When feasible, clustering of warning lights should be maintained in order to increase driver detection potential.

Size

The appropriate size for an Over-width Notification/Warning PCMS is a function of the roadway speed limit and/or approaching vehicle speed, and is also subject to the constraints of the roadway shoulder. The size should be at least 48 in. wide by 48 in. tall for lower speeds and upwards of 108 in. wide by 60 in. tall for higher speeds.

Content

No more than two phases should be used and no more than three lines of text. A specific ratio of 1 inch of letter height per 30 ft of legibility distance should be used. The maximum length of a message should be dictated by the number of units of information contained in the message in addition to the size of the PCMS. A unit of information should not be more than four words. Based on previous systems developed for over-height applications, it is recommended that the content be evaluated and validated prior to implementation and that it consist of two alternating phases:

1. Phase 1: "Over-width Detected"
2. Phase 2: "Exit Immediately"

The two phases above provide the same meaningful information regardless of order. Using previously identified PCMS design standards and the two recommended phases above, a total time for display can be calculated. Using a 1 s per word/unit and a 0.3 s between-display duration, a resulting value of 5.3 s is found.

Location/Placement

The Over-width Notification/Warning PCMS will only be activated when a vehicle has been measured and found in violation of the lane-restricted work zone ahead. Therefore, this PCMS should not be considered as normal work-zone signage (does not provide constant information for all roadway traffic). This indicates that these PCMSs should not be subject to traditional warning signage spacing requirements as provided in the MUTCD Section 6C.04 as Table 6C-1 and Section 6F.17. These Over-width Notification/Warning PCMSs should not replace any standard work-zone signage.

The Vehicle-width Measurement System and the Over-width Notification/Warning PCMS should be installed in advance of a work zone that contains a road section with a width of less than 14 ft and also in advance of the last alternative route (advanced warning area [FHWA, 2009]). Based on Federal and Virginia guidelines and standards, the PCMS should be placed off of the road on the right hand side when feasible. When the PCMS is not being used to display TTC messages, it should be relocated such that it is outside of the clear zone or shielded behind a traffic barrier and turned away from traffic. If relocation or shielding is not practical, the PCMS should be delineated with retroreflective TTC devices. The bottom of the message sign should be no lower than 7 ft off the ground. The Over-width Notification/Warning PCMS message should be designed to be legible from a minimum distance of 600 ft for nighttime conditions and 800 ft for normal daylight conditions (FHWA, 2009, p. 326). These minimum placement requirements are subject to vehicle speed and driver detection/perception constraints and should be considered minimums only.

The requirements for the Over-width Notification/Warning PCMS activation and distance placement from the measurement system are subject to four primary factors: 1) vehicle speed, 2) driver perception and reaction time, 3) time lag resulting from measurement system processing, signal transmission, signal reception, and warning system processing, and 4) display duration.

Vehicle Speed

The distance of the Over-width Notification/Warning PCMS in relation to the measurement system should be determined based on the expected roadway characteristics and approaching over-width vehicles. For example, a conservative estimate of over-width vehicle speeds in that area should be used (e.g. posted speed limit with a 5+ mph increase for cushion).

Driver Perception and Reaction Time

In recent research on the development of collision-warning system algorithms for driver warning-light detection, a value for assumed driver perception-reaction time of 1.5 s was used (Schaudt et al., in press; Burgett et al., 1998). In order to include a situation in which an approaching driver is also involved in a visually distracting task, a *Time to Look-up* value of 1.5 s was also introduced (Schaudt et al., in press). The purpose of this value, to be added to the perception-reaction time resulting in a total of 3.0 s of adjustment, was to adjust for the time it takes for a driver involved in a visually distracting task to have his/her visual gaze returned to the forward roadway. It is recommended that at least 3.0 s of adjustment be included in the Over-width Notification/Warning PCMS placement decision.

Time Lag

It will be important to include time lags associated with system information processing and signal transfer. Although this time lag value will likely be adjusted after system development, a conservative value of 3.0 s will be used for current Over-width Notification/Warning PCMS placement recommendations.

Display Duration

As previously calculated and described, the content is recommended to be displayed for 5.3 s based on previously identified CMS standards.

Distance between Measurement System and Warning System

Based on the above values, an equation for calculating the recommended distance between the measurement system and the warning system is below:

$$D = 1.4\overline{667}v(t_{pr} + t_d + t_l) \tag{1}$$

In this equation:

- D is the recommended minimum distance between the measurement system and the warning system (ft).
- v is the estimated closing rate of an approaching over-width vehicle for the selected roadway (mph).
- t_{pr} is the perception-reaction time of the approaching driver (s).
- t_d is the warning system display duration (s).
- t_l is the lag time associated with measurement system processing, signal transmission to receipt, and any other associated warning system process time required (s).

Table 6 provides minimum recommended distances based on the equation above using previously provided parameter values and presented by expected vehicle speeds.

Table 6. Minimum recommended distances between measurement system and notification/warning system by expected vehicle speed.

Expected Vehicle Speed	Minimum Distance (ft)
75 mph	1243
70 mph	1160
65 mph	1077
60 mph	994
55 mph	912
50 mph	829
45 mph	746
40 mph	663
35 mph	580
30 mph	497
25 mph	414
20 mph	331
15 mph	249
10 mph	166
5 mph	83

Notification/Warning System Summary

The guidelines provided in this section should be considered preliminary and may require adjustments during final system development. In addition to these guidelines, there are other human factors design characteristics that should be considered during the design and development of an Over-width Notification/Warning PCMS. These characteristics (or functional specifications) will help toward the development of a robust, final system. Three primary human factors characteristics are described below for consideration during development (but not limited to):

- Reliability – The Over-width Notification/Warning PCMS must be reliable in that it consistently activates and displays the information based on set parameters. Furthermore, the hardware and software of the system should require minimal maintenance. If the system becomes unreliable, an increase in work zone over-width vehicle violations may result.

- Adaptability to Various Environmental Conditions – The Over-width Notification/Warning PCMS must operate correctly in a variety of environmental conditions (e.g., time of day, adverse weather conditions, varying highway geometry, etc.).
- Non-Encumbering Design – The Over-width Notification/Warning PCMS should not obstruct or impede other road users for safety purposes. The system should not be overly distracting or increase discomfort glare to a point of creating a safety disbenefit to road users.

Vehicle-width Measurement Technology

The objective for the vehicle-width measurement technology portion of this project was to evaluate existing vehicle dimension measurement systems, identify design gaps, and examine promising sensor technologies to address these design gaps. Design gaps were identified by comparing existing vehicle dimension measurement systems to the vehicle-width measurement design criteria detailed in Task 2.

Existing Vehicle Dimension Measurement Systems

Two existing, in-use vehicle dimension measurement systems were found for initial evaluation in this project: 1) the Swiss Heavy Goods Vehicle (HGV) Control Centers system, and 2) the German Toll Collect System (Fontaine, 2010). The German Toll Collect System uses gantry-mounted laser scan technology to profile vehicles in height, width, and length. Vehicles beyond the size restrictions are flagged for mobile enforcement units. This pre-screening process narrows the focus of enforcement efforts, but requires human intervention. The benefit of this system is the capability to pre-screen at high speeds. In a similar manner, the Swiss HGV Control Centers use gantry-mounted sensors to measure vehicles as they pass through a specified gantry framework. However, the Swiss HGV control center requires mobile enforcement units to first identify potential vehicle-width violators, then escort them to the HGV control center where speed is restricted to less than 3 mph.

A third system, although a developmental prototype, was created by CalTrans and was included in the initial evaluation; however, after further review the system was not deemed successful in measuring the width of vehicles and was removed from further examination. Based on VTTI’s initial evaluation, none of the identified existing vehicle dimension measurement systems met the design criteria detailed in Task 2. The design gaps identified were used to select promising sensors for further evaluation in overcoming these design gaps.

Potential Sensor Solutions

During Task 2 of this research project, VTTI finalized a set of design criteria with assistance from project stakeholders (Table 1). The measurement sensor component influenced overall system power requirements, bracket requirements and, most importantly, measurement capability. Therefore, the primary system component decision relied on sensor potential.

Through literature review and subject matter expertise, nine potential sensors were identified. These potential sensors were each compared to the design criteria to evaluate the potential for success in a vehicle-width measurement system prior to acquisition and testing. Initial evaluation used design specifications provided by the manufacturers for each sensor. Additional evaluation consisted of contacting manufacturers to discuss the intended use and feasibility for success. Of the nine identified sensors that were compared to the design criteria, six were eliminated from contention. These six sensors and the corresponding justifications for elimination are listed below:

- Scanning Laser - Faro Laser Scanner Focus^{3D}
  - Discussion with manufacturer indicated that the sensor was not capable of meeting the performance requirements. Therefore, this sensor was eliminated from contention.
- LIDAR - Velodyne HDL 32E
  - Due to the extremely high cost and extensive acquisition time, the LIDAR was eliminated from contention.
- RADAR - SMS UMRR-090301-1F0300 Automotive Radar
  - Discussion with manufacturer indicated that the sensor was not capable of meeting the performance requirements. Therefore, the RADAR was eliminated from contention.
- Infrared Camera - PMD[vision]® CamCube 2.0
  - Performance specifications identified to be out of the bounds of the design criteria. Therefore, the infrared camera was eliminated from contention.
- Stereo Vision - Point Grey Research Bumblebee2
  - Performance specifications identified to be out of the bounds of the design criteria. Therefore, the stereo vision option was eliminated from contention.
- LeddarTech Sensor - Leddar™ d-tec
  - Discussion with manufacturer indicated that the sensor was not capable of meeting the performance requirements. Therefore, this sensor was eliminated from contention.

The three potential measurement sensor technologies remaining for further testing were:

- Rotary Laser - Acuity AR4000-LIR Laser Rangefinder
- Ultrasonic - Senix TSPC-21S-485
- Computer Vision – Sony XCHR57 High Speed Progressive Scan Video Camera – or – the Grasshopper® IEEE-1394b (Firewire) Digital Camera

Method

The purpose of sensor tests was to assess and determine their feasibility in measuring vehicle widths in real-world conditions. Each sensor required additional development time after procurement, which consisted of software development for interfacing with each sensor and the creation of bracket modules for roadside or overhead mounting. The testing procedures for the ultrasonic sensors and the rotary laser were similar and will be described together in each Method subsection. The computer vision testing procedures will be described separately.

Apparatus

Ultrasonic Sensors and Rotary Laser

The time to acquire ultrasonic sensors was the shortest and completed first. Research and discussion with the ultrasonic sensor manufacturer indicated a signal spread of approximately 2.5 ft. Based on the height potential for a vehicle carrying a wide load, five ultrasonic sensors were acquired. After acquisition of all five sensors, testing was performed to ensure the sensors functioned properly. Finally, the necessary in-house software testing for the ultrasonic sensors on the Virginia Smart Road was performed. The ultrasonic sensors required a data acquisition module (Senix UA-USB-485-ISO USB to RS485 converter), and a control/interface module (Dell laptop).

A bracket module was designed and constructed to simulate sensor positioning with regard to height and angle for roadside deployment. The first bracket designed and constructed was the ultrasonic sensor bracket module. To empirically observe a full tractor-trailer, the sensors were placed vertically to account for 11 ft of vertical distance. The bottom sensor was 12 inches from the ground plane and each sensor was placed 2.5 ft above the previous one. Figure 7 below shows a diagram of the completed bracket and installed sensors.

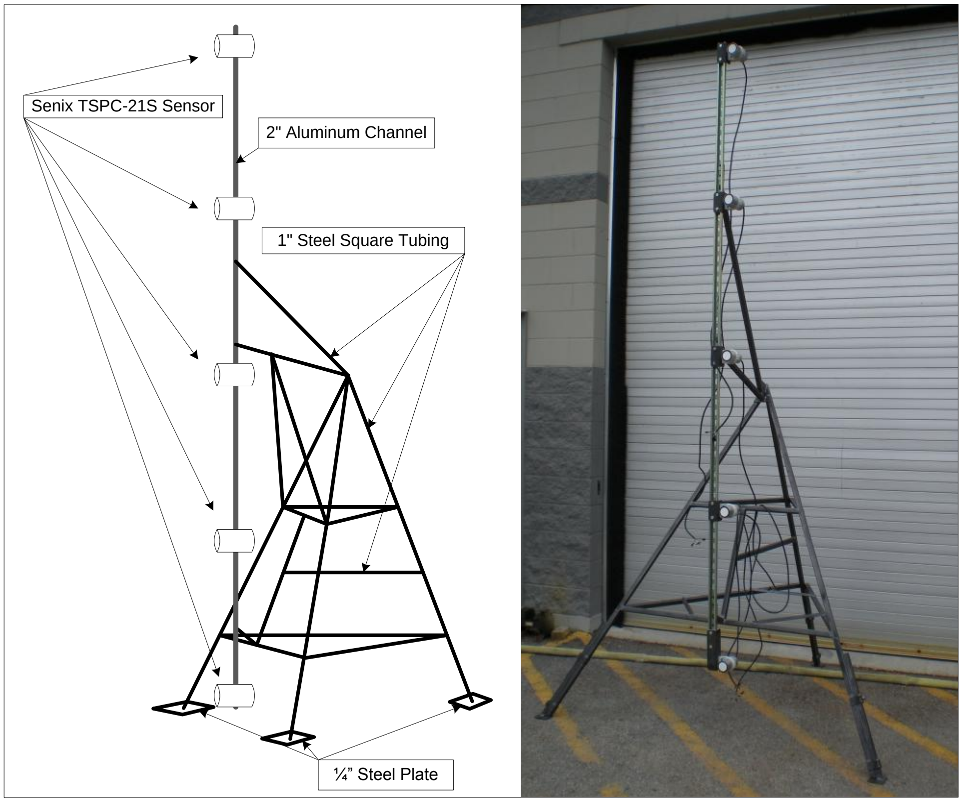


Figure 7. ultrasonic sensor bracket module.

Each ultrasonic sensor provided a signal to, and was powered through, a universal serial bus (USB) to RS485 converter unit that aggregated signals and interfaced with the control/interface module and data acquisition module. For testing purposes a Dell laptop computer was used for control and data acquisition. The power supply module for the complete measurement component was an EU2000i Honda Generator.

The next sensor acquired was the rotary laser. The rotary laser also required a software development effort to operate and test. The rotary laser also required a control/interface module (Dell desktop computer and peripherals), and a data acquisition module (Acuity PCI HSIF card) to test and collect data. The rotary laser used a specific and separate voltage regulating device, while the control/interface module, data logging module, and data acquisition module were powered directly from an EU2000i Honda Generator. The rotary laser's voltage regulating device was placed between the same EU2000i Honda Generator and the rotary laser power supply. A Dell desktop computer and peripherals served as the control/interface module and data acquisition module. The data logging module was the Acuity PCI HSIF card converting the laser signal to an appropriate file format for measurement reporting.

A second bracket module was designed and constructed for the Acuity AR4000-LIR Laser Rangefinder module. Bracket design was focused on a roadside orientation (side-fire) rather than an overhead orientation. This was done because the overhead orientation could potentially fail in detecting width when the cone of sensor observation was blocked by the top of a vehicle, as shown in Figure 8.

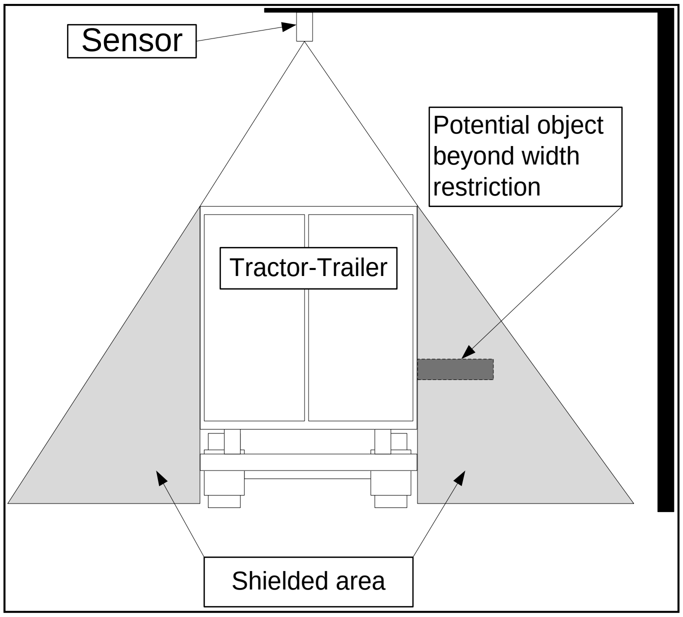


Figure 8. **Overhead orientation and potential shielding.**

This issue would be resolved if the system used a sensor for each edge of detection zone required. For single lane observation, one sensor would be placed at each of the right and left lane lines looking straight down. Figure 9 shows a graphical representation of the bracket module as placed at the side of the roadway.

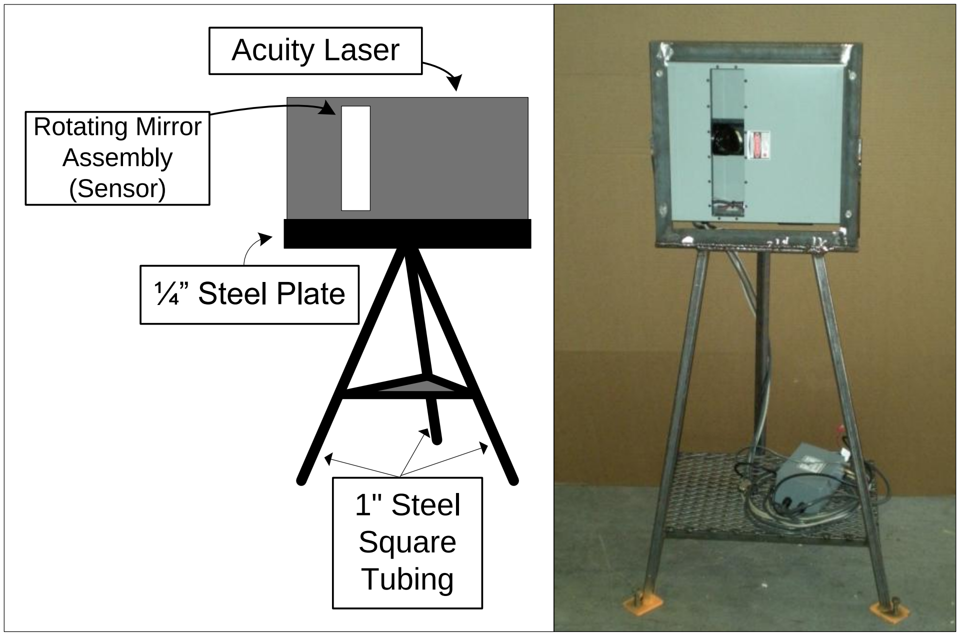


Figure 9. Rotary laser sensor bracket module.

For both measurement sensor components, VTTI developed software to control the sensors and record appropriate measurement values. Software design efforts were limited in scope to that necessary for testing the sensor. No graphical user interface work was performed to increase the flexibility, usability, or intuitiveness of the software for this portion of testing. After bracket development and the addition of necessary modules (i.e., data logging, data acquisition, control/interface, and power supply), each sensor component was set up and tested for basic functionality.

Computer Vision

To further explore the computer vision option, the third sensor investigated was camera-based. Two cameras were acquired for testing: 1) Grasshopper® IEEE-1394b (Firewire) Digital Camera, and 2) XCHR57 High Speed Progressive Scan Video Camera manufactured by Sony. The XCHR57 High Speed Progressive Scan Video Camera was acquired through purchase, and the Grasshopper® IEEE-1394b (Firewire) Digital Camera was already in-house. During initial development efforts, complications with interfacing to the XCHR57 High Speed Progressive Scan Video Camera occurred and it was determined that further work would be abandoned with this camera. The Grasshopper® IEEE-1394b (Firewire) Digital Camera development was completed and moved on to the testing phase.

The Grasshopper® IEEE-1394b (Firewire) Digital Camera required a power supply (EU2000i Honda Generator), a data acquisition module (Dell laptop), software, and other miscellaneous peripherals. The provided software allowed the component to function, but did not provide analysis for width determination. A small bracket was fabricated for overhead mounting on a bridge for testing.

Procedure

Ultrasonic Sensors and Rotary Laser

Both the rotary laser and the ultrasonic sensors were evaluated through component testing to better understand their behavior under real-world conditions. Both sensors were evaluated within the same constraints and conditions except where noted. The purpose of the sensor evaluation was to determine if each sensor could provide the appropriate responses under design-criteria conditions. Using a side-fire orientation, both sensors were tested to determine the capability and accuracy of each for independently obtaining the minimum distance recorded for each trial. The minimum recorded distance was defined as the distance from the sensor to the closest point on the truck. The minimum recorded distance corresponded to the widest portion of the vehicle, thus enabling determination of the vehicle width, assuming a full system to include measurement of the opposite side of the vehicle at the same time.

Pilot testing was performed first with a pedestrian, followed by a 2005 Toyota Tacoma at 10 mph. Both systems were then refined to account for identified issues in pilot testing and redeployed. Secondary pilot testing was conducted on the Virginia Smart Road using a 1994 Peterbilt tractor (power unit only). Tests were conducted at 15 mph, 25 mph, 35 mph, 45 mph, and 55mph. The results were analyzed to better design final sensor testing procedures. In addition, procedural techniques were refined; for instance, ensuring sensors were exactly 50 inches from lane edge, measuring the truck edge on each trial to ensure capture of the actual distance, and assigning the starting point for the truck to allow for optimum speed prior to reaching the sensors.

Following testing protocol development, final testing was performed using a tractor-trailer combination and both sensors operating simultaneously. Actual testing was conducted on the Smart Road using a 2006 Freightliner Cascadia tractor with a 53-foot trailer (Figure 10). Each sensor was placed on the traffic-right shoulder of the Smart Road at 50 inches from the right lane line. Figure 11 provides a graphical representation of the test setup.

Figure 10. Tractor-trailer used during Smart Road testing.

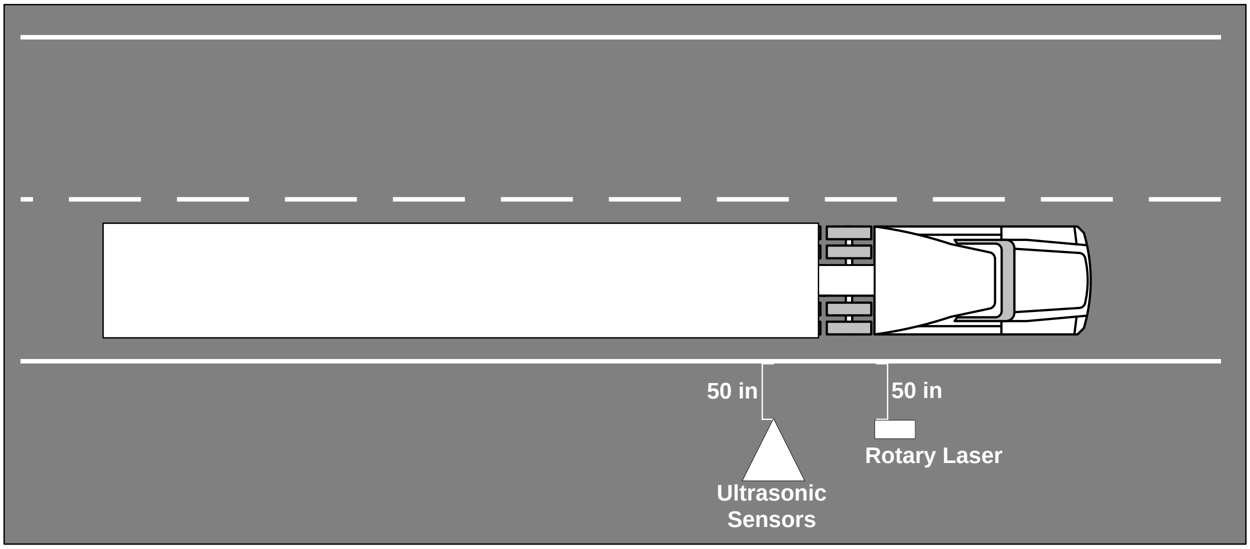


Figure 11. Apparatus map for Smart Road testing.

A trial consisted of the tractor-trailer passing both sensors at the designated speed while both sensor components were operating and collecting measurements. Ten trials were conducted per test speed, with test speeds at 5 mph increments from 5 mph to 60 mph (5 mph - 40 mph for the rotary laser). In some cases an additional trial was performed when researchers suspected data collection issues. The right lane-line was used to guide the tractor-trailer on each trial with the intent of maintaining a consistent distance from both measurement components. However, small variations still occurred on most trials. To compensate for these, researchers observed the point of actual tire-edge to the lane-line and adjusted the distance value for each assigned trial. These adjustments were measured using a tape measure to get distance between lane line and tire-edge. As will be discussed later in the Results section, this distance value was used to compare against minimum distances reported by each sensor to calculate error values.

Each ultrasonic sensor recorded distances independently and reported to a unique data stream for data collection. Minimum and maximum distance restrictions were placed on each to narrow the collection process. Therefore, each sensor ignored readings less than 36 inches and more than 148 inches. For each trial, the single minimum value reported from all five sensors was used to determine the closest point of the vehicle as it passed the measurement sensor component. The sampling frequency for the sensors was constant throughout testing, thus a varied number of samples was acquired per trial based largely on the speed of the vehicle. For example, the number of samples per sensor decreased as the speed of the vehicle increased, as expected.

Computer Vision

A third sensor presented as a potential solution to the measurement sensor component for the overall vehicle-width measurement system was the Grasshopper® IEEE-1394b (Firewire) Digital Camera. This camera was tested for its potential capability in determining vehicle-width measurement. Accuracy was not tested due to a substantial development effort required that was out of the current project scope. Rather, simple data collection was performed to evaluate the possibility of developing custom software that could enable the camera to assess vehicle width at highway speeds in real time. The camera was attached to a weight-anchored bracket extending the camera 4 ft over the edge of an existing overpass pointing down at traffic (overhead orientation). A Dell laptop was used as the control/interface module and data acquisition module. Commercially available software (Point Grey "Flycapture") was used to record the video.

Results

Ultrasonic Sensor Testing Results

Testing resulted in 121 trials across 12 speed categories for the ultrasonic sensors. Final trial counts for each test speed category are provided in Table 7. Trials were restricted to a maximum speed of 60 mph due to safety concerns with operating the tractor-trailer beyond this speed on the Virginia Smart Road.

Table 7. Ultrasonic sensor trial counts by speed category.

Speed (mph)	# of Trials
5	10
10	10
15	10
20	11
25	10
30	10
35	10
40	10
45	11
50	11
55	9
60	9

As mentioned, the actual tractor-trailer distance in each trial was compared against the single most minimum value returned from the five ultrasonic sensors. The difference between these values was calculated and an absolute error value in inches resulted. After all data across the 121 trials were collected, individual ultrasonic sensor performance was evaluated and all were compared to determine reliability. Absolute error values for each sensor were plotted in a box plot and shown in Figure 12. Ultrasonic sensor 5 clearly stands out from the other sensors with much larger apparent data dispersion. A review of the raw data shows that sensor 5 recorded several large measurements in most trials, often three or four times as large as the reported minimum. Sensor 5 is the lowest sensor in the vertical orientation at 12 inches from the road surface. At 12 inches from the ground plane, sensor 5 is at the appropriate height to measure the inside of the wheel wells and vehicle undercarriage. This issue is likely the underlying reason for this sensor's greater data dispersion. Overall, the results presented in this box plot indicate that the median was consistent across all sensors, indicating reliable performance by each sensor.

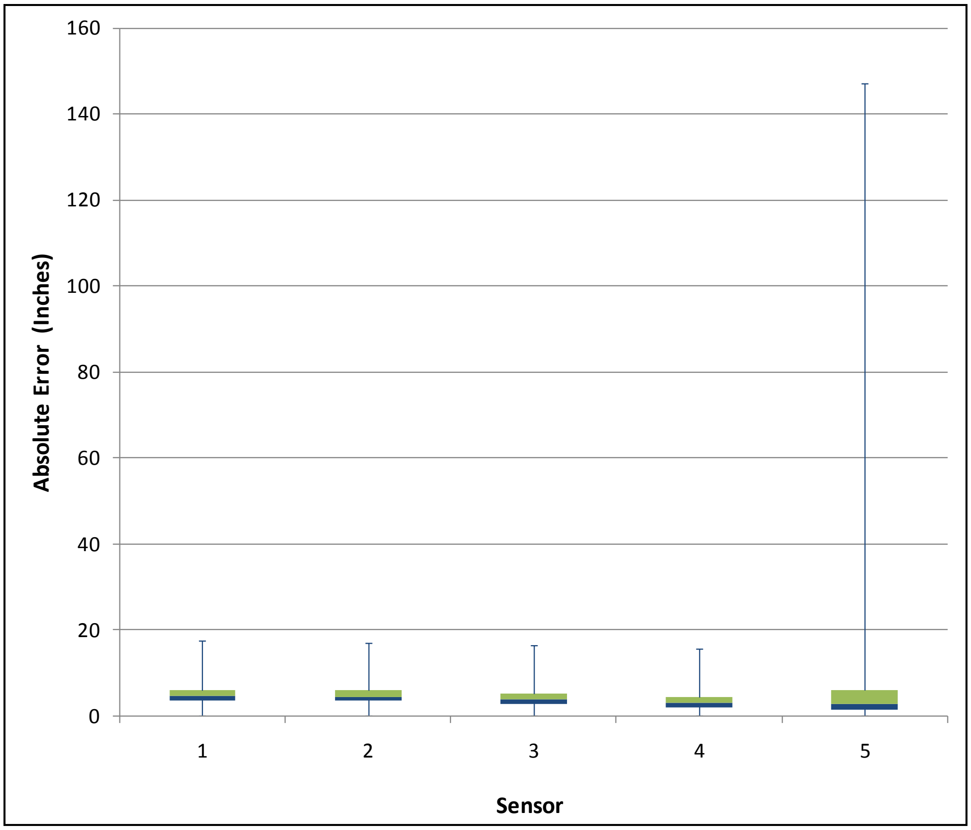


Figure 12. Box plot of individual ultrasonic sensor absolute error values.

After sensor reliability was confirmed, absolute error values were analyzed using a simple linear regression to evaluate the relationship between speed and performance. The results of the regression indicated that the relationship between speed and absolute error was weak (R^2=0.012). A t-test was conducted to test if the slope (β) was significantly different than zero and it was found not to be statistically significant ($t(1)=-1.39$, $p=0.227$). Results indicate that across all speed categories, the change in minimum value reporting performance of the ultrasonic sensors was not statistically significant. As a result, mean absolute error values for each speed category were calculated and are presented in Figure 13. As the figure shows, the ultrasonic sensors' mean absolute error ranged from 1.77 to 3.68 inches across all speed categories.

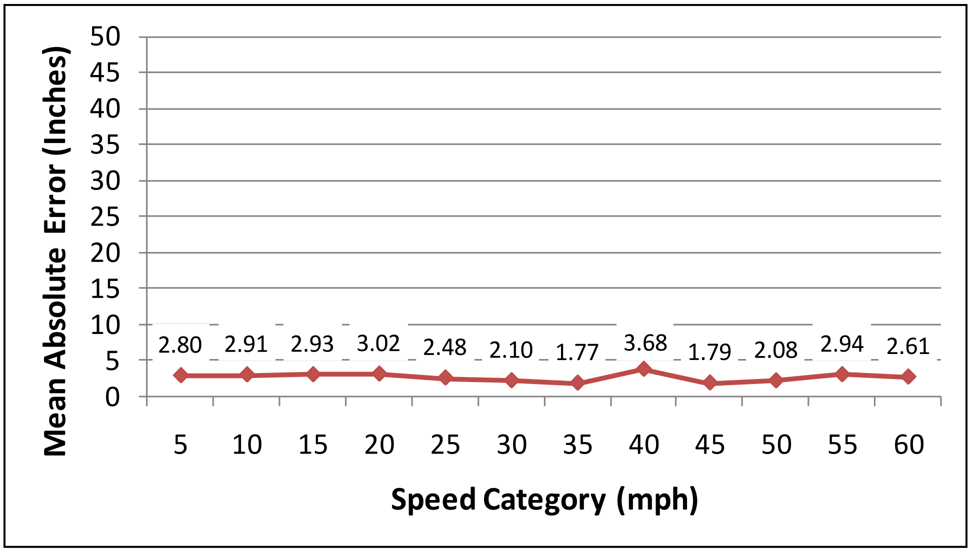


Figure 13. Mean absolute error for ultrasonic sensors by speed.

Results indicated that performance of the ultrasonic sensors did not change with regard to increases in vehicle speed. However, it is important to note that the vehicle used for testing was a tractor pulling a 53-foot box-van trailer (a conservative scenario). It is likely that many of the over-width loads transported on Virginia roadways will consist of awkward and inconsistent shapes. This indicates that a vehicle-width measurement system must be capable of measuring at a fairly high resolution. The resolution of the ultrasonic sensors is proportional to speed and sampling rate. An empirical account of the sampling rate was determined by a count of data points per trial across all speeds. Figure 14 presents the average number of data points collected by speed. At 5 mph in the conservative scenario tested, the average data points were 31.6 per trial. This equates to 27.85 inches between samples recorded. As noted in Figure 14, the average data points per trial when the tractor-trailer was traveling at 60 mph was 3.3 samples recorded. At that rate, 266.67 inches will pass between samples recorded. This resolution will most likely be insufficient for the intended purpose. To help improve this performance, it is possible to increase the sampling rate of the ultrasonic sensors from 40Hz to upwards of 100Hz; however, the manufacturer indicated that increasing the sample rate would dramatically decrease the life span of the sensor, and could risk an immediate failure upon sensor activation.

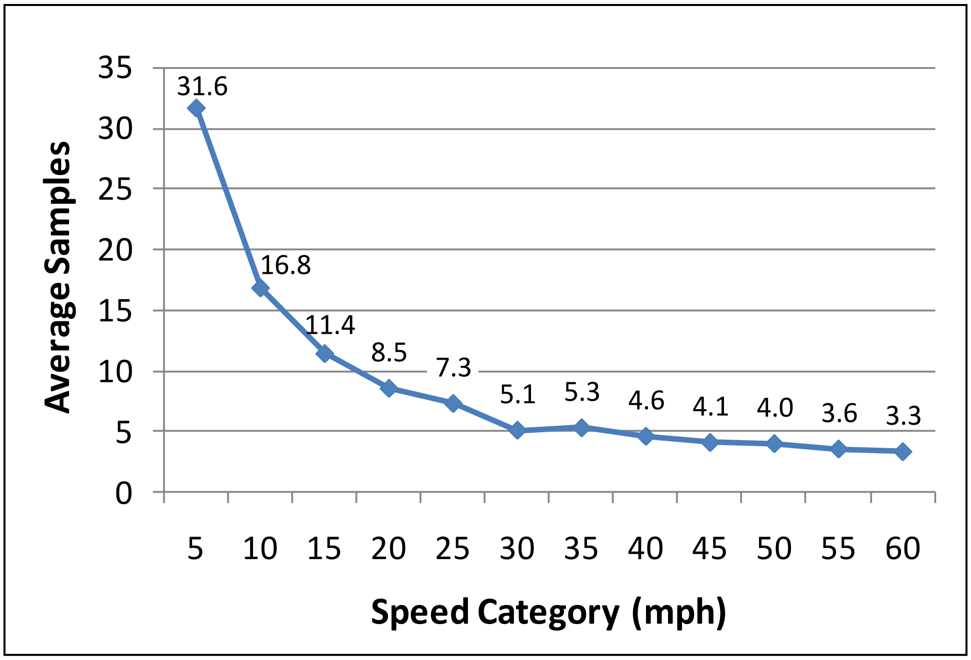


Figure 14. Average samples collected by ultrasonic sensors across all speeds.

Rotary Laser Results

During pilot testing with the rotary laser, it was determined that collecting data at high speeds on the Smart Road was not necessary as data collected at lower speeds could be post-processed to simulate higher speed trials. For example, data collected at 30 mph at a sampling rate of 20,000 Hz could be post-processed to simulate data collected at 60 mph by removing every other data point collected. Therefore, only 81 trials across eight speed categories of 5 mph increments (5-40 mph) were performed for the rotary laser. The remaining trials for four more speed categories (50, 60, 70, & 80 mph) were simulated using this post-processing method. The final trial count, including the post-processed trials for analysis, was 121. Final trial counts for each test speed category used for analysis are provided in Table 8.

Table 8. Rotary laser trial counts by speed category.

Speed (mph)	# of Trials
5	10
10	10
15	10
20	11
25	10
30	10
35	10
40	10
50	10
60	10
70	10
80	10

Again, actual tractor-trailer distance in each trial was compared against the minimum value returned from the rotary laser to determine the widest point of the vehicle. The difference between these values was calculated and an absolute error value in inches resulted. Absolute error values were analyzed using a Simple Linear Regression to evaluate the relationship between speed and performance. The results of the regression indicated that the relationship between speed and absolute error was weak (R^2=0.01). A t-test was conducted to test if the slope (β) was significantly different than zero and it was found not to be statistically significant, (t(1)=-1.39, p=0.27). Results indicate that across all speed categories, the change in minimum value reporting performance of the rotary laser was not statistically significant. As a result, mean absolute error values for each speed category were calculated and are presented in Figure 15. As the figure shows, the rotary laser mean absolute error ranged from 1.43 to 4.47 inches across all speed categories.

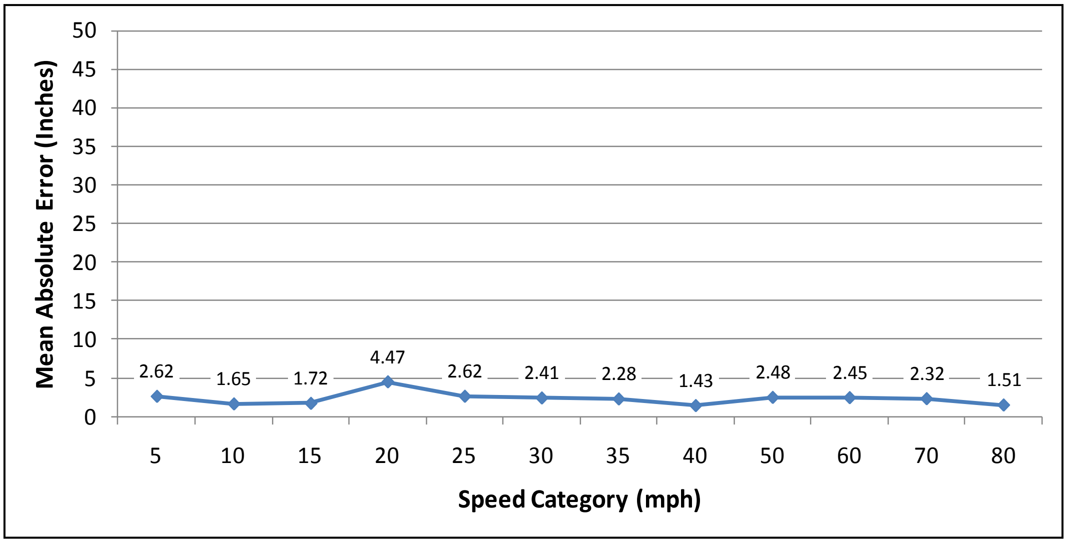


Figure 15. Mean absolute error for rotary laser by speed.

Results of the rotary laser testing show similar performance to that of the ultrasonic sensors. Contrary to the ultrasonic sensors, the rotary laser recorded upwards of 50,000 data points per trial. Due to the quantity of data collected, counts were not specifically tracked. However, resolution was calculated based on the rotary laser sampling rate specifications. The sampling rate for the rotary laser is defined by the motor speed spinning the mirror. Each time the mirror spins a full 360 degrees, a single set of measurements is collected through the 110-degree field-of-view lens at the front of the enclosure. Although the sensor collects multiple points per exposure (revolution), the points are vertical rather than horizontal. Therefore, a moving vehicle traveling perpendicular to the sensor lens is measured at a frequency based on the mirror rotation. Maximum power for the rotary laser should provide 2500 rpm and was the case during testing. For a vehicle traveling at 5 mph, the estimated distance between measurements along a horizontal axis is 2.11 inches. At 60 mph, the estimated distance between measurements is 25.45 inches.

Computer Vision

As previously mentioned, a simple exploratory evaluation of computer vision vehicle-width measurement was performed. An examination of accuracy performance was not tested due to a substantial custom software development effort required that was out of the current project scope. Existing in-house resources were used to perform post-processing assessments of the raw video data. The purpose of these assessments was to determine the potential capability of a high speed video camera at defining vehicle edges at high vehicle speeds. The ability to define a vehicle edge at high speeds would indicate potential capabilities of measuring a vehicle's width in a real-world application. Figure 16 shows a frame capture containing the passenger side of a tractor. Figure 17 shows a visual representation of the first step in the post-processing assessment that only displays new data different from the previous frame (i.e., tractor and tractor shadow). Figure 18 provides the final step in the post-processing assessment of the introduction of a threshold to remove noise from the image (i.e., shadow, miscellaneous other artifacts). VTTI software engineers agreed that this final step provides a clean and distinct vehicle edge useful for vehicle-width measurement.

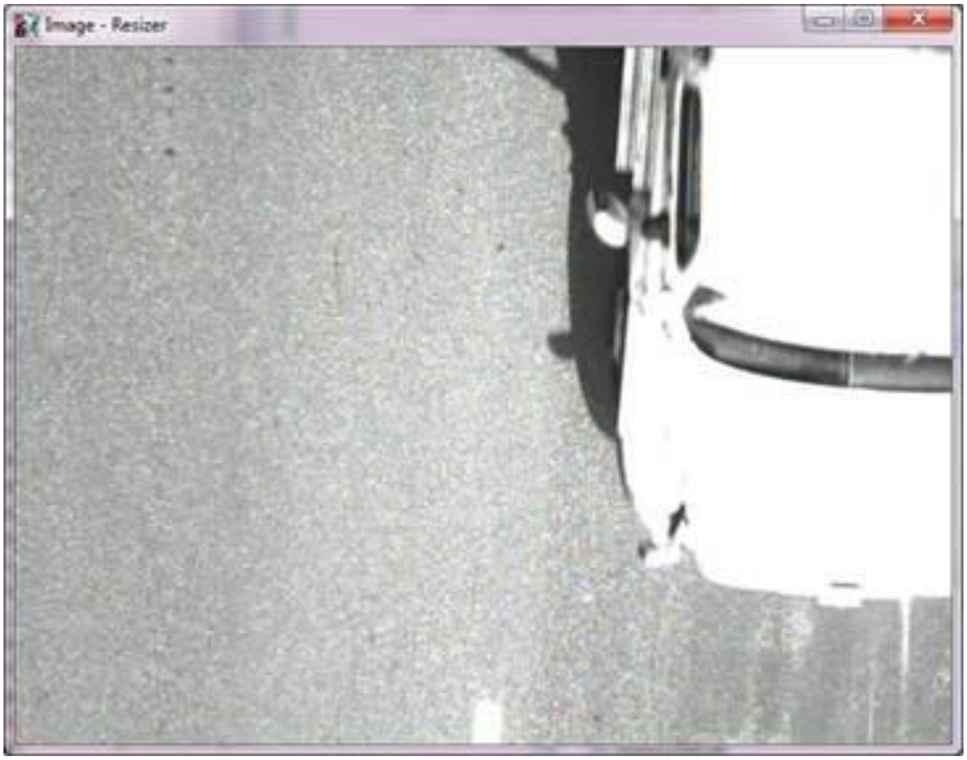


Figure 16. Original frame capture from raw video file.

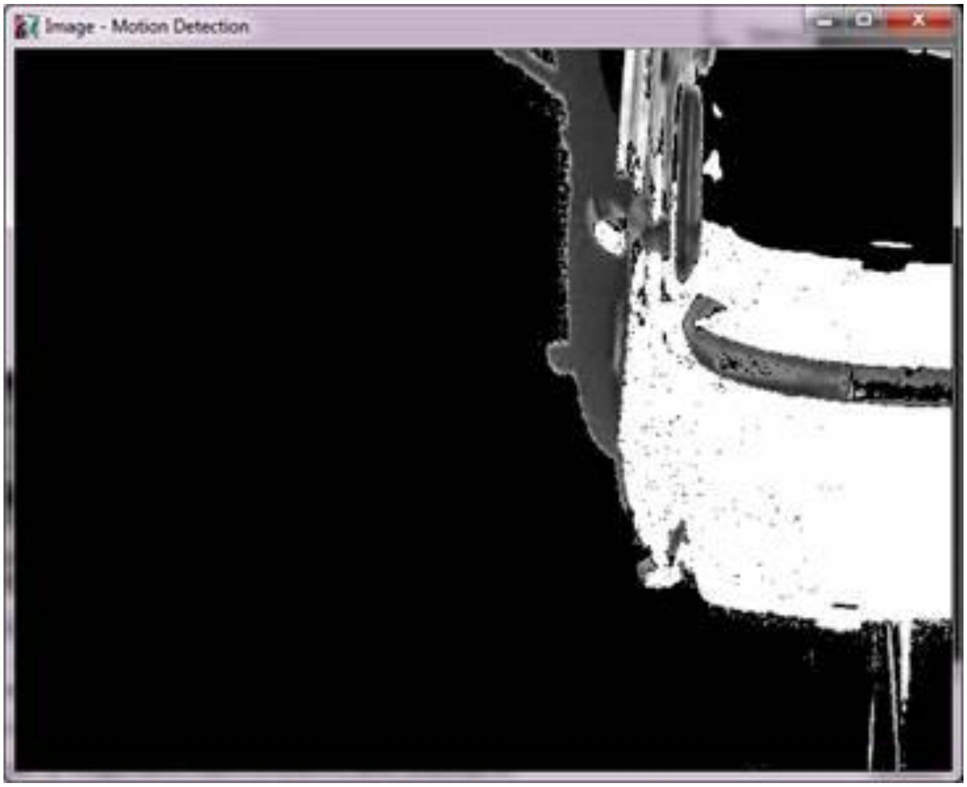


Figure 17. Frame capture processed to show only data different from previous frame.

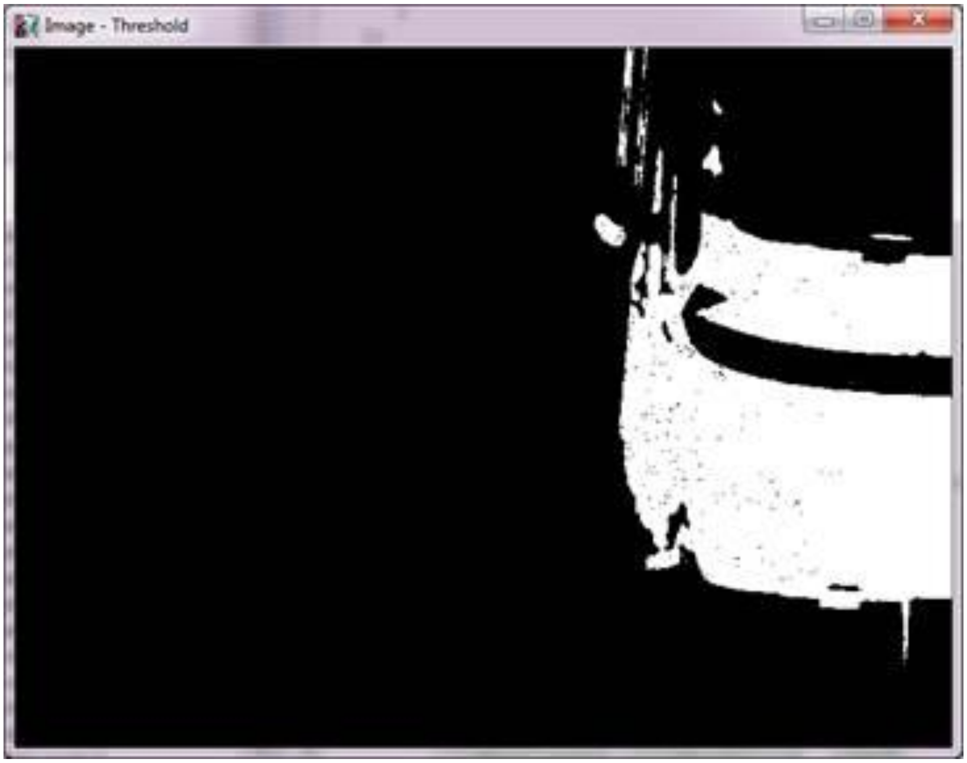


Figure 18. Frame capture further processed by threshold introduction to remove noise.

Testing Summary and Conclusions

There were two primary factors considered during sensor testing: 1) accuracy of the measurement sensor, and 2) the resolution of the measurement sensor. The accuracy of the sensor needs to be reasonably high to reduce the number of false positives or false negatives that occur in the system. False positives occur when the system activates an alarm for a vehicle that is NOT over the set width restriction. False negatives would be the instances where a vehicle is over the width restriction and is not detected by the system. The ultrasonic sensors' mean absolute error ranged from 1.77 to 3.68 inches and the rotary laser's mean absolute error ranged from 1.43 to 4.47 inches (see Figure 19).

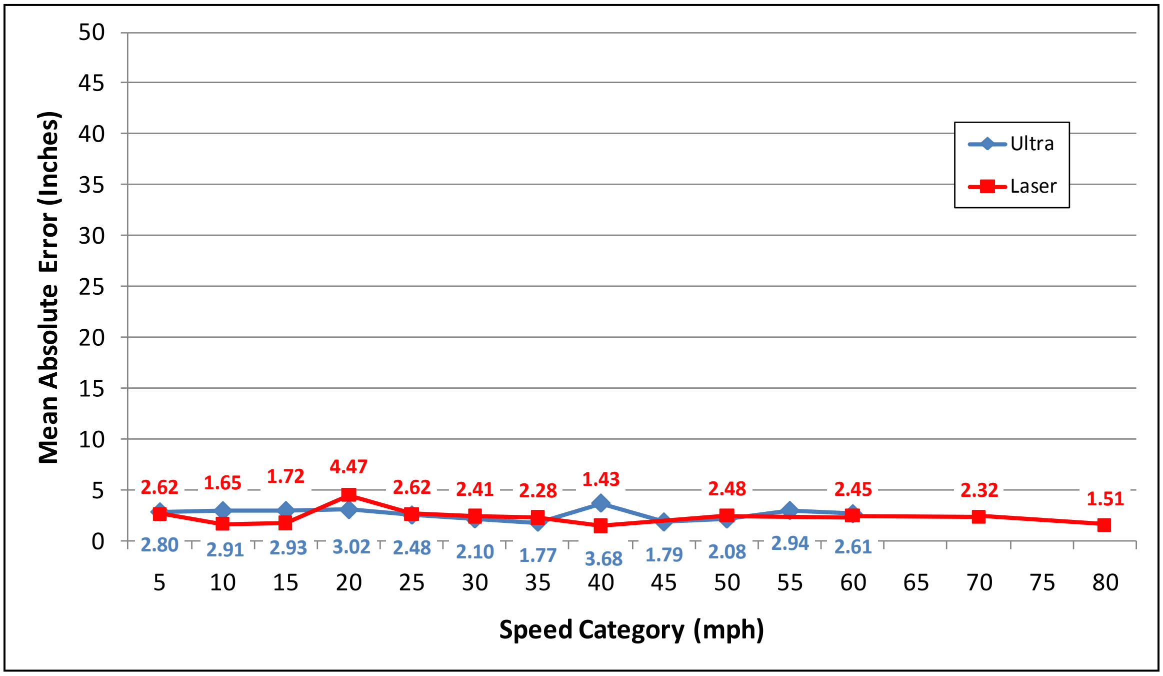


Figure 19. Mean absolute error for ultrasonic sensors and rotary laser by speed category.

Although the accuracy of each sensor type was good, the ultrasonic sensors at high speeds resulted in low sampling counts, indicating low resolution. At that rate, there is a significant risk of missing the widest point of the vehicle, causing a false negative for the vehicle-width detection system. The ultrasonic sensors' resolution could be improved by designing a bracket to hold multiple sensors horizontally as well as vertically, dramatically increasing the component cost. According to the manufacturer, there is also the potential to raise the sampling rate; however, a maximum level increase to 100Hz (2.5 times the tested frequency) would at best decrease the resolution to approximately 106 inches between samples. The life span of the component is expected to decrease as well, according to the manufacturer, and the resolution would still be beyond the bounds of the design criteria. The rotary laser has a much higher resolution than the ultrasonic sensors at all speeds and, based on this reason, has the most potential for inclusion in a vehicle-width measurement system.

VTTI software engineers determined that additional development work could be performed to improve the resolution of the rotary laser. Based on tests, the rotary laser was found to be somewhat susceptible to interference from sunlight. The additional noise impacted the initial data, but filtering was employed to improve data quality. Figure 20 shows the raw data plotted in a surface mapping software package. As can be seen, there is a significant amount of noise interfering with accurate edge detection.

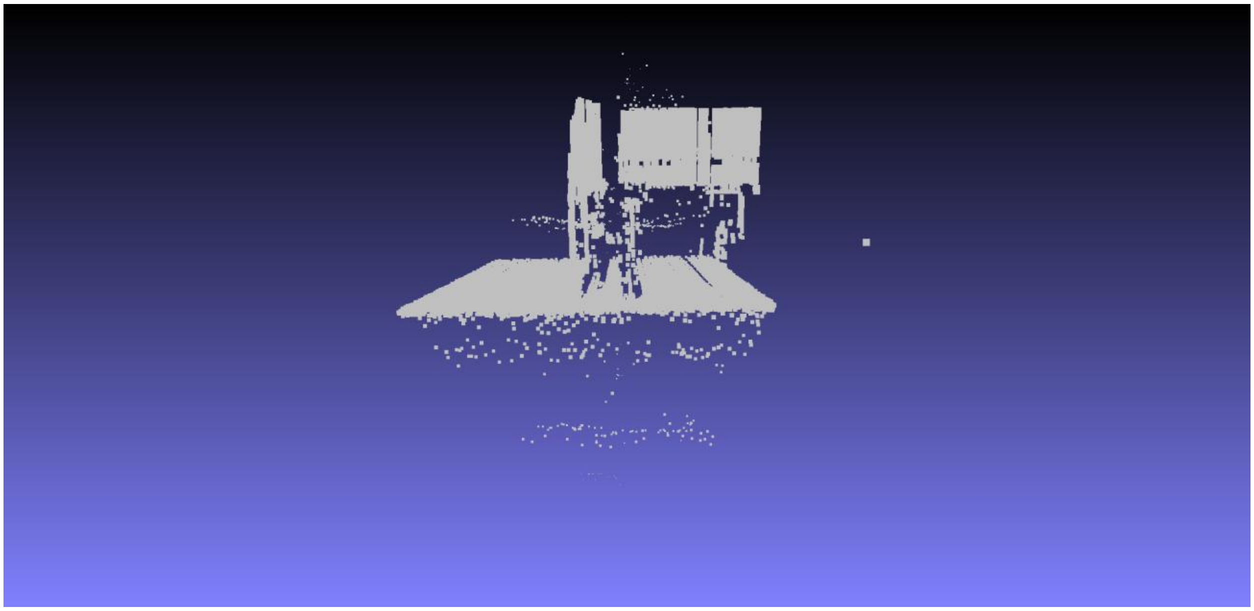


Figure 20. Rendering of all data points collected for a single trial.

By post-process filtering for low ambient signals, the majority of noise was reduced, allowing a more obvious depiction of the tractor-trailer. Figure 21 shows this post-process filtered result. Although a significant reduction in noise was found, there were clearly still some artifacts found in the data. For instance, there were points found in non-existent space and points found below the ground plane.

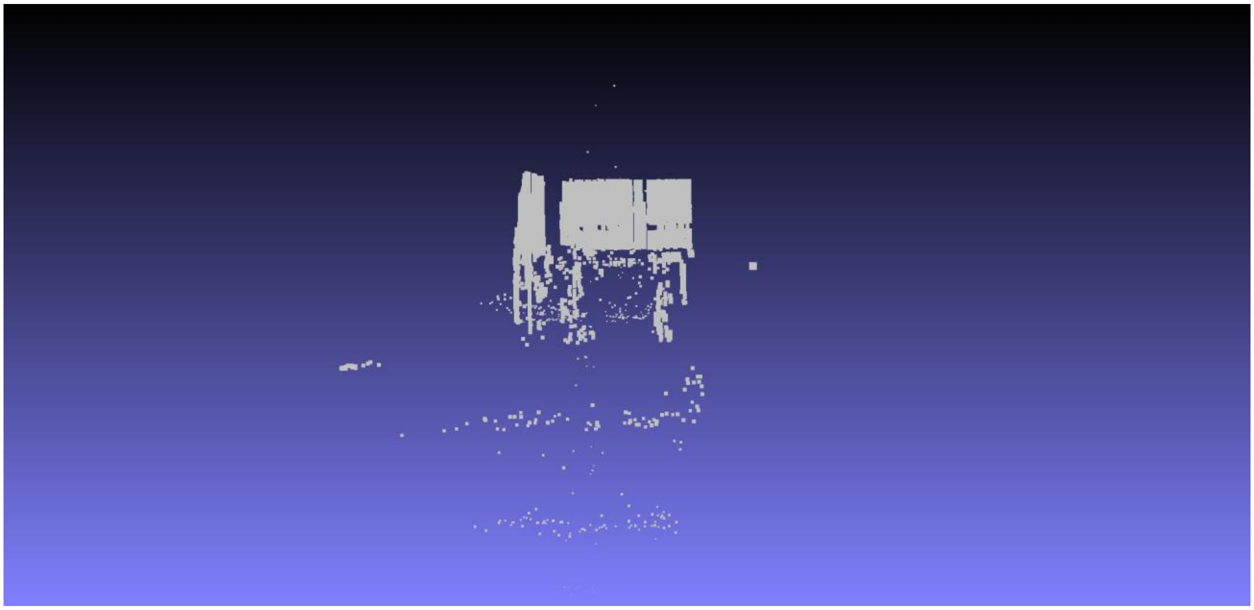


Figure 21. Rendering after post-processing to remove noise and obvious ground plane.

The purpose of filtering was to identify the closest existing point to the sensor which is part of the tractor-trailer. It is anticipated that future rotary laser development would include more sophisticated data filtering to improve accuracy. For example, assuming that each point that is actually part of the tractor-trailer should exist within a certain proximity to another point, allows a cloud point analysis to be feasible. This analysis, similar to methods used for resolving radar data, could provide a sophisticated and more accurate measurement. For testing, VTTI manually removed the ground plane to simulate this process to some extent. The value in this exercise was to demonstrate the potential for even greater use of the rotary laser with additional software development effort. It appears that this entire process could be automated to be performed in real time for a vehicle-width measurement system including the rotary laser as the measurement sensor component. Figure 22 shows the same data as the past two figures with additional points removed that did not lie within a threshold proximity to the calculated plane representing the truck-edge.

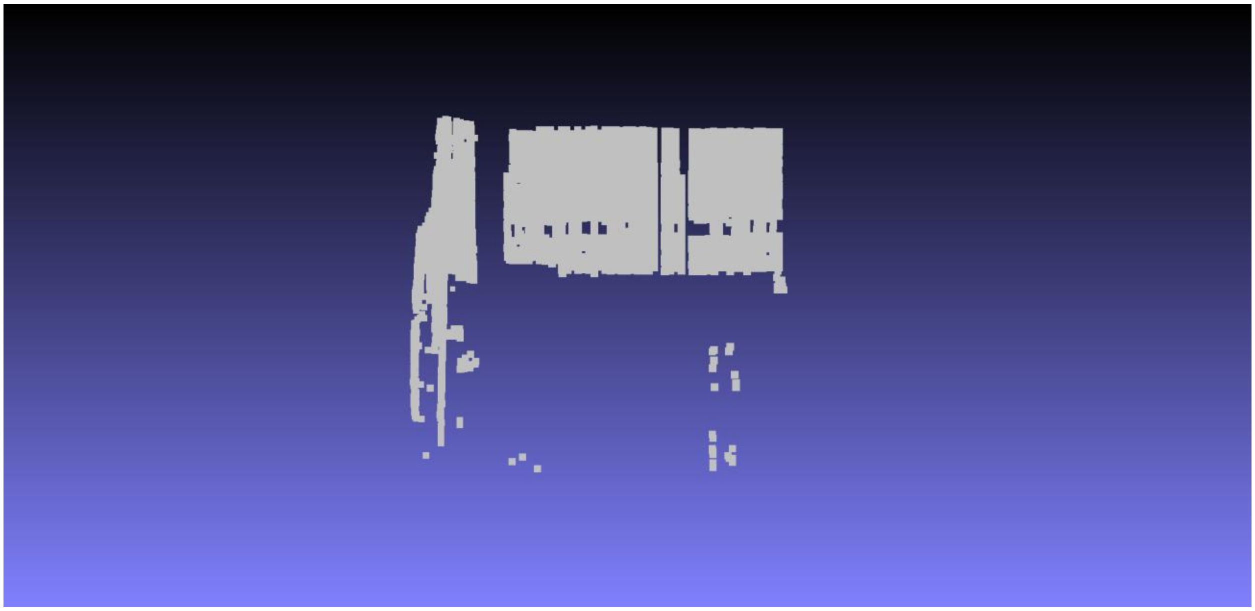


Figure 22. Rendering to remove points outside determined proximity to truck edge.

The exploratory effort into computer vision feasibility for measuring a vehicle’s width showed promising results. Due to a lack of accurate performance testing on the computer vision option, there are no data to provide a resolution estimate. However, VTTI software engineers are confident – based on data collected – that computer vision is a viable option given appropriate time for development. To calculate a vehicle’s width, a second edge must be detected; thus, a second camera would be necessary. Therefore, the necessary number of cameras for vehicle width detection is $n+1$ where n = lane count.

Finally, the measurement sensor components tested were the low-cost options to determine feasibility for use in the overall system. Thus, each option requires additional sensors for system functionality that were not tested. For the side-fire options (rotary laser and ultrasonic sensors), a second sensor bracket and appropriate equipment would need to be located on the opposite side of traffic. This doubles the cost for this portion of the system over the testing costs. That is, the ultrasonic sensor option would require a minimum of 10 sensors to complete the measurement: the rotary laser option would require two sensors (at current resolution, four sensors could provide the aforementioned improvement in resolution), and the computer vision option would require a minimum of two cameras for a single lane deployment (add one camera for each additional lane).

Vehicle-width Measurement System Architecture

VTTI researchers designed a preliminary vehicle-width measurement system architecture based on the design criteria from Task 2 and the results obtained from the vehicle-width technology evaluation. This preliminary system architecture is non-sensor specific (see Appendix O). The major system components and modules of the preliminary system architecture include:

- I. General Measurement and Warning System
  - A. Measurement Component
    - 1. Measurement Sensor Module
      - a) Sensor
      - b) Central Processing Unit (CPU)
        - (1) Data Logging Module (Convert sensor signal to data where necessary)
        - (2) Laptop Computer
          - (a) Data Acquisition Module
          - (b) Control/Interface Module
      - c) Power Supply
        - (1) Generator, Fuel Cells, or Power Cabling
      - d) CPU Communication Device
        - (1) Wireless communication card
      - e) Long Range Communication Unit (Transceiver)
  - B. Warning/Notification Component
    - 1. Warning/Notification Device (Sign)
    - 2. Power Supply
        - (1) Generator, Fuel Cells, or Power Cabling
    - 3. Long Range Communication Unit (Transceiver)
  - C. Redundant Measurement Component
    - 1. Active Measurement Sensor Module
      - a) Sensor
      - b) Central Processing Unit (CPU)
        - (1) Data Logging Module (Convert sensor signal to data where necessary)
        - (2) Laptop Computer
          - (a) Data Acquisition Module
          - (b) Control/Interface Module
      - c) Power Supply

        - (1) Generator, Fuel Cells, or Power Cabling
      - d) CPU Communication Device
        - (1) Wireless communication card
      - e) Long Range Communication Unit (Transceiver)
      - f) Secondary Long Range Communication Unit (Transceiver)
- D. Final Warning/Notification Component
  - 1. Warning/Notification Device (Sign)
  - 2. Power Supply
    - (1) Generator, Fuel Cells, or Power Cabling
  - 3. Long Range Communication Unit (Transceiver)
- E. Work Zone Warning/Notification Component
  - 1. Warning/Notification Device (Audible/Haptic Alert Device)
  - 2. Power Supply
    - (1) Generator, Fuel Cells, or Power Cabling
  - 3. Long Range Communication Unit (Transceiver)

Using this preliminary system architecture, the previously tested sensors were implemented to form three additional sensor-specific vehicle-width measurement system architectures (Appendix P). In addition to developing system architectures for each previously tested sensor, a cost estimate was developed for each system to allow comparison. The cost analysis was broken down into development costs, material costs, materials and equipment costs, cost of warning devices, and total cost. The two key estimated costs (i.e., largest impact to the overall system estimated cost) were the Development Costs and Materials and Equipment Costs. The system with the lowest estimated cost was the ultrasonic sensors specific system. Therefore, each of the estimated system costs were compared to that base cost, forming a system total cost ratio. Table 9 provides the cost ratio for each system, and the breakdown of both key estimated costs.

Table 9. Cost (estimated) ratio analysis for comparing system options.

System Type	Development Cost	Materials/Equipment	Cost Ratio
Ultrasonic Sensors	15%	53%	1.0
Rotary Laser	15%	55%	1.4
Computer Vision	26%	38%	1.4

Note: Only the two major components impacting costs were highlighted, thus percentages do not total 100%.

Both the rotary laser system and the computer vision system are estimated to cost approximately 1.4 times that of the ultrasonic sensors system. It is important to note that the development costs for the computer vision system are greater than those of the rotary laser system. Moreover, the materials and equipment costs for the rotary laser system are estimated to be over half the cost of the system as opposed to the computer vision system with a materials and equipment estimate of less than 40% of the total system cost. Therefore, the fixed costs for the computer vision system are estimated to be much less than those of the rotary laser system.

Time to develop is also accounted for in labor costs (under the development cost category). VTTI believes that the computer vision system will require the most time to develop, largely due to software development and beta testing. The rotary laser system is expected to require slightly less time to develop. The ultrasonic sensor system is estimated to require the least development time and, in combination with the least expensive sensor technologies, accounts for the lowest cost option. Finally, in reference to the system-specific cost analysis, the estimates are all calculated based on the systems' architectures (Appendix P) and do not reflect suggested improvements (e.g., an array of ultrasonic sensors to improve resolution).

Conclusions and Recommendations

The focus of this project was to develop a vehicle-width measuring and alerting system to reduce over-width vehicle violations in VDOT work zones. These over-width vehicle violations often result in traffic congestion and work disruptions while the offending vehicle is being turned around by law enforcement officers.

As mentioned, measuring maximum vehicle width at highway speeds (i.e., 50-55 mph) from a portable platform creates several design challenges (e.g., sampling rate, measurement quality, power, and weather) that must be systematically addressed using a systems engineering approach. This project has two phases. During this initial phase, VTTI: 1) generated design criteria from stakeholders (e.g., VCTIR and VDOT), 2) assessed existing vehicle width measuring systems against these criteria to determine design gaps, 3) explored solutions (e.g., new technologies) for design gaps, 4) assessed initial performance of promising solutions, and (5) generated and provided the system architecture for a promising vehicle-width measurement system. In a potential follow-on phase, VTTI will: 1) further the development of the prototype vehicle-width measuring system, 2) assess its performance under near-operational conditions (i.e., on the Virginia Smart Road), and 3) assess its performance under operational conditions (i.e., within VDOT's roadway system).

The key finding of this vehicle-width measuring and alerting system is that, due to the demanding operational environment, a simple technological solution may not be feasible for measuring vehicle widths. There are two design criteria, namely Vehicle Speed and Detection Resolution, which complicate the system architecture. These two competing design requirements have an inverse relationship; i.e., as vehicle speed increases, detection resolution decreases, and vice versa.

This finding is evident in the design of existing vehicle-measurement systems. For example, the Swiss HGV Control Center system requires vehicles to travel at an extremely slow speed (i.e., 3 mph) to obtain a high-resolution scan (i.e., accurate to within 0.6 inches) of the vehicle's dimensions. Another existing detection system, the German Toll Collect System, does not restrict vehicle speeds but only uses laser scanning to estimate the vehicle size to alert a mobile enforcement officer to then pull over the subject vehicle and manually measure its dimensions. As concluded by Fontaine (2010), VTTI agrees that there are no proven systems commercially available that would be applicable for vehicle width detection at highway speeds.

The primary design gap to fill in is the measurement sensor. Therefore, the research team set out to determine if recent advances in technology have been sufficient to overcome the barrier of vehicle speed versus resolution. Of the numerous technologies initially explored, three appeared to have the most promise of achieving the desired design criteria: ultrasonic sensors, rotary laser, and computer vision. However, testing of these sensors revealed that even these advanced sensors had varying degrees of difficulty for achieving all design criteria. Table 10 lists the strengths and weaknesses of each of these three sensor technologies.

Table 10. Vehicle over-width measurement technology strengths and weaknesses.

Technology	Strengths	Weaknesses
Ultrasonic Sensors	• Lower Equipment Cost • Less Development Time	• Insufficient Resolution at highway vehicle speeds
Rotary Laser	• Increased Accuracy	• Higher Equipment Cost • Insufficient Resolution at highway vehicle speeds with current configurations
Computer Vision	• Increased Resolution • Lower Equipment Cost	• Development Time

Based on this preliminary testing, the research team provides the following recommendations:

Recommendation 1: Further Explore Rotary Laser with Modifications

The rotary laser showed great promise in achieving the desired scan resolution at the operational highway vehicle speeds. There are two actions that can be explored in follow-on testing. The first is working with the rotary laser vendor to increase the sampling rate (achieved by increasing the speed of the rotating mirror). The primary drawbacks to this increased mirror rotation speed are the need for additional power supply and the decreased component life. As the vendor currently does not offer such a device, there will be some additional development time and cost for the vendor to change their equipment configuration. The second action is using multiple sensors placed side-by-side to effectively increase the number of scans down the side of the tractor-trailer. This action will require additional work to synchronize the scans and fuse the sensor data into a single cloud of points from which the vehicle width measurements can be determined.

Recommendation 2: Further Explore Camera-based Sensors

Of the three tested technologies, camera-based sensors offer the simplest option for achieving the desired resolution at operational highway vehicle speeds. However, this technology has not been applied to vehicle measurement in the past; therefore, software development (approximately 4 person-months) is required to produce a system that can effectively measure vehicle widths. As mentioned, multiple cameras will be needed above the roadway to overcome parallax problems. As with the multiple rotary laser solution, these multiple cameras will need to be linked and their images sewn together for an accurate vehicle-width measurement to be taken.

Recommendation 3: Explore Administrative Solution for Determining Vehicle Widths

With the barriers found with the current technologies, the research team also brainstormed other options for achieving the goal of detecting an over-width vehicle approaching a restricted-lane-width condition. One idea that holds promise is using the administrative process of applying for an over-width permit along with a radio-frequency identification (RFID) tag and reader. When someone applies for an over-width permit, they will receive a permit that incorporates an RFID tag that contains the vehicle dimensions (approved height and width) along with an additional tag that will be affixed to the load itself. This equipped over-width permit will be required to accompany the load while in transit. Like US DOT numbers and placards, vehicle operators could be required to affix the RFID tag to the load in a conspicuous manner that will allow enforcement officers to visually ensure the load is compliant. Then, simple RFID readers can be set up along the roadway as prescribed by the desired design criteria. These RFID readers can be easily configured to read the tags as they pass by at operational vehicle speeds and they will not be affected by the number of vehicles present or weather conditions. The readers would be linked to a wireless communication device that would provide in-vehicle notification to the driver and escort as well as the appropriate VDOT personnel and work zone workers.

Despite the advantages, there are possible drawbacks. The first is the change to the current permit issuing process as new permits and new issuing procedures would need to be created. The second is training. Both issuing agency personnel and over-width vehicle operators would need to be trained on the new process and requirements as well as given an overview of the technology and its purpose. The third is out-of-state or rogue over-width vehicles. This solution has great promise for those who are compliant; however, loads coming from out-of-state or unscrupulous vehicle operators may go undetected because an RFID tag does not accompany the load. In these cases, only a direct measurement system (such as the rotary laser or camera-based sensor systems) would be needed to ensure over-width vehicle detection. Still, this administrative solution has the potential to readily solve the over-width detection problem for the vast number of occurrences.

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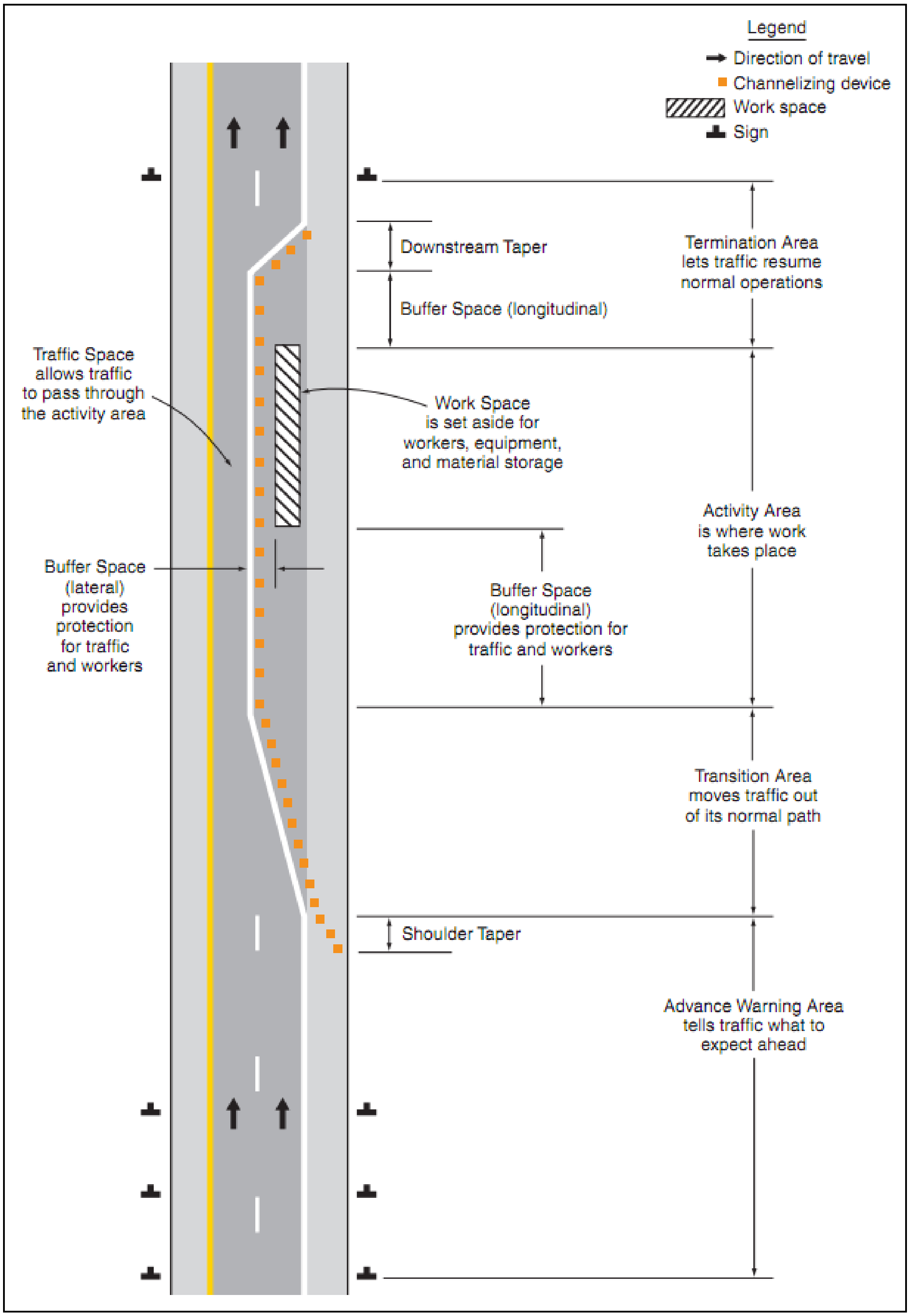
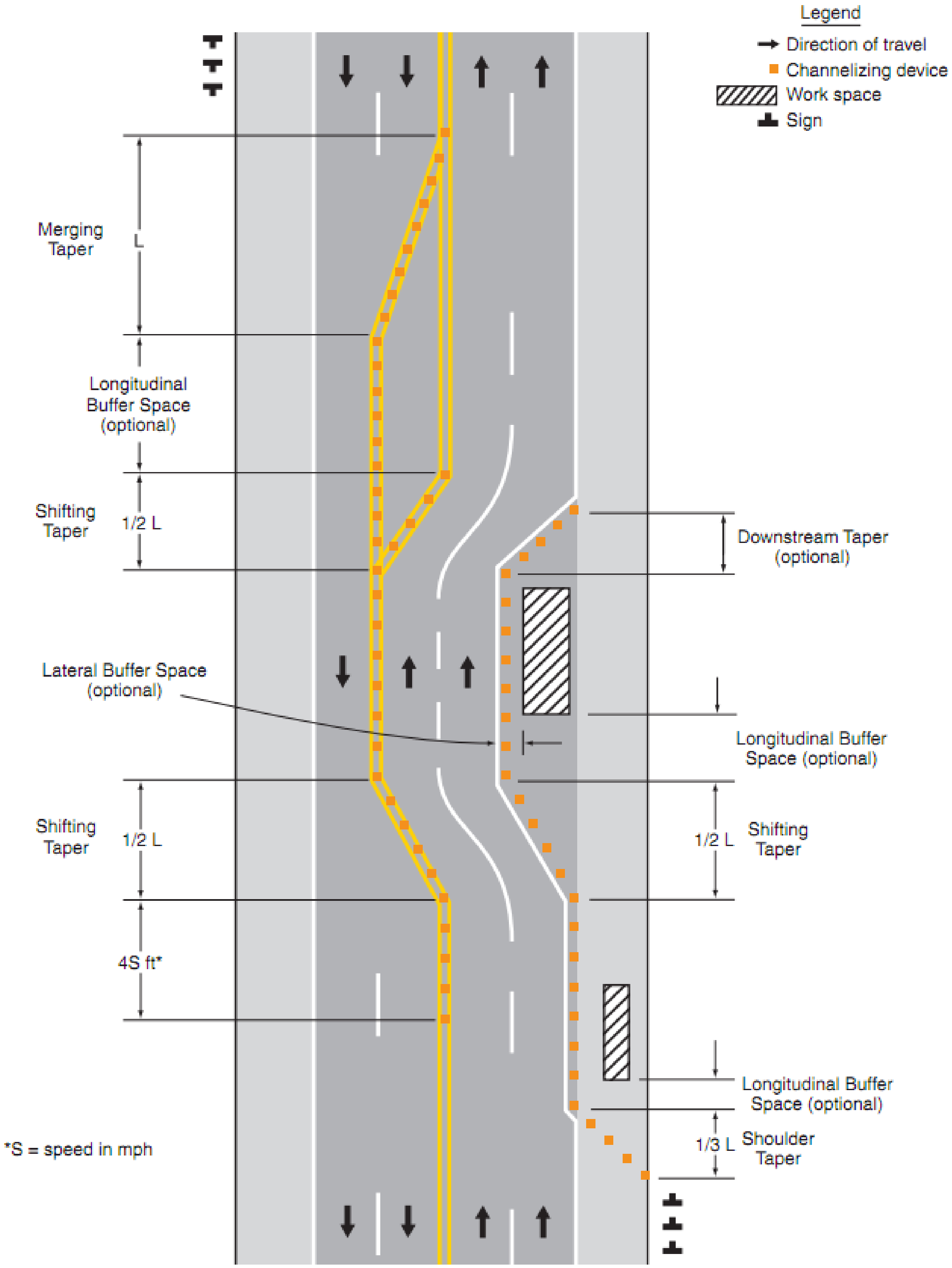
APPENDIX A.
MUTCD FIGURE 6C-1. COMPONENT PARTS OF A TTC ZONE



Source: FHWA, 2009, p. 553

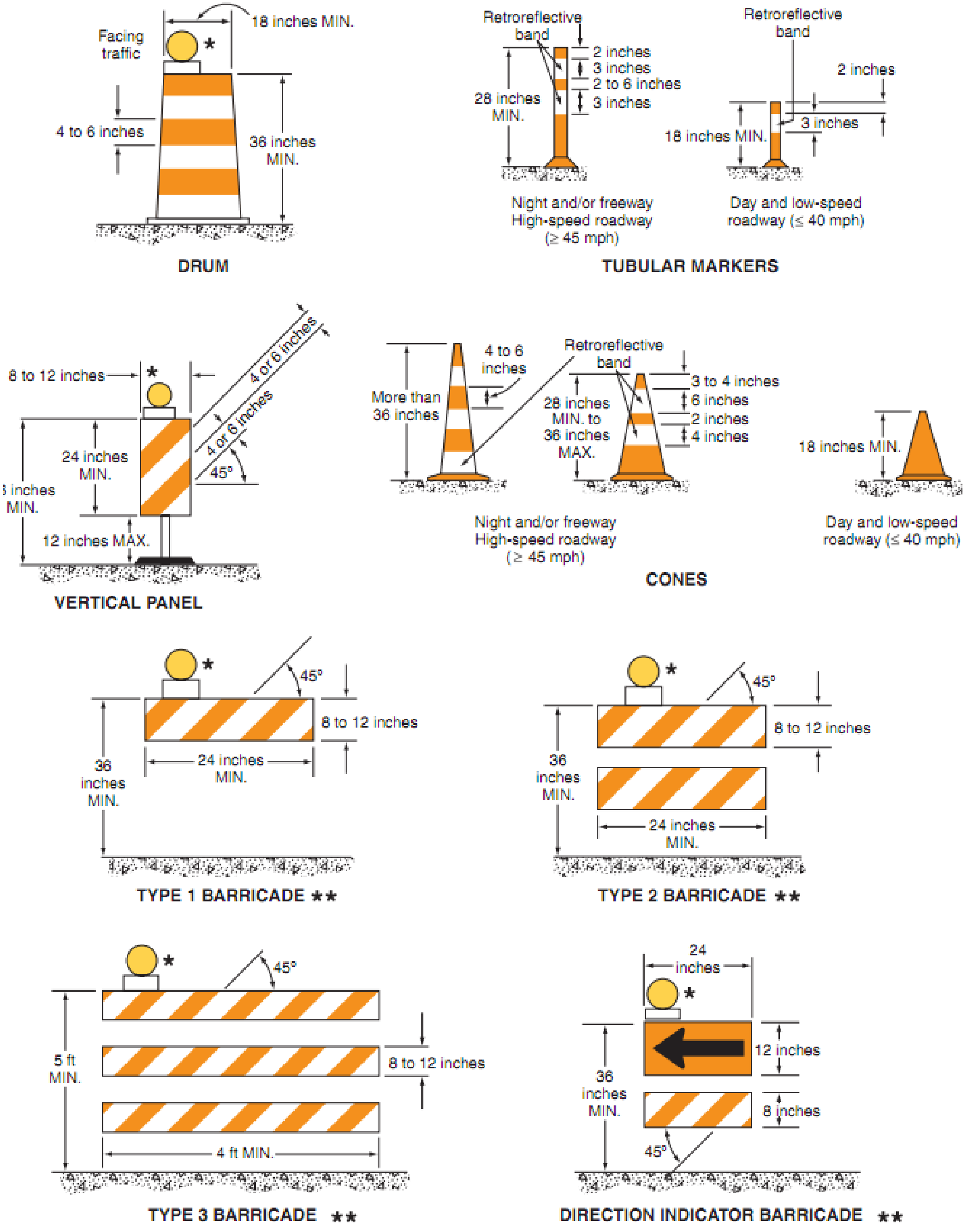
APPENDIX B.
MUTCD FIGURE 6C-2. TYPES OF TAPERS AND BUFFER SPACES



Source: FHWA, 2009, p. 556

APPENDIX C.
MUTCD FIGURE 6F-7. CHANNELIZING DEVICES

Figure 6F-7. Channelizing Devices



* Warning lights (optional)

** Rail stripe widths shall be 6 inches, except that 4-inch wide stripes may be used if rail lengths are less than 36 inches. The sides of barricades facing traffic shall have retroreflective rail faces.

Source: FHWA, 2009, p. 605

APPENDIX D.
MUTCD TABLE 6F-1. TTC ZONE SIGN AND PLAQUE SIZES

Sign or Plaque	Sign Designation	Section	Conventional Road	Freeway or Expressway	Minimum
Stop	R1-1	6F.06	30 x 30*	—	—
Stop (on Stop/Slow Paddle)	R1-1	6E.03	18 x 18	—	—
Yield	R1-2	6F.06	36 x 36 x 36*	—	30 x 30 x 30
To Oncoming Traffic (plaque)	R1-2aP	6F.06	36 x 30	48 x 36	24 x 18
Wait on Stop	R1-7	6E.05	24 x 30	24 x 30	—
Go on Slow	R1-8	6E.05	24 x 30	24 x 30	—
Speed Limit	R2-1	6F.12	24 x 30*	36 x 48	—
Fines Higher (plaque)	R2-6P	6F.12	24 x 18	36 x 24	—
Fines Double (plaque)	R2-6aP	6F.12	24 x 18	36 x 24	—
$XX Fine (plaque)	R2-6bP	6F.12	24 x 18	36 x 24	—
Begin Higher Fines Zone	R2-10	6F.12	24 x 30	36 x 48	—
End Higher Fines Zone	R2-11	6F.12	24 x 30	36 x 48	—
End Work Zone Speed Limit	R2-12	6F.12	24 x 36	36 x 54	—
Movement Prohibition	R3-1,2,3,4,18,27	6F.06	24 x 24*	36 x 36	—
Mandatory Movement (1 lane)	R3-5	6F.06	30 x 36	—	—
Optional Movement (1 lane)	R3-6	6F.06	30 x 36	—	—
Mandatory Movement (text)	R3-7	6F.06	30 x 30*	—	—
Advance Intersection Lane Control	R3-8	6F.06	Varies x 30	—	—
Do Not Pass	R4-1	6F.06	24 x 30	36 x 48	—
Pass With Care	R4-2	6F.06	24 x 30	36 x 48	—
Keep Right	R4-7	6F.06	24 x 30	36 x 48	—
Narrow Keep Right	R4-7c	6F.06	18 x 30	—	—
Stay in Lane	R4-9	6F.11	24 x 30	36 x 48	—
Do Not Enter	R5-1	6F.06	30 x 30*	36 x 36	—
Wrong Way	R5-1a	6F.06	36 x 24*	42 x 30	—
One Way	R6-1	6F.06	36 x 12*	54 x 18	—
One Way	R6-2	6F.06	24 x 30*	36 x 48	—
No Parking (symbol)	R8-3	6F.06	24 x 24	36 x 36	—
Pedestrian Crosswalk	R9-8	6F.13	36 x 18	—	—
Sidewalk Closed	R9-9	6F.14	24 x 12	—	—
Sidewalk Closed, Use Other Side	R9-10	6F.14	24 x 12	—	—
Sidewalk Closed Ahead, Cross Here	R9-11	6F.14	24 x 18	—	—
Sidewalk Closed, Cross Here	R9-11a	6F.14	24 x 12	—	—
Road Closed	R11-2	6F.08	48 x 30	—	—
Road Closed - Local Traffic Only	R11-3a,3b,4	6F.09	60 x 30	—	—
Weight Limit	R12-1,2	6F.10	24 x 30	36 x 48	—
Weight Limit (with symbols)	R12-5	6F.10	24 x 36	36 x 48	—
Turn and Curve Signs	W1-1,2,3,4	6F.16	36 x 36	48 x 48	30 x 30
Reverse Curve (2 or more lanes)	W1-4b,4c	6F.48	36 x 36	48 x 48	30 x 30
One-Direction Large Arrow	W1-6	6F.16	48 x 24	60 x 30	—
Chevron	W1-8	6F.16	18 x 24	30 x 36	—
Stop Ahead	W3-1	6F.16	36 x 36	48 x 48	30 x 30
Yield Ahead	W3-2	6F.16	36 x 36	48 x 48	30 x 30
Signal Ahead	W3-3	6F.16	36 x 36	48 x 48	30 x 30
Be Prepared to Stop	W3-4	6F.16	36 x 36	48 x 48	30 x 30
Reduced Speed Limit Ahead	W3-5	6F.16	36 x 36	48 x 48	30 x 30

Sign or Plaque	Sign Designation	Section	Conventional Road	Freeway or Expressway	Minimum
XX MPH Speed Zone Ahead	W3-5a	6F.16	36 x 36	48 x 48	30 x 30
Merging Traffic	W4-1,5	6F.16	36 x 36	48 x 48	36 x 36
Lane Ends	W4-2	6F.24	36 x 36	48 x 48	30 x 30
Added Lane	W4-3,6	6F.16	36 x 36	48 x 48	30 x 30
No Merge Area (plaque)	W4-5P	6F.16	18 x 24	24 x 30	—
Road Narrows	W5-1	6F.16	36 x 36	48 x 48	30 x 30
Narrow Bridge	W5-2	6F.16	36 x 36	48 x 48	30 x 30
One Lane Bridge	W5-3	6F.16	36 x 36	48 x 48	30 x 30
Ramp Narrows	W5-4	6F.26	36 x 36	48 x 48	30 x 30
Divided Highway	W6-1	6F.16	36 x 36	48 x 48	30 x 30
Divided Highway Ends	W6-2	6F.16	36 x 36	48 x 48	30 x 30
Two-Way Traffic	W6-3	6F.32	36 x 36	48 x 48	30 x 30
Two-Way Traffic	W6-4	6F.76	12 x 18	12 x 18	—
Hill (symbol)	W7-1	6F.16	36 x 36	48 x 48	30 x 30
Next XX Miles (plaque)	W7-3aP	6F.53	24 x 18	36 x 30	—
Bump	W8-1	6F.16	36 x 36	48 x 48	30 x 30
Dip	W8-2	6F.16	36 x 36	48 x 48	30 x 30
Pavement Ends	W8-3	6F.16	36 x 36	48 x 48	30 x 30
Soft Shoulder	W8-4	6F.44	36 x 36	48 x 48	30 x 30
Slippery When Wet	W8-5	6F.16	36 x 36	48 x 48	30 x 30
Truck Crossing	W8-6	6F.36	36 x 36	48 x 48	30 x 30
Loose Gravel	W8-7	6F.16	36 x 36	48 x 48	30 x 30
Rough Road	W8-8	6F.16	36 x 36	48 x 48	30 x 30
Low Shoulder	W8-9	6F.44	36 x 36	48 x 48	30 x 30
Uneven Lanes	W8-11	6F.45	36 x 36	48 x 48	30 x 30
No Center Line	W8-12	6F.47	36 x 36	48 x 48	30 x 30
Fallen Rocks	W8-14	6F.16	36 x 36	48 x 48	30 x 30
Grooved Pavement	W8-15	6F.16	36 x 36	48 x 48	30 x 30
Motorcycle (plaque)	W8-15P	6F.54	24 x 18	30 x 24	—
Shoulder Drop Off (symbol)	W8-17	6F.44	36 x 36	48 x 48	30 x 30
Shoulder Drop-Off (plaque)	W8-17P	6F.44	24 x 18	30 x 24	—
Road May Flood	W8-18	6F.16	36 x 36	48 x 48	24 x 24
No Shoulder	W8-23	6F.16	36 x 36	48 x 48	30 x 30
Steel Plate Ahead	W8-24	6F.46	36 x 36	48 x 48	30 x 30
Shoulder Ends	W8-25	6F.16	36 x 36	48 x 48	30 x 30
Lane Ends	W9-1,2	6F.16	36 x 36	48 x 48	30 x 30
Center Lane Closed Ahead	W9-3	6F.23	36 x 36	48 x 48	30 x 30
Grade Crossing Advance Warning	W10-1	6F.16	36 dia.	—	—
Truck	W11-10	6F.36	36 x 36	48 x 48	30 x 30
Double Arrow	W12-1	6F.16	30 x 30	—	—
Low Clearance	W12-2	6F.16	36 x 36	48 x 48	30 x 30
Advisory Speed (plaque)	W13-1P	6F.52	24 x 24	30 x 30	18 x 18
On Ramp (plaque)	W13-4P	6F.25	36 x 36	36 x 36	—
No Passing Zone (pennant)	W14-3	6F.16	48 x 48 x 36	64 x 64 x 48	40 x 40 x 30
XX Feet (plaque)	W16-2P	6F.16	24 x 18	30 x 24	—
Road Work (with distance)	W20-1	6F.18	36 x 36	48 x 48	30 x 30

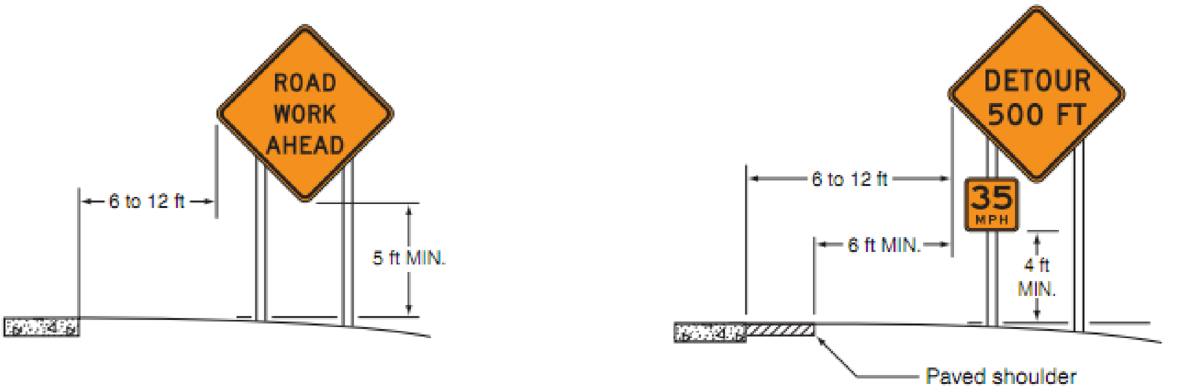
Sign or Plaque	Sign Designation	Section	Conventional Road	Freeway or Expressway	Minimum
Detour (with distance)	W20-2	6F.19	36 x 36	48 x 48	30 x 30
Road (Street) Closed (with distance)	W20-3	6F.20	36 x 36	48 x 48	30 x 30
One Lane Road (with distance)	W20-4	6F.21	36 x 36	48 x 48	30 x 30
Lane(s) Closed (with distance)	W20-5,5a	6F.22	36 x 36	48 x 48	30 x 30
Flagger (symbol)	W20-7	6F.31	36 x 36	48 x 48	30 x 30
Flagger	W20-7a	6F.31	36 x 36	48 x 48	30 x 30
Slow (on Stop/Slow Paddle)	W20-8	6E.03	18 x 18	—	—
Workers	W21-1,1a	6F.33	36 x 36	48 x 48	30 x 30
Fresh Oil (Tar)	W21-2	6F.34	36 x 36	48 x 48	30 x 30
Road Machinery Ahead	W21-3	6F.35	36 x 36	48 x 48	30 x 30
Slow Moving Vehicle	W21-4	6G.06	36 x 18	—	—
Shoulder Work	W21-5	6F.37	36 x 36	48 x 48	30 x 30
Shoulder Closed	W21-5a	6F.37	36 x 36	48 x 48	30 x 30
Shoulder Closed (with distance)	W21-5b	6F.37	36 x 36	48 x 48	30 x 30
Survey Crew	W21-6	6F.38	36 x 36	48 x 48	30 x 30
Utility Work Ahead	W21-7	6F.39	36 x 36	48 x 48	30 x 30
Mowing Ahead	W21-8	6G.06	36 x 36	48 x 48	30 x 30
Blasting Zone Ahead	W22-1	6F.41	36 x 36	48 x 48	30 x 30
Turn Off 2-Way Radio and Cell Phone	W22-2	6F.42	42 x 36	42 x 36	—
End Blasting Zone	W22-3	6F.43	42 x 36	42 x 36	36 x 30
Slow Traffic Ahead	W23-1	6F.27	48 x 24	48 x 24	—
New Traffic Pattern Ahead	W23-2	6F.30	36 x 36	48 x 48	30 x 30
Double Reverse Curve (1 lane)	W24-1	6F.49	36 x 36	48 x 48	30 x 30
Double Reverse Curve (2 lanes)	W24-1a	6F.49	36 x 36	48 x 48	30 x 30
Double Reverse Curve (3 lanes)	W24-1b	6F.49	36 x 36	48 x 48	30 x 30
All Lanes	W24-1cP	6F.49	24 x 24	30 x 30	—
Road Work Next XX Miles	G20-1	6F.56	36 x 18	48 x 24	—
End Road Work	G20-2	6F.57	36 x 18	48 x 24	—
Pilot Car Follow Me	G20-4	6F.58	36 x 18	—	—
Work Zone (plaque)	G20-5aP	6F.12	24 x 18	36 x 24	—
Exit Open	E5-2	6F.28	48 x 36	48 x 36	—
Exit Closed	E5-2a	6F.28	48 x 36	48 x 36	—
Exit Only	E5-3	6F.29	48 x 36	48 x 36	—
Detour	M4-8	6F.59	24 x 12	30 x 15	—
End Detour	M4-8a	6F.59	24 x 18	24 x 18	—
End	M4-8b	6F.59	24 x 12	24 x 12	—
Detour	M4-9	6F.59	30 x 24	48 x 36	—
Bike/Pedestrian Detour	M4-9a	6F.59	30 x 24	—	—
Pedestrian Detour	M4-9b	6F.59	30 x 24	—	—
Bike Detour	M4-9c	6F.59	30 x 24	—	—
Detour	M4-10	6F.59	48 x 18	—	—

* See Table 2B-1 for minimum size required for signs facing traffic on multi-lane conventional roads

Notes: 1. Larger signs may be used wherever necessary for greater legibility or emphasis
2. Dimensions are shown in inches and are shown as width x height

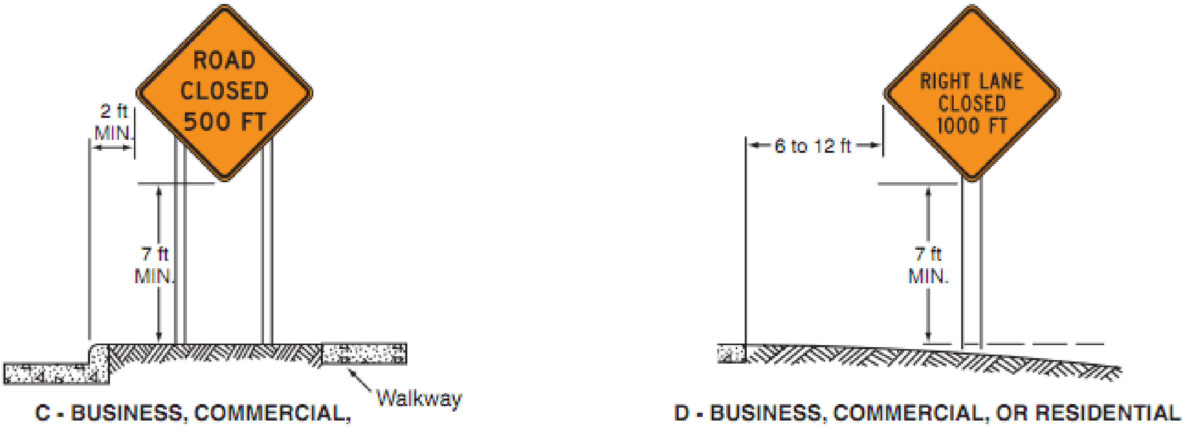
Source: FHWA, 2009 pp. 578-580

APPENDIX E.
MUTCD FIGURE 6F-1. HEIGHT AND LATERAL LOCATIONS OF SIGNS – TYPICAL INSTALLATIONS



A - RURAL AREA

B - RURAL AREA WITH ADVISORY SPEED PLAQUE

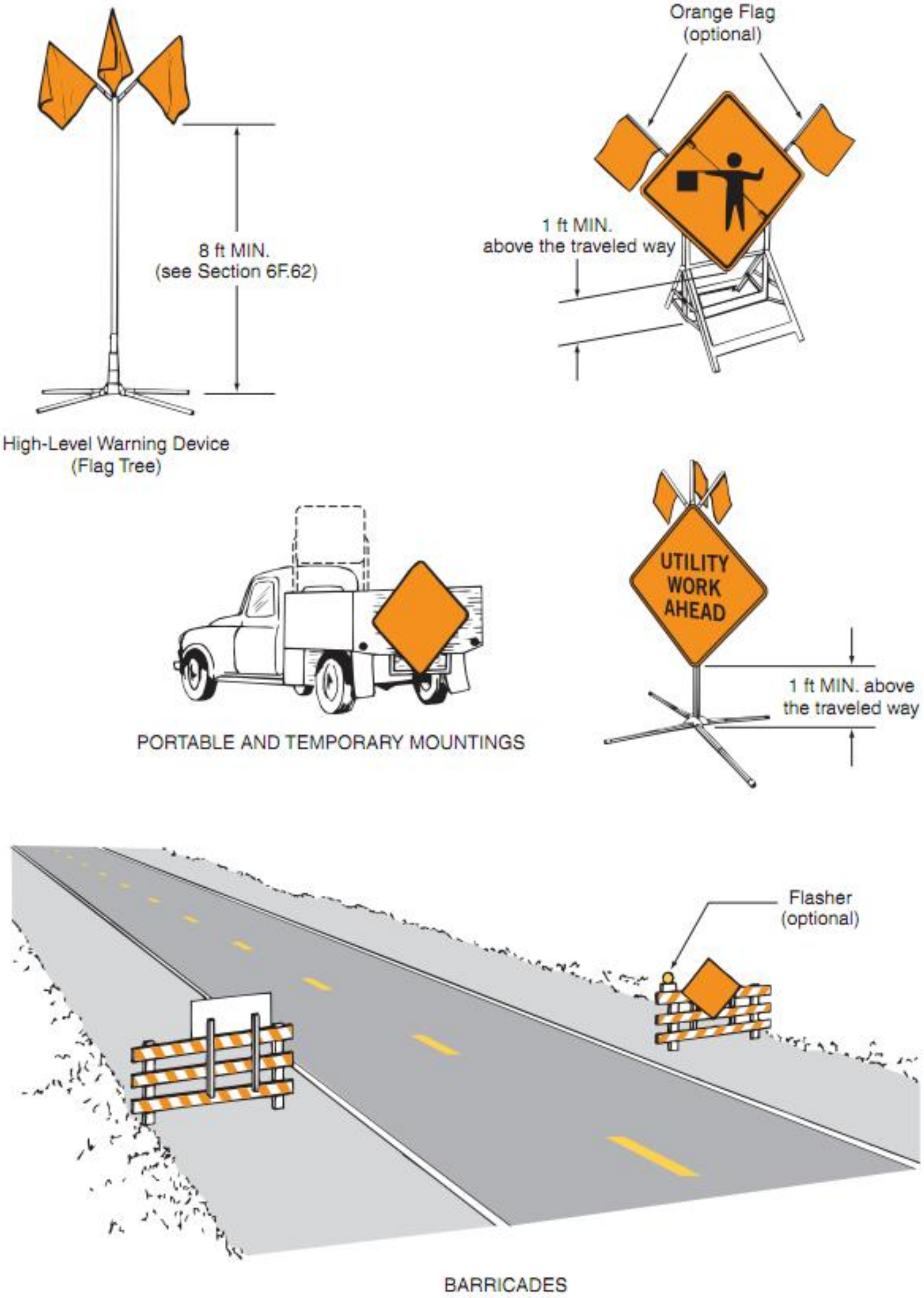


C - BUSINESS, COMMERCIAL, OR RESIDENTIAL AREA

D - BUSINESS, COMMERCIAL, OR RESIDENTIAL AREA (WITHOUT CURB)

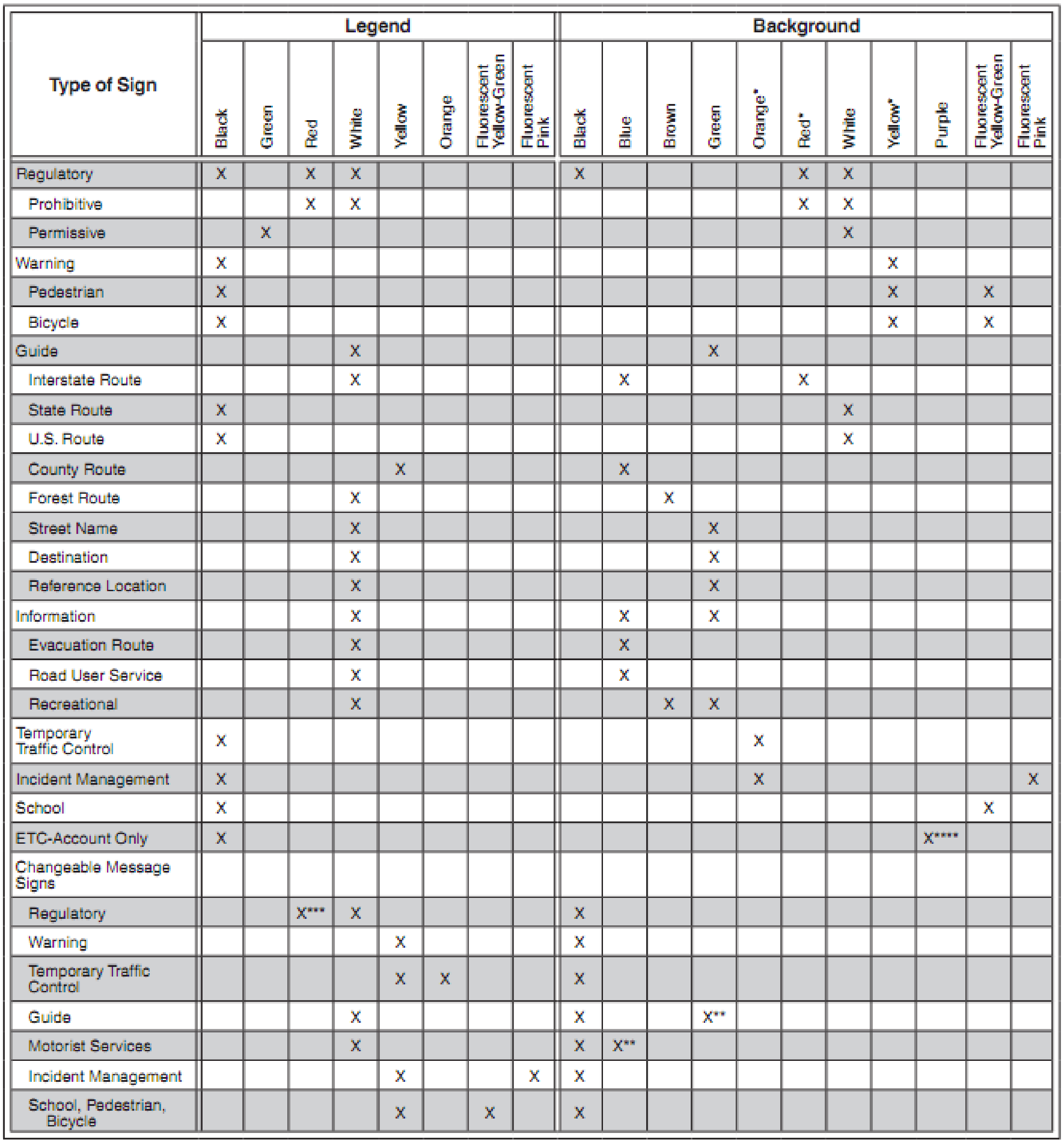
Source: FHWA, 2009, p. 581

APPENDIX F.
MUTCD FIGURE 6F-2. METHODS OF MOUNTING SIGNS OTHER THAN ON POSTS



Source: FHWA, 2009, p. 582

APPENDIX G.
MUTCD TABLE 2A-5. COMMON USES OF SIGN COLORS



Type of Sign	Legend								Background										
	Black	Green	Red	White	Yellow	Orange	Fluorescent Yellow-Green	Fluorescent Pink	Black	Blue	Brown	Green	Orange*	Red*	White	Yellow*	Purple	Fluorescent Yellow-Green	Fluorescent Pink
Regulatory	X		X	X					X					X	X				
Prohibitive			X	X										X	X				
Permissive		X													X				
Warning	X															X			
Pedestrian	X															X		X	
Bicycle	X															X		X	
Guide				X								X							
Interstate Route				X						X				X					
State Route	X														X				
U.S. Route	X														X				
County Route					X					X									
Forest Route				X							X								
Street Name				X								X							
Destination				X								X							
Reference Location				X								X							
Information				X						X		X							
Evacuation Route				X						X									
Road User Service				X						X									
Recreational				X							X	X							
Temporary Traffic Control	X												X						
Incident Management	X												X						X
School	X																	X	
ETC-Account Only	X																X****		
Changeable Message Signs																			
Regulatory			X***	X					X										
Warning					X				X										
Temporary Traffic Control					X	X			X										
Guide				X					X			X**							
Motorist Services				X					X	X**									
Incident Management					X			X	X										
School, Pedestrian, Bicycle					X		X		X										

* Fluorescent versions of these background colors may also be used.

** These alternative background colors would be provided by blue or green lighted pixels such that the entire CMS would be lighted, not just the legend.

*** Red is used only for the circle and slash or other red elements of a similar static regulatory sign.

**** The use of the color purple on signs is restricted per the provisions of Paragraph 1 of Section 2F.03.

Source: FHWA, 2009

APPENDIX H.
MUTCD TABLE 1A-2 AND 1A-3 ACCEPTABLE AND UNACCEPTABLE PCMS ABBREVIATIONS

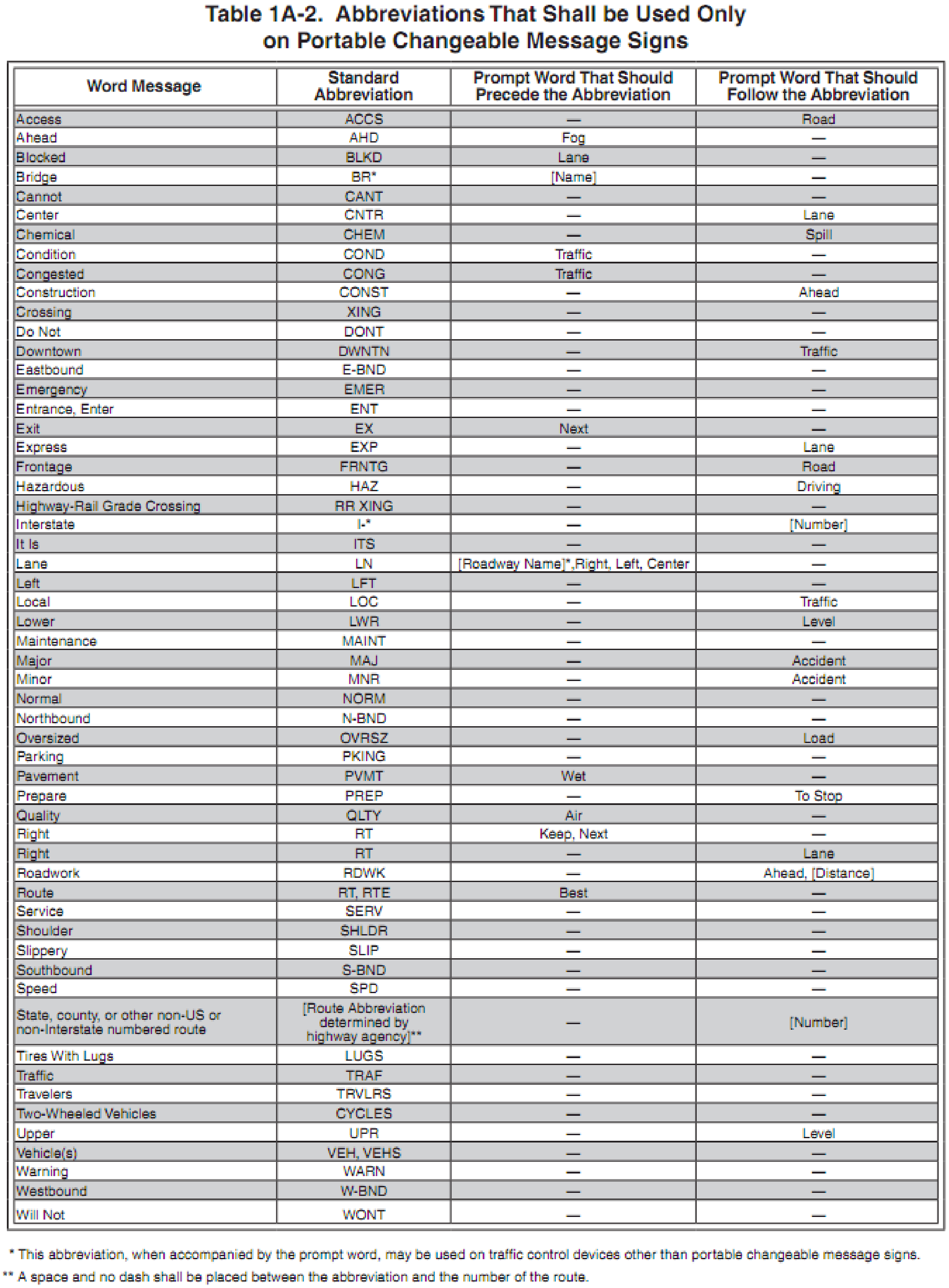


Table 1A-2. Abbreviations That Shall be Used Only on Portable Changeable Message Signs

Word Message	Standard Abbreviation	Prompt Word That Should Precede the Abbreviation	Prompt Word That Should Follow the Abbreviation
Access	ACCS	—	Road
Ahead	AHD	Fog	—
Blocked	BLKD	Lane	—
Bridge	BR*	[Name]	—
Cannot	CANT	—	—
Center	CNTR	—	Lane
Chemical	CHEM	—	Spill
Condition	COND	Traffic	—
Congested	CONG	Traffic	—
Construction	CONST	—	Ahead
Crossing	XING	—	—
Do Not	DONT	—	—
Downtown	DWNTN	—	Traffic
Eastbound	E-BND	—	—
Emergency	EMER	—	—
Entrance, Enter	ENT	—	—
Exit	EX	Next	—
Express	EXP	—	Lane
Frontage	FRNTG	—	Road
Hazardous	HAZ	—	Driving
Highway-Rail Grade Crossing	RR XING	—	—
Interstate	I-*	—	[Number]
It Is	ITS	—	—
Lane	LN	[Roadway Name]*,Right, Left, Center	—
Left	LFT	—	—
Local	LOC	—	Traffic
Lower	LWR	—	Level
Maintenance	MAINT	—	—
Major	MAJ	—	Accident
Minor	MNR	—	Accident
Normal	NORM	—	—
Northbound	N-BND	—	—
Oversized	OVRSZ	—	Load
Parking	PKING	—	—
Pavement	PVMT	Wet	—
Prepare	PREP	—	To Stop
Quality	QLTY	Air	—
Right	RT	Keep, Next	—
Right	RT	—	Lane
Roadwork	RDWK	—	Ahead, [Distance]
Route	RT, RTE	Best	—
Service	SERV	—	—
Shoulder	SHLDR	—	—
Slippery	SLIP	—	—
Southbound	S-BND	—	—
Speed	SPD	—	—
State, county, or other non-US or non-Interstate numbered route	[Route Abbreviation determined by highway agency]**	—	[Number]
Tires With Lugs	LUGS	—	—
Traffic	TRAF	—	—
Travelers	TRVLRS	—	—
Two-Wheeled Vehicles	CYCLES	—	—
Upper	UPR	—	Level
Vehicle(s)	VEH, VEHS	—	—
Warning	WARN	—	—
Westbound	W-BND	—	—
Will Not	WONT	—	—

* This abbreviation, when accompanied by the prompt word, may be used on traffic control devices other than portable changeable message signs.

** A space and no dash shall be placed between the abbreviation and the number of the route.

Source: FHWA, 2009, p. 25

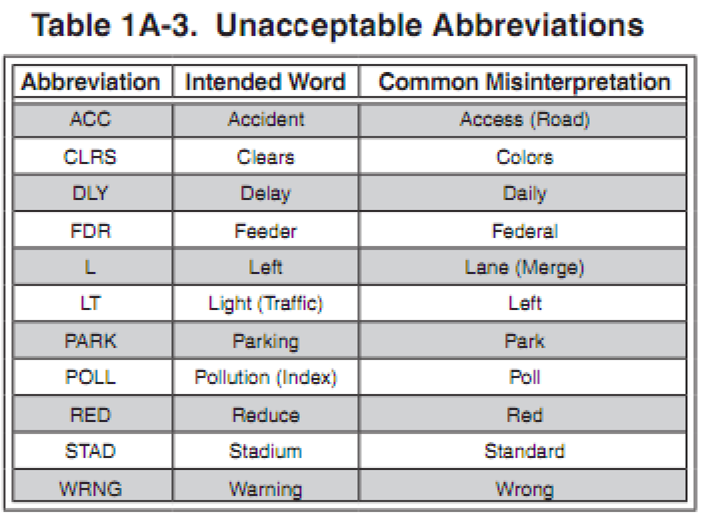
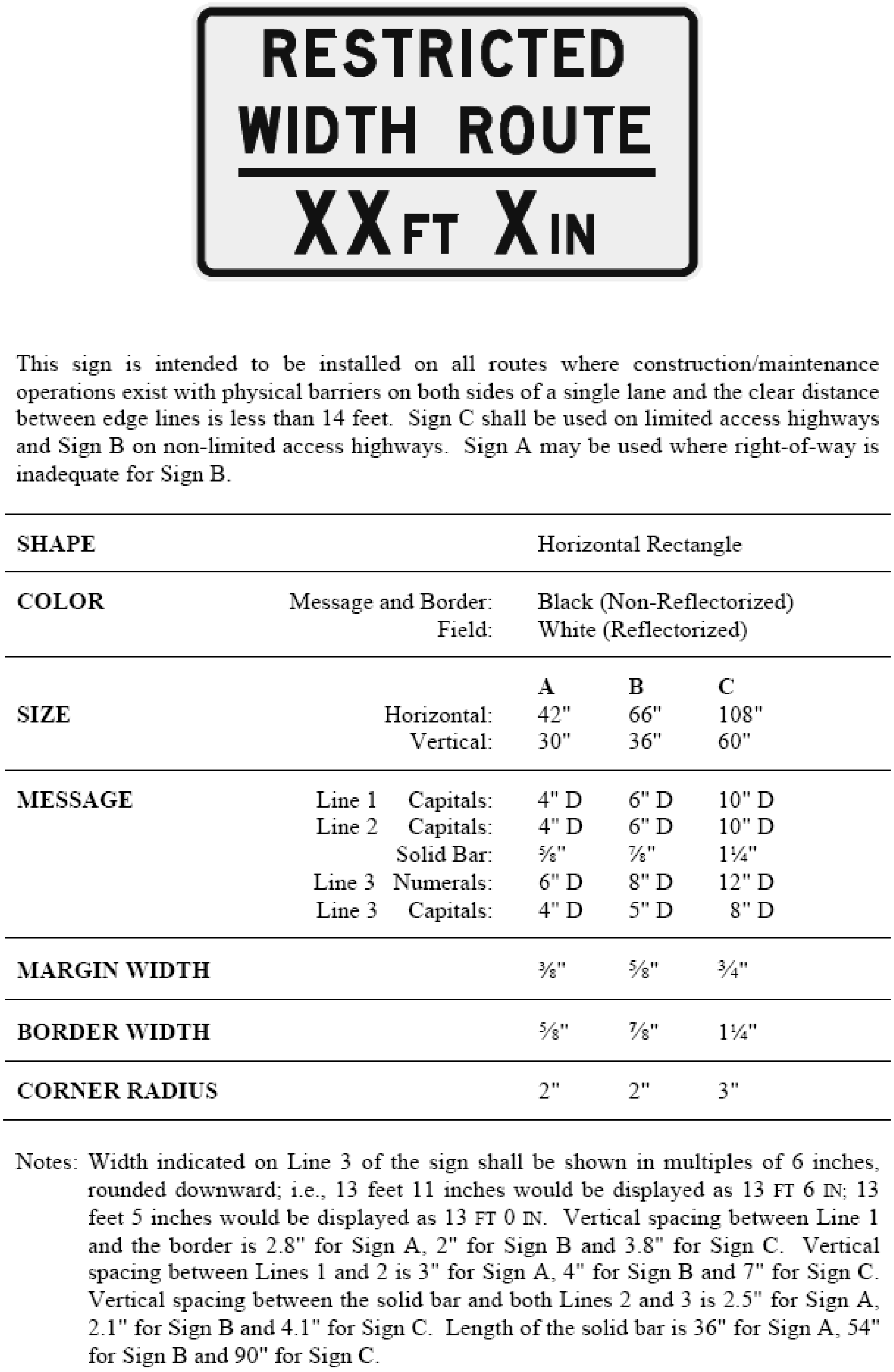


Table 1A-3. Unacceptable Abbreviations

Abbreviation	Intended Word	Common Misinterpretation
ACC	Accident	Access (Road)
CLRS	Clears	Colors
DLY	Delay	Daily
FDR	Feeder	Federal
L	Left	Lane (Merge)
LT	Light (Traffic)	Left
PARK	Parking	Park
POLL	Pollution (Index)	Poll
RED	Reduce	Red
STAD	Stadium	Standard
WRNG	Warning	Wrong

Source: FHWA, 2009, p. 26

APPENDIX I.
VIRGINIA'S RESTRICTED WIDTH ROUTE SIGN ENGINEERING DETAILS



This sign is intended to be installed on all routes where construction/maintenance operations exist with physical barriers on both sides of a single lane and the clear distance between edge lines is less than 14 feet. Sign C shall be used on limited access highways and Sign B on non-limited access highways. Sign A may be used where right-of-way is inadequate for Sign B.

SHAPE		Horizontal Rectangle		
COLOR	Message and Border:	Black (Non-Reflectorized)		
	Field:	White (Reflectorized)		
		A	**B**	**C**
SIZE	Horizontal:	42"	66"	108"
	Vertical:	30"	36"	60"
MESSAGE	Line 1 Capitals:	4" D	6" D	10" D
	Line 2 Capitals:	4" D	6" D	10" D
	Solid Bar:	⅝"	⅞"	1¼"
	Line 3 Numerals:	6" D	8" D	12" D
	Line 3 Capitals:	4" D	5" D	8" D
MARGIN WIDTH		⅜"	⅝"	¾"
BORDER WIDTH		⅝"	⅞"	1¼"
CORNER RADIUS		2"	2"	3"

Notes: Width indicated on Line 3 of the sign shall be shown in multiples of 6 inches, rounded downward; i.e., 13 feet 11 inches would be displayed as 13 FT 6 IN; 13 feet 5 inches would be displayed as 13 FT 0 IN. Vertical spacing between Line 1 and the border is 2.8" for Sign A, 2" for Sign B and 3.8" for Sign C. Vertical spacing between Lines 1 and 2 is 3" for Sign A, 4" for Sign B and 7" for Sign C. Vertical spacing between the solid bar and both Lines 2 and 3 is 2.5" for Sign A, 2.1" for Sign B and 4.1" for Sign C. Length of the solid bar is 36" for Sign A, 54" for Sign B and 90" for Sign C.

Source: Khoury, 2006, p. 3

APPENDIX J.
MINNESOTA'S INTELLIGENT WORK ZONE TOOLBOX 2008 EDITION VEHICLE RESPONSIVE OVER DIMENSION WARNING DESIGN

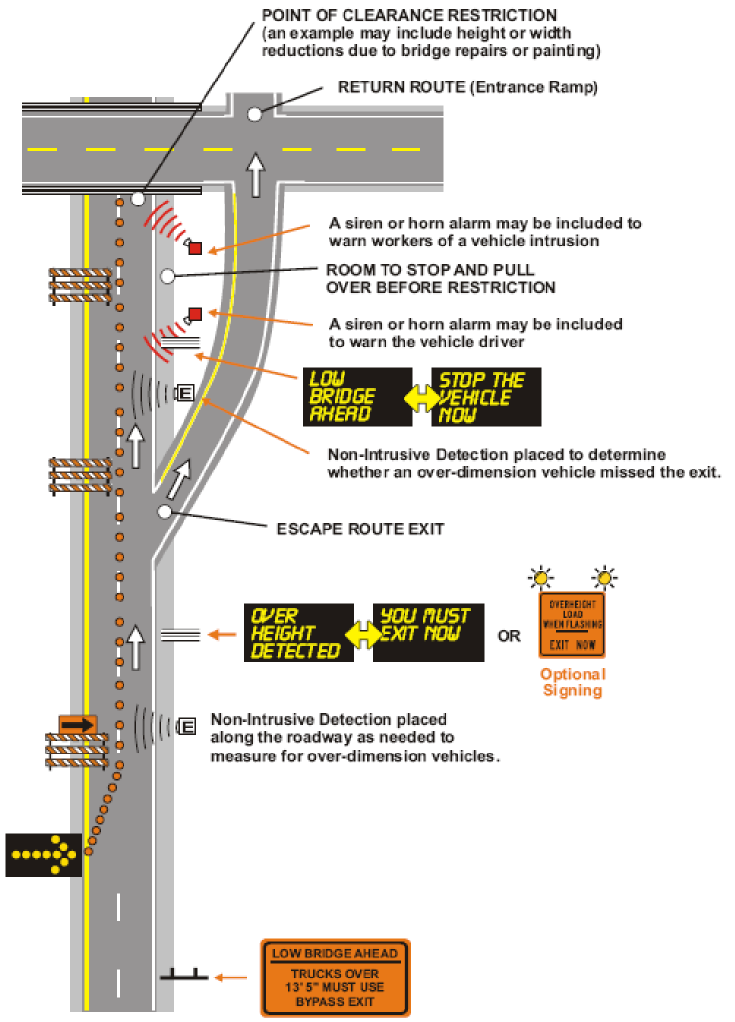
WARRANTS

- Construction causes temporary minimal clearance (or less than minimum) for large vehicles using the roadway, or
- A minimal clearance condition exists within a work zone and construction vehicles must be warned of the condition.

BENEFITS

- The system should alert a driver that their vehicle is over-dimension and they are required to use an escape route.
- The system should alert drivers of their route mistake and provide sufficient time to conduct the escape maneuver.
- The second portion of the system warns a driver to stop if he failed to use the designated escape route.

Layouts are NOT drawn to scale.



OPTIONS

NOTES

- Advance warning signs and other standard temporary traffic control devices have not been shown on this figure. Refer to the MN MUTCD including the 2007 Field Manual or the TTC Layout Templates for typical layout examples.
- All IWZ Guide Signs and CMS should be reviewed by the Mn/DOT Office of Traffic, Safety, & Operations for design and message approval.
- Approved CMS messages should be listed in the Special Provisions, and approx CMS locations should shown on the TTC plans. All CMS displays should be blank when messages are not warranted.
- Refer to the Toolbox Definitions Section for graphic symbols and terms.

Intelligent Work Zone Systems Toolbox	VEHICLE RESPONSIVE	OVER DIMENSION WARNING	Last Revision Date: 04-29-08

Source: Minnesota Department of Transportation Office of Traffic, Safety, and Operations, 2008, p. 18

APPENDIX K.
STATE AUTOMATED VEHICLE OVER-HEIGHT MEASUREMENT SYSTEM SUMMARIES

Source: Agrawal, 2010a

Item/Description	**Missouri**	**Maryland**	**Texas**	**Hawaii**	**Minnesota**	**Maine**	**Alaska**	**Virginia**
Besides passive and automated over-height detection systems, have you considered any other alternatives	No	Police Enforcement	No	No	No	No	Hanging bar/chains/plastic tubes	No
Type of Device	Z-Pattern System	Optic	Pipes on Cable	Pulsed Infra-Red / Pulsed LED & IR	Infrared light	Z-Pattern dual beam units	Laser	Dual beam
Manufacturer	Trigg	Sick	Custom	Trigg	Trigg	Trigg	Trigg	Jo-Kell
Initial Cost	$7,700-8,900	$50-100K	$10,000	$13,000-14,300	$45,231	$150-200K	$1.33 million	$1,230-2,400
Maintenance and Operating Costs	Approximately $50/year	$5-10K	$1,500	$400	N/A	$600	On Warranty	
Number of Years in Service	4-8	10-15	10	4-12	6	1-3	3	12-17
Reduction in bridge hits after installation of automated systems (on a scale of 1 to 10)	8.5	8	9	10	9	8	N/A	10
Reduction in number of trucks on unauthorized highways with restriction on trucks (on a scale of 1 to 10)	N/A	N/A		10	N/A	8	0	N/A
Do your installations have any operational/maintenance issues	Systems hit by lightening and by a vehicle	Insufficient space because of fitting to existing tunnel approach	Only for low speed/only low volume roadways	Difficult maintenance due to accessibility. OH located on side of a bridge	Voltage regulator and detection components damaged by lightening	No	Many issues, too complex mechanism, very poor truck discrimination built in, or documentation devices when bridges are hit	Fake alarms because of the direction of the receiver with respect to the sun, because of bird activity

Item/Description	Missouri	Maryland	Texas	Hawaii	Minnesota	Maine	Alaska	Virginia
Have you observed any operational issues during snow	No problems during snow	Snow, rain, birds, exhaust from trucks will cause false sensor trips. We use multiple sensors to reduce the impacts, e.g.: Two sensors a foot or so apart	N/A		No	During cold weather false positives increase	Significant – false calls constant. Snow plowing at truck speeds impact, bend, clog sign boards	During very heavy snow we sometimes have false alarms
Do you use advanced signaling to supplement automated over-height detection devices (Y/N)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
What is the frequency of false positives? Do you use any mitigation approaches for false positives?	We don't experience false positives because the unit has directional detection as well as speed indicator	There are individual false positive hits on sensors. We use multiple sensors to try and reduce the impact. Generally, it is more acceptable to falsely trigger the warning signs than not to trigger the signs at all		1 per month		One every three months	Constant during snowfall. Loop design poor. Research retrofit for improved truck verification and snowfall screening	Most of the false alarms are caused by environmental factors, e.g., sun shining directly into the receivers, try to avoid pointing the receivers due east or west
What is the local power source for the automated over-height detection system	120 volt	120 volt utility company feed		Using freeway lighting 277 Volt down to 120 Volt	120 +/-10% 50/60 Hz	Hard wired	Freeway lighting load center	Tunnel power systems, standard "neighborhood" sources

Item/Description	**Missouri**	**Maryland**	**Texas**	**Hawaii**	**Minnesota**	**Maine**	**Alaska**	**Virginia**
Is the environment around the device, such as high bird area, gusty winds, debris, etc., a problem in the detection of over-height vehicles? Please describe.	No problem	Birds will false trigger single devices. Poor pavement will cause trucks to bounce limiting accuracy also. It's an IR beam so anything that blocks it will cause a trigger	Yes- Leads to many of the false positives	No	No	High pigeon area	Gusty area. Not enough room to set devices on stronger posts. Steep interchange embankments	Minor problem. Most of mainline over-height detectors have backup detectors. We also have some visual coverage with our tower mounted CCTV cameras.
How long do you expect the system to last (functionally and technologically?	15 years	12-15 years		20 years		15 years	5 years with retrofit	15 years
What is your overall opinion of the system and its cost effectiveness?	Very reliable, also used to detect vehicles over 10 feet tall that are traveling faster than 20 mi/h for advanced flashers for a sharp curve in the road	It is effective at reducing damage in the tunnel from over-height vehicles. It is effective enough that operations places a high demand on the system being functional		Very good. After installation cost, the maintenance cost is minimal	Has worked well so far	Satisfied with system	Used less knowledgeable designer, builder. Need to use a turnkey Design/Build option instead.	Very effective and necessary to protect our tunnel ceilings. In the past, one over-height vehicle caused over $1M in damages to a tunnel ceiling

Item/Description	**Missouri**	**Maryland**	**Texas**	**Hawaii**	**Minnesota**	**Maine**	**Alaska**	**Virginia**
Please describe any specific notable approaches/factors (such as unique traffic laws) that have been effective in reducing the frequency of bridge hits?	N/A	Our system is focused on over-heights getting into tunnels; a pre-warning system activates a sign prior to the last exit before the tunnel. If the truckers fail to get off, the second system alerts on-duty police and the truck is pulled over and ticketed, the fie is very high. The combination of warning systems, enforcement, and high fines greatly reduce over-heights in the tunnel. They do still occasionally get in though.		None			Region wide posting of low bridges based on hit frequency	We have had the support of our local legislature to have laws implemented to issue severe fines and up to 3 points applied against the driver's CDL license

APPENDIX L.
CONSENT FORMS FOR OVER-WIDTH LOAD ESCORTS AND DRIVERS

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

INFORMED CONSENT FOR PARTICIPANTS OF INVESTIGATIVE PROJECTS: ESCORT DRIVERS

Title of Project: Vehicle-Width Measurement Technology Development: Phase I

Investigators: Darrell Bowman, Andy Schaudt, Andrew Marinik, Tammy Trimble, and Stephanie Baker of the Virginia Tech Transportation Institute, Virginia Tech.

I. THE PURPOSE OF THIS RESEARCH PROJECT

The purpose of this research study is to develop an advanced over-width measurement and warning system for Virginia. During the phone interview we will ask you for your experience and opinions regarding current over-width signage. We'd also like your input concerning how the new measurement and warning system should work.

II. PROCEDURES

You have been invited to take part in a phone interview. The interview will last approximately 15 minutes and will be audio recorded. The interview will be an informal discussion where you will have the opportunity to share your thoughts and opinions about current over-width signage and the development of a new over-width measurement and warning system.

III. RISKS

There is minimal risk involved in this study. The minimal risks include: possible minor discomfort from being audio recorded or expressing your opinions.

IV. BENEFITS

No promise or guarantee of benefits will be made to encourage your participation. You may find the discussion interesting and your opinions may influence the design of a novel and advanced over-width measurement and warning system for Virginia.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The data gathered in this interview will be treated with confidentiality. Coding (i.e., Participant#01) will be used so participant names will not be linked with any data collected. Data that is reported or shared with any outside group or people will be de-identified (e.g., no names attached) so that your participation will remain confidential. The interview will be audio recorded. The data from this study will be stored at the Virginia Tech Transportation Institute. The audio recordings will be destroyed after the study results have been prepared.

It is possible that the Institutional Review Board (IRB) may view this study's collected data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research. Access to the data will be under the supervision of Darrell Bowman, Andy Schaudt, Andrew Marinik, Tammy Trimble, and Stephanie Baker (VTTI Research Team). Darrell Bowman or Andy Schaudt may grant other VTTI researchers access to de-identified data (e.g. no names attached) collected in this study to be used in additional IRB approved research projects. All data collected in this study will be saved for at least 5 years and a decision to destroy the data will be made at that time.

VI. COMPENSATION

No offer or promise of compensation or benefit for your participation is being made to you.

VII. FREEDOM TO WITHDRAW

As a voluntary participant in this study, you are free to withdraw at any time for any reason. There is no penalty if you choose to withdraw at any point from the study. You are also free to refrain from answering any questions that you would rather not answer.

VIII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University. This approval is good for the period of time listed at the end of this document.

IX. PARTICIPANT'S RESPONSIBILITIES

If you voluntarily agree to participate in this study, you will have the following responsibilities:

1. To be physically free of any substances (alcohol, drugs, etc.) that might impair your ability to participate in the interview discussion.
2. Acknowledge that you are at least 18 years old, currently (in past six months) escorting over-width vehicles in Virginia, and while on the job (in VA) you have seen width restriction related signage.

X. PARTICIPANT'S PERMISSION

I have read and understand the requirements, procedures, and conditions of this project. I have had all of my questions answered. By providing my verbal consent at the start of the phone interview, I voluntarily agree to participate in this study and have my voice recorded during the interview. If I participate in this study, I understand that I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Should I have any questions about this research or its conduct, I may contact:

Darrell Bowman, Principal Investigator	(540) 231-1068, dbowman@vtti.vt.edu
Andy Schaudt, Co-Principal Investigator	(540) 231-1591, aschaudt@vtti.vt.edu

If I should have any questions about the protection of human research participants regarding this study, I may contact:

Dr. David Moore,
Chair of the Virginia Tech Institutional Review Board for the Protection of Human Subjects
(540) 231-4991
moored@vt.edu
Research Compliance Office
1880 Pratt Drive, Suite 2006 (0497)
Blacksburg, VA 24061

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

INFORMED CONSENT FOR PARTICIPANTS OF INVESTIGATIVE PROJECTS: COMMERCIAL VEHICLE DRIVERS

Title of Project: Vehicle-Width Measurement Technology Development: Phase I

Investigators: Darrell Bowman, Andy Schaudt, Andrew Marinik, Tammy Trimble, and Stephanie Baker of the Virginia Tech Transportation Institute, Virginia Tech.

I. THE PURPOSE OF THIS RESEARCH PROJECT

The purpose of this research study is to develop an advanced over-width measurement and warning system for Virginia. During the phone interview we will ask you for your experience and opinions regarding current over-width signage. We'd also like your input concerning how the new measurement and warning system should work.

II. PROCEDURES

You have been invited to take part in a phone interview. The interview will last approximately 15 minutes and will be audio recorded. The interview will be an informal discussion where you will have the opportunity to share your thoughts and opinions about current over-width signage and the development of a new over-width measurement and warning system.

III. RISKS

There is minimal risk involved in this study. The minimal risks include: possible minor discomfort from being audio recorded or expressing your opinions.

IV. BENEFITS

No promise or guarantee of benefits will be made to encourage your participation. You may find the discussion interesting and your opinions may influence the design of a novel and advanced over-width measurement and warning system for Virginia.

V. EXTENT OF ANONYMITY AND CONFIDENTIALITY

The data gathered in this interview will be treated with confidentiality. Coding (i.e., Participant#01) will be used so participant names will not be linked with any data collected. Data that is reported or shared with any outside group or people will be de-identified (e.g., no names attached) so that your participation will remain confidential. The interview will be audio recorded. The data from this study will be stored at the Virginia Tech Transportation Institute. The audio recordings will be destroyed after the study results have been prepared.

It is possible that the Institutional Review Board (IRB) may view this study's collected data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research. Access to the data will be under the supervision of Darrell

Bowman, Andy Schaudt, Andrew Marinik, Tammy Trimble, and Stephanie Baker (VTTI Research Team). Darrell Bowman or Andy Schaudt may grant other VTTI researchers access to de-identified data (e.g. no names attached) collected in this study to be used in additional IRB approved research projects. All data collected in this study will be saved for at least 5 years and a decision to destroy the data will be made at that time.

VI. COMPENSATION

No offer or promise of compensation or benefit for your participation is being made to you.

VII. FREEDOM TO WITHDRAW

As a voluntary participant in this study, you are free to withdraw at any time for any reason. There is no penalty if you choose to withdraw at any point from the study. You are also free to refrain from answering any questions that you would rather not answer.

VIII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University. This approval is good for the period of time listed at the end of this document.

IX. PARTICIPANT'S RESPONSIBILITIES

If you voluntarily agree to participate in this study, you will have the following responsibilities:

1. To be physically free of any substances (alcohol, drugs, etc.) that might impair your ability to participate in the interview discussion.
2. Acknowledge that you are at least 18 years old, currently (in the past six months) operating an over-width vehicle in Virginia, and while on the job have seen width restriction related signage.

X. PARTICIPANT'S PERMISSION

I have read and understand the requirements, procedures, and conditions of this project. I have had all of my questions answered. By providing my verbal consent at the start of the phone interview, I voluntarily agree to participate in this study and have my voice recorded during the interview. If I participate in this study, I understand that I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Should I have any questions about this research or its conduct, I may contact:

Darrell Bowman, Principal Investigator	(540) 231-1068, dbowman@vtti.vt.edu
Andy Schaudt, Co-Principal Investigator	(540) 231-1591, aschaudt@vtti.vt.edu

If I should have any questions about the protection of human research participants regarding this study, I may contact:

Dr. David Moore,
Chair of the Virginia Tech Institutional Review Board for the Protection of Human Subjects

(540) 231-4991
moored@vt.edu
Research Compliance Office
1880 Pratt Drive, Suite 2006 (0497)
Blacksburg, VA 24061

APPENDIX M.
VERBAL CONSENT PROCESS

Vehicle Width Measurement Study Verbal Consent Process

GREETING

- Hello, our names are (INSERT names). We are researchers at VTTI. We want to thank you for taking the time to share your thoughts and opinions with us today.

PURPOSE

- The purpose of this interview is to discuss current over-width signage and the development of a new over-width measurement and warning system.

CONFIDENTIALITY

- We are recording the discussion so please speak loudly and clearly so that we get a good recording of your comments.
- We will make a transcript of our discussion, but will not match comments with names.
- If you feel uncomfortable, you can refuse to answer a question or you may stop the questioning at any time.

LOGISTICS

- This interview will run for approximately 15 minutes.

COMPENSATION

- There will be no compensation for participation in this interview, though we hope that you find the discussion interesting.

VERBAL CONSENT

- By participating in this interview you confirm that you are at least 18, have seen width restriction related signage while on the job, and are currently working as (*read A or B*): (A) a commercial driver operating an over-width vehicle in Virginia (B) an escort driver escorting over-width vehicles in Virginia.
- Do you have any questions?
- If you have no further questions, I just want to confirm that you understand your rights and responsibilities as a participant and wish to take part in this study?
    - ***If yes***: Thank you! We'll get started.
    - ***If no***: Thank you very much for your time.

APPENDIX N.
INTERVIEW QUESTIONS

Vehicle Width Measurement Study Interview Questions by Driver Type

Questions for Virginia Certified Escort Drivers

1. How long have you been working in Virginia as an escort driver?
2. What has been the most effective over-width signage that you have experienced while escorting over-width vehicles in Virginia? Why was it effective?
3. What has been the least effective over-width signage you have experienced while escorting over-width vehicles in Virginia? Why was it ineffective?
4. Have you had an experience where you entered a lane restricted area such as a work zone while escorting an over-width vehicle? If so, what caused this to happen? What kind of over-width warning do you think would have helped you avoid such an area? Please explain.

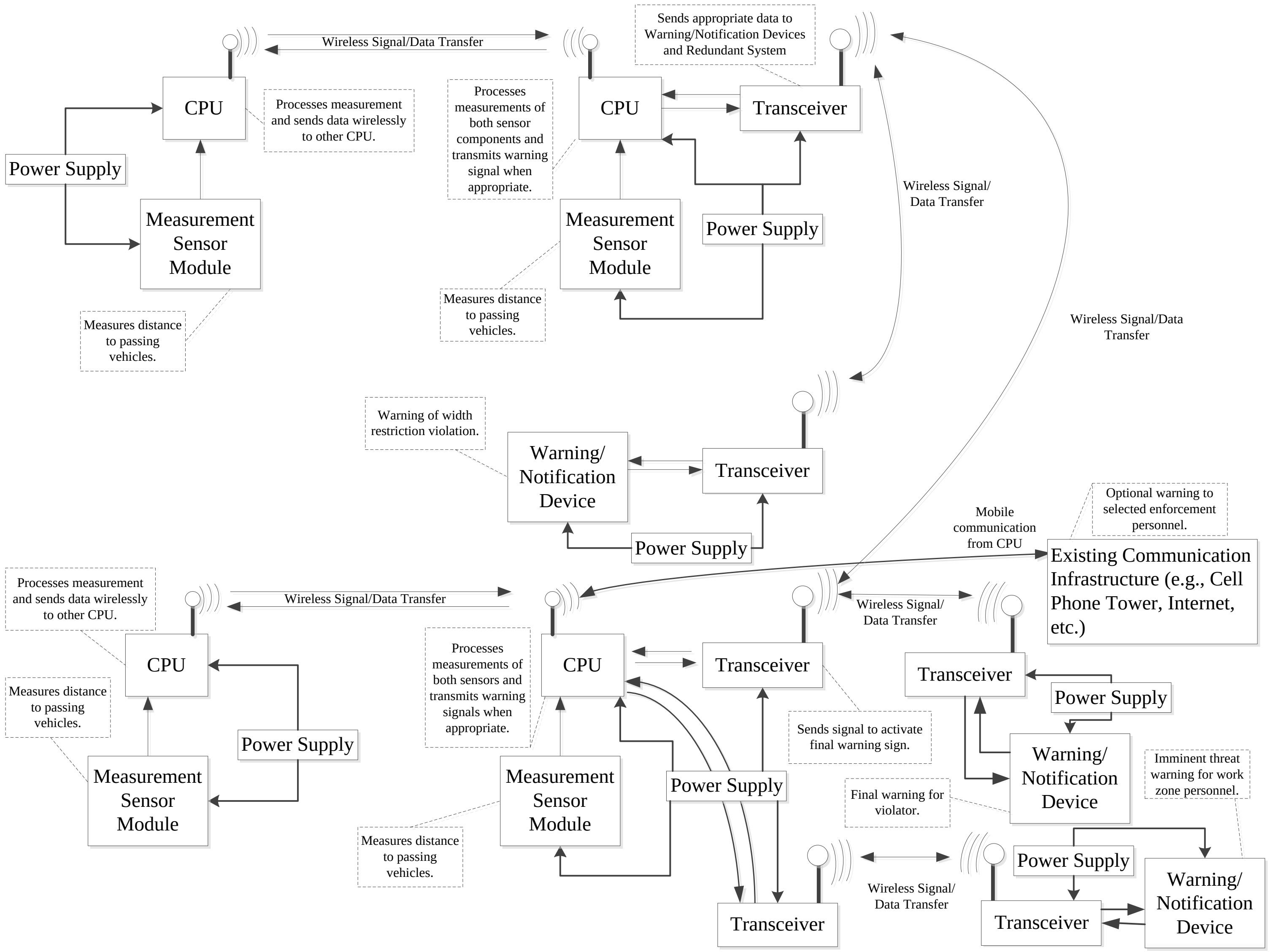
Questions for Driver's Operating Over-width Vehicles in VA

1. How long have you been driving over-width vehicles in Virginia? Have you ever operated under a Virginia Exempt Blanket Hauling Permit?
2. What has been the most effective over-width signage that you have experienced while driving an over-width vehicle in Virginia? Why was it effective?
3. What has been the least effective over-width signage you have experienced while driving an over-width vehicle in Virginia? Why was it ineffective?
4. Have you had an experience where you entered a lane restricted area such as a work zone while operating an over-width vehicle? If so, what caused this to happen? What kind of over-width warning do you think would have helped you avoid such an area? Please explain.

Conclusion (All)

1. Is there anything important that you think we missed today that you want to add? Or any other comments related to this topic that you think would help us in the development of an over-width vehicle measurement and warning system? Your input is important to us.
2. Thank CONTACT for his/her time.

APPENDIX O.
PRELIMINARY VEHICLE-WIDTH MEASUREMENT SYSTEM ARCHITECTURE



Processes measurement and sends data wirelessly to other CPU.

Measures distance to passing vehicles.

Processes measurements of both sensor components and transmits warning signal when appropriate.

Sends appropriate data to Warning/Notification Devices and Redundant System

Measures distance to passing vehicles.

Warning of width restriction violation.

Optional warning to selected enforcement personnel.

Processes measurement and sends data wirelessly to other CPU.

Measures distance to passing vehicles.

Processes measurements of both sensors and transmits warning signals when appropriate.

Measures distance to passing vehicles.

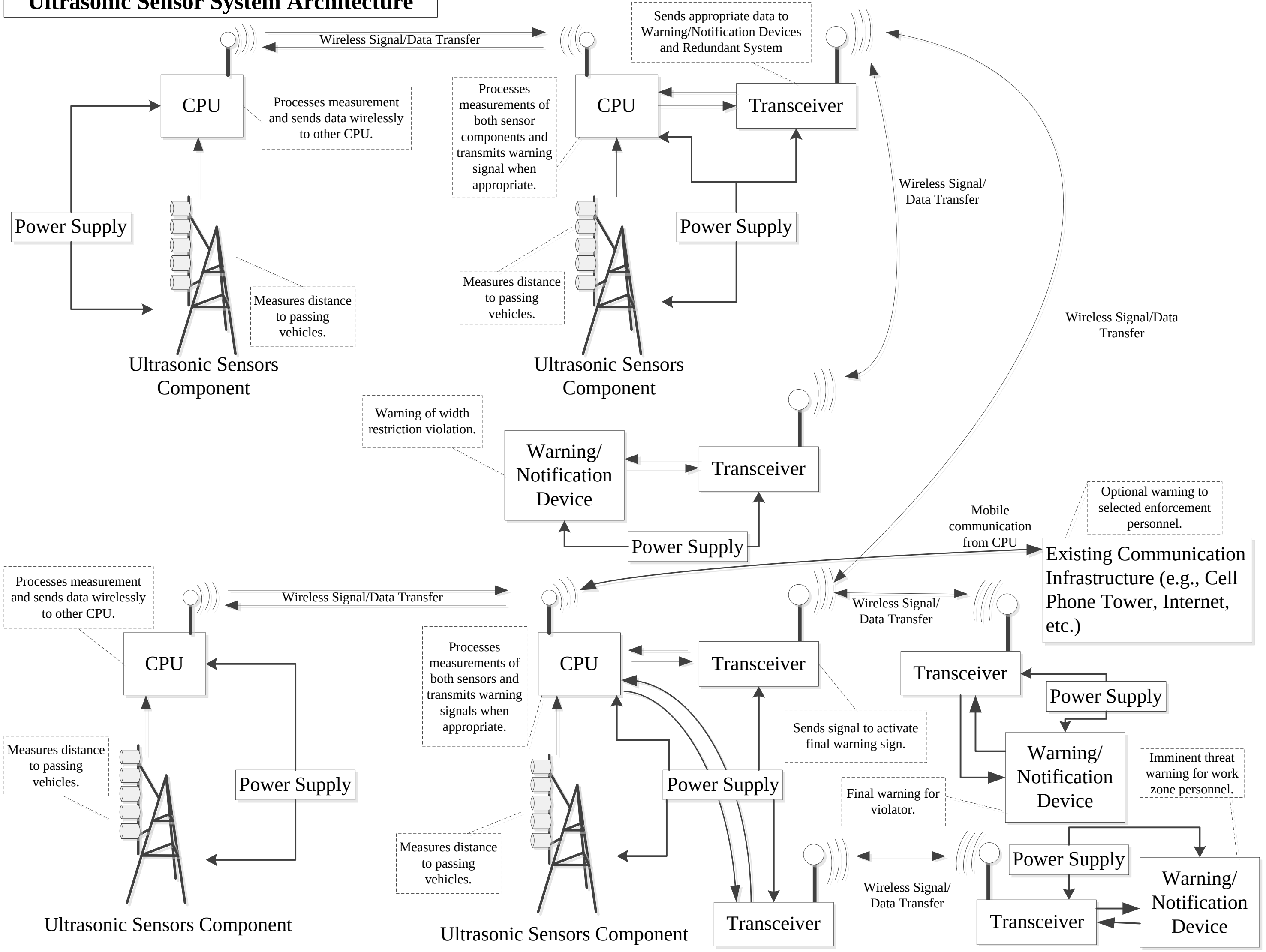
Sends signal to activate final warning sign.

Final warning for violator.

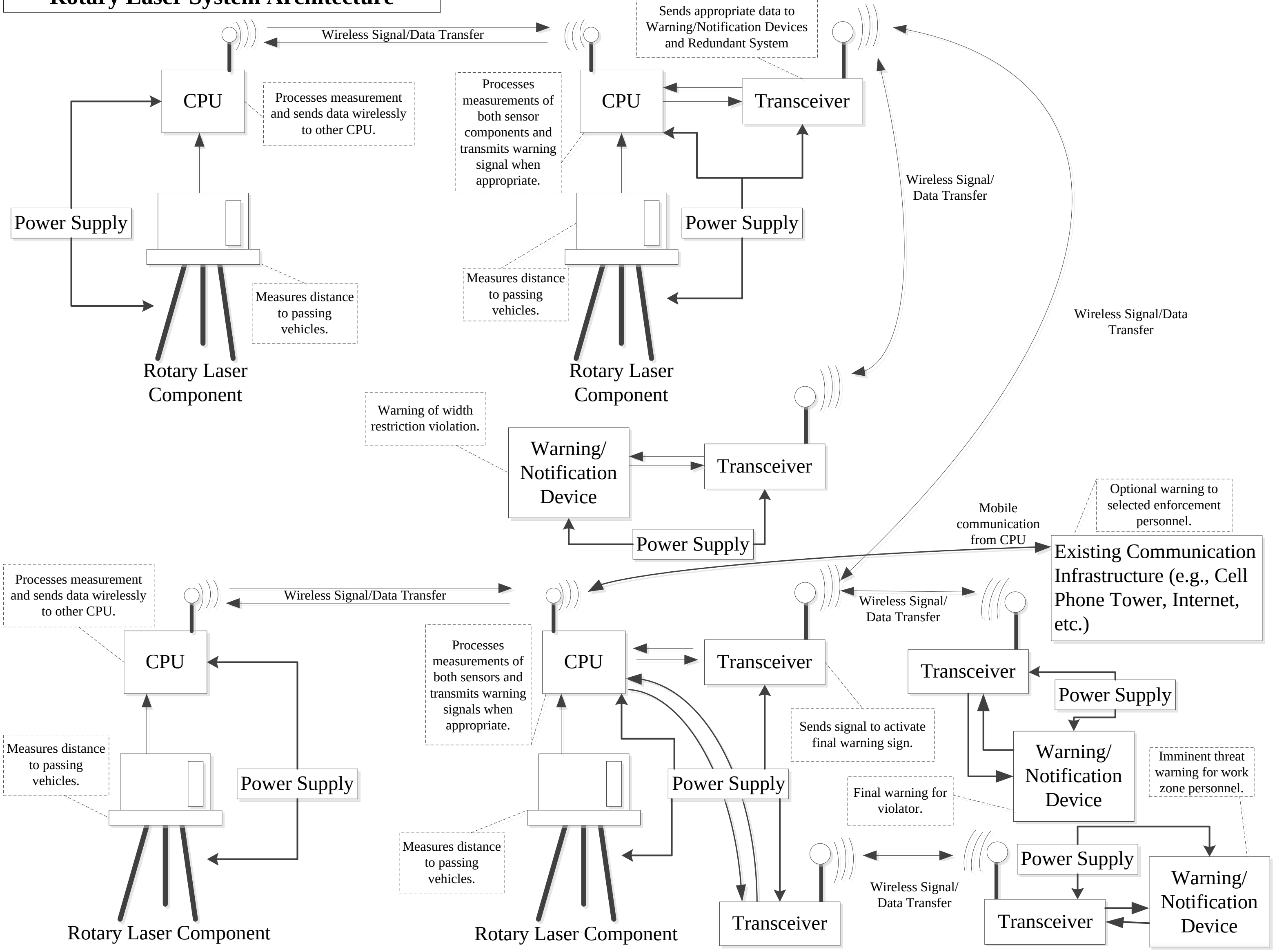
Imminent threat warning for work zone personnel.

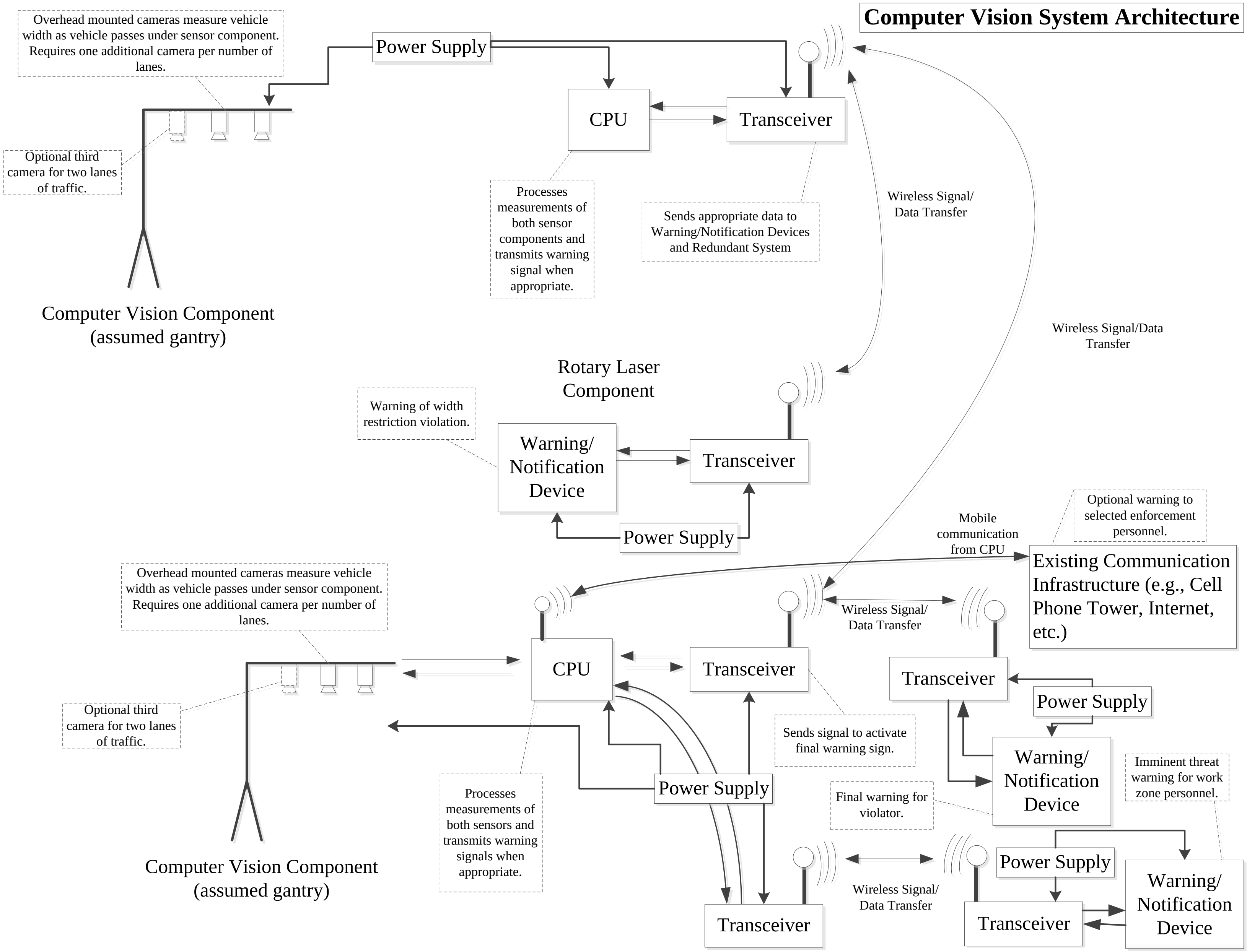
APPENDIX P.
SENSOR-SPECIFIC VEHICLE-WIDTH MEASUREMENT SYSTEM ARCHITECTURES

Ultrasonic Sensor System Architecture



Rotary Laser System Architecture




Computer Vision System Architecture
Overhead mounted cameras measure vehicle width as vehicle passes under sensor component. Requires one additional camera per number of lanes.
Power Supply
CPU
Transceiver
Optional third camera for two lanes of traffic.
Processes measurements of both sensor components and transmits warning signal when appropriate.
Sends appropriate data to Warning/Notification Devices and Redundant System
Wireless Signal/ Data Transfer
Computer Vision Component (assumed gantry)
Wireless Signal/Data Transfer
Rotary Laser Component
Warning of width restriction violation.
Warning/ Notification Device
Transceiver
Power Supply
Mobile communication from CPU
Optional warning to selected enforcement personnel.
Existing Communication Infrastructure (e.g., Cell Phone Tower, Internet, etc.)
Overhead mounted cameras measure vehicle width as vehicle passes under sensor component. Requires one additional camera per number of lanes.
CPU
Transceiver
Wireless Signal/ Data Transfer
Transceiver
Power Supply
Optional third camera for two lanes of traffic.
Sends signal to activate final warning sign.
Warning/ Notification Device
Power Supply
Imminent threat warning for work zone personnel.
Processes measurements of both sensors and transmits warning signals when appropriate.
Final warning for violator.
Computer Vision Component (assumed gantry)
Power Supply
Wireless Signal/ Data Transfer
Transceiver
Transceiver
Warning/ Notification Device