Development of a Low-Cost Work Zone Queue Warning System

Final Report
January 2020

SWZDI
Smart Work Zone Deployment Initiative

Sponsored by
Smart Work Zone Deployment Initiative
(TPF-5(295))
Federal Highway Administration
(Part of InTrans Project 19-535)

About the Smart Work Zone Deployment Initiative

Iowa, Kansas, Missouri, and Nebraska created the Midwest States Smart Work Zone Deployment Initiative (SWZDI) in 1999 and Wisconsin joined in 2001. Through this pooled-fund study, researchers investigate better ways of controlling traffic through work zones. Their goal is to improve the safety and efficiency of traffic operations and highway work.

The preparation of this report was financed in part through funds provided by the Iowa Department of Transportation through its "Second Revised Agreement for the Management of Research Conducted by Iowa State University for the Iowa Department of Transportation" and its amendments.

Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient's Catalog No.**
Part of TPF-5(295)		

4. Title	**5. Report Date**
Development of a Low-Cost Work Zone Queue Warning System	January 2020
	6. Performing Organization Code

7. Author(s)	**8. Performing Organization Report No.**
Madhav V. Chitturi, William Bremer, and David A. Noyce	Part of InTrans Project 19-535

9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Civil and Environmental Engineering University of Wisconsin - Madison Room 1241 Engineering Hall 1414 Engineering Drive Madison, WI 53706	**11. Contract or Grant No.**

12. Sponsoring Organization Name and Address		**13. Type of Report and Period Covered**
Smart Work Zone Deployment Initiative Iowa Department of Transportation 800 Lincoln Way Ames, Iowa 50010	Federal Highway Administration U.S. Department of Transportation 1200 New Jersey Avenue SE Washington, DC 20590	Final Report **14. Sponsoring Agency Code** Part of TPF-5(295)

15. Supplementary Notes

Visit https://swzdi.intrans.iastate.edu/ for color pdfs of this and other Smart Work Zone Deployment Initiative research reports.

16. Abstract

Back-of-queue crashes are a significant safety hazard in highway work zones—especially those with intermittent congestion. A number of intelligent transportation systems (ITS) have been developed to provide queue warning, but historically the cost and complexity of these systems have limited their use.

The objective of this project was to design a low-cost queue warning system (QWS) to reduce costs, simplify deployment, and test in the field. The developed low-cost QWS could allow back-of-queue warning signs to be installed wherever queuing is anticipated (even for short-term projects). Modular design of the low-cost QWS will allow the system to be extended as far upstream as necessary to provide ample driver notification in high-, medium-, and low-demand situations.

The sign support system for a low-cost QWS went through several iterations of design in order to find a design that has been crash tested and approved to the Manual for Assessing Safety Hardware (MASH) standards. The final design of the sign support system is based on a non-proprietary support system crash tested by the Texas A&M Transportation Institute. The proposed sign support design for the low-cost QWS has not been able to be field tested for several reasons. The most notable reason is highway agencies are strongly encouraged for safety and liability reasons to only use hardware systems that have successfully completed crash-testing protocols in accordance to the safety standards in the MASH. To date, only a select few sign support systems have been crash tested to MASH criteria, and none with the type of low-cost QWS hardware required for this prototype.

The second reason was the inability to find field test sites on conventional two-lane highways with 55 mph speed limits and the requirement that the equipment be located outside of a clear zone or shielded by protective barriers. Expressway and freeway facilities can't be used for testing for this design because the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) requires larger size signs and font letter sizes for the message required on these types of facilities. Therefore, before field testing can be undertaken on highways open to traffic, an investment in funding for crash testing is strongly recommended.

17. Key Words	**18. Distribution Statement**
highway safety—intelligent transportation systems—queue warning system—work zone safety	No restrictions.

19. Security Classification (of this report)	**20. Security Classification (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified.	Unclassified.	32	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

DEVELOPMENT OF A LOW-COST WORK ZONE QUEUE WARNING SYSTEM

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January 2020

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Sponsored by the Smart Work Zone Deployment Initiative and
the Federal Highway Administration (FHWA) Pooled Fund Study TPF-5(295):
Illinois, Iowa (lead state), Kansas, Missouri, Nebraska, and Wisconsin

Preparation of this report was financed in part
through funds provided by the Iowa Department of Transportation
through its Research Management Agreement
with the Institute for Transportation
(InTrans Project 19-535)

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ACKNOWLEDGMENTS

This research was conducted under the Smart Work Zone Deployment Initiative (SWZDI) and Federal Highway Administration (FHWA) Pooled Fund Study TPF-5(295) using Federal SPR Part II, CFDA 20.205 funds with support from the following state departments of transportation:

- Illinois
- Iowa (lead state)
- Kansas
- Missouri
- Nebraska
- Wisconsin

The authors would like to thank the FHWA, the Iowa Department of Transportation (DOT), and the other pooled fund state partners for their financial support and technical assistance.

EXECUTIVE SUMMARY

According to a Federal Highway Administration (FHWA) brochure published in 2014, 4,400 people died and over 200,000 people were injured in work zones in the previous five years, and rear-end crashes were the most common type of crash in work zones. Back-of-queue crashes are a significant safety hazard in highway work zones—especially those with intermittent congestion. According to the National Highway Traffic Safety Administration (NHTSA) Fatal Analysis Reporting System (FARS), fatal front-to-rear crashes occurred at an average rate of 150 per year in US work zones during the period from 2014–2018, representing 22.5% of work zone fatalities.

A number of intelligent transportation system (ITS) technologies have been developed to provide queue warning, but historically the cost and complexity of these systems have limited their use. Even when queue warning is deployed, the spatial coverage is sometimes inadequate due to the highly variable queue lengths that are typical for most sites. The objective of this project was to design a low-cost queue warning system (QWS) to reduce costs, simplify deployment, and test in the field. The developed low-cost QWS could allow back-of-queue warning signs to be installed wherever queuing is anticipated (even for short-term projects). Modular design of the low-cost QWS will allow the system to be extended as far upstream as necessary to provide ample driver notification in high-, medium-, and low-demand situations.

The research team went through an iterative process and various revisions were involved in the development of the sign support hardware system and sign legend for the low-cost QWS. The revisions were based on feedback from the technical advisory committee (TAC) and the FHWA, as well as the need for a design that has been crash tested and approved to American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH) standards. The final design of the sign support system is based on a non-proprietary support system crash tested by the Texas A&M Transportation Institute (TTI), using sign sizes restricted to a maximum of 36 in. × 36 in. However, the changes to the TTI sign support system to accommodate the low-cost QWS would require crash testing to verify the sign support system will comply with MASH.

The proposed low-cost QWS sign support design, with 36 in. × 36 in. signs, has not been tested in the field for two reasons. The most notable reason is highway agencies are strongly encouraged for safety and liability reasons to only use hardware systems that have successfully completed crash-testing protocols in accordance to the safety standards in the MASH. To date, only a select few sign support systems have been crash tested to MASH criteria, and none with the type of low-cost QWS hardware required for this prototype. The second reason was the inability to find field test sites on conventional two-lane highways with 55 mph speed limits and the requirement that the equipment be located outside of a clear zone or shielded by protective barriers. Expressway and freeway facilities can’t be used for testing for this design because the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) requires larger size signs and font letter sizes for the message required on these types of facilities.

Therefore, before field testing can be undertaken on highways open to traffic, an investment in funding for crash testing is strongly recommended.

CHAPTER 1. INTRODUCTION

Back-of-queue crashes are a significant safety hazard in highway work zones—especially those with intermittent congestion. According to Fatal Analysis Reporting System (FARS) data from National Highway Traffic Safety Administration (NHTSA), fatal front-to-rear crashes occurred at an average rate of 150 per year in US work zones during the period from 2014–2018, representing 22.5% of work zone fatalities. Typically, these crashes involve a vehicle travelling at high speed that approaches a line of stopped or slowed traffic; if the approaching vehicle fails to decelerate sufficiently, the result can be a severe collision at the back of the queue. Visibility obstructions such as vertical or horizontal curves are sometimes a contributing factor.

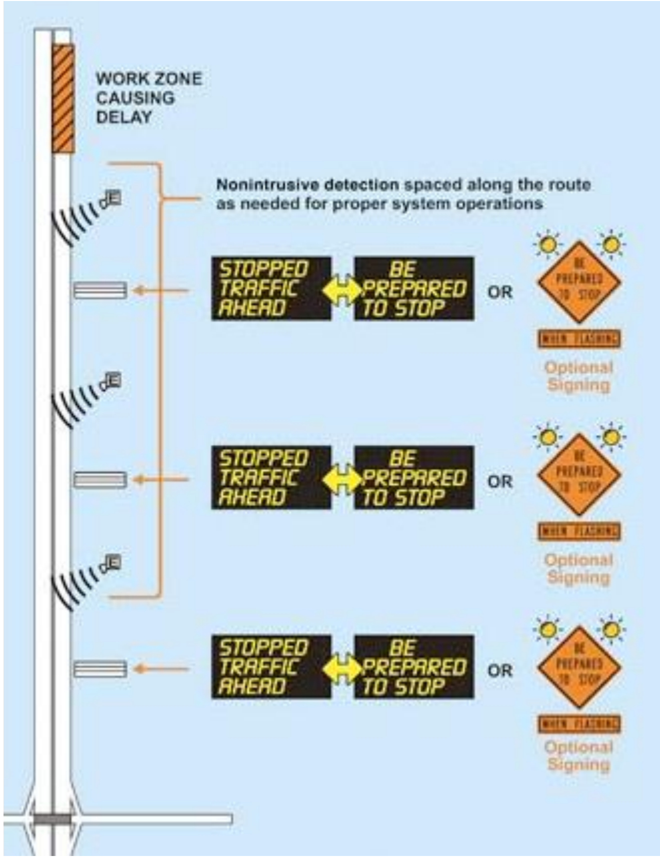
A number of intelligent transportation system (ITS) technologies have been developed to provide queue warning, but historically the cost and complexity of these systems have limited their use. Even when queue warning is deployed, the spatial coverage is sometimes inadequate due to the highly variable queue lengths that are typical for most sites. Figure 1 illustrates a conventional queue warning system.

UDOT Communications 2014

Figure 1. Conventional queue warning system

These systems typically use side-fire radar for speed detection and trailer-mounted portable changeable message signs (PCMS) to display the warning message to drivers. The equipment can be relatively expensive (many thousands of dollars), based on an ITS Knowledge Resources cost database website maintained by the U.S. Department of Transportation's ITS Joint Program Office (U.S. DOT 2019). The detectors and signs require generators or large solar panels due to their considerable energy consumption. These design characteristics increase weight, add complexity, and make the equipment relatively difficult to reposition as work progresses. In most cases, the detectors require recalibration each time a unit is moved or traffic lanes are repositioned. The design of conventional systems affects the cost and complexity of deployment. Similarly, a number of designs require telecommunications backhaul to a traffic operations center (TOC), rendering them unsuitable for remote sites or jurisdictions that do not have a TOC.

The objective of this project was to design a low-cost, mobile, and easy-to-deploy, queue warning system (QWS) for use on all types of highways, and test a prototype in the field. The developed low-cost QWS could allow multiple back-of-queue warning signs to be installed wherever queuing is anticipated (even for short-term projects). Modular design of the low-cost QWS will allow a multiple sign system to be extended as far upstream as necessary to provide ample driver notification in high-, medium-, and low-demand situations. A schematic diagram of a generic low-cost QWS layout, with multiple detectors and signs, as envisioned at the beginning of the project development stage is shown in Figure 2.



MnDOT 2018

Figure 2. Low-cost QWS using multiple detectors and signs

During the course of this research, a low-cost QWS system was designed in partnership with Traffic & Parking Control Co., Inc. (TAPCO). Given that the proposed sign support system for the low-cost QWS has not been crash tested and the challenges in finding locations to field test the low-cost QWS where the sign support system would not be exposed to traffic, i.e., behind positive protection barriers, the field testing was not accomplished.

Chapter 2 presents a review of literature on the effectiveness of back-of-queue warning in work zones. Chapter 3 describes the process of developing the low-cost QWS. Chapter 4 presents conclusions and recommendations for future research.

CHAPTER 2. LITERATURE REVIEW

This chapter presents a review of literature on work zone safety and the safety effectiveness of back-of-queue warning in work zones.

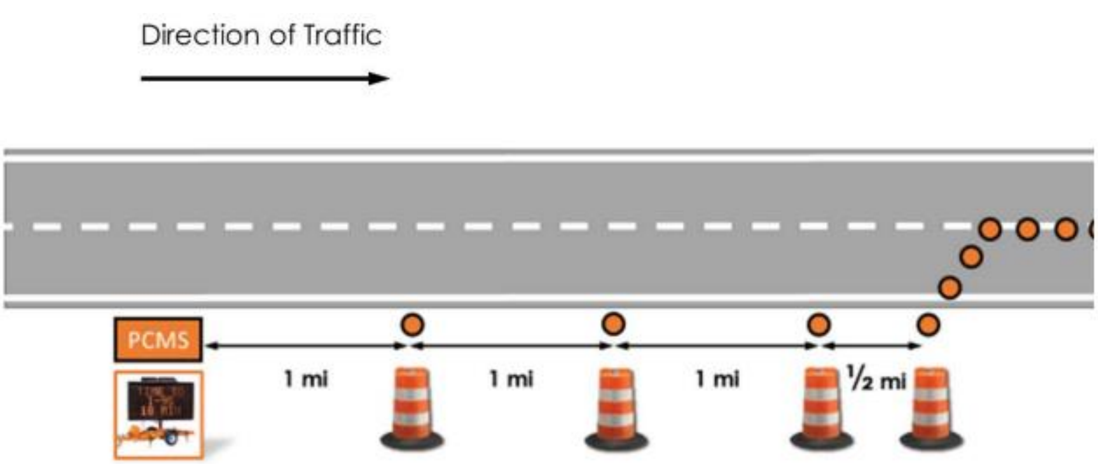
Work Zone Safety

According to a Federal Highway Administration (FHWA) brochure published in 2014, 4,400 people died and over 200,000 people were injured in work zones in the previous five years, and rear-end crashes were the most common type of crash in work zones (FHWA 2014). Garber and Zhao (2002) studied crashes in work zones in Virginia and also reported that rear-end crashes are the most predominant type of crash in work zones. Silverstein et al. (2014) compared fatal crashes between work zones and non-work zone conditions using data from National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS) data from 2010 through 2012. Negative binomial regression and multinomial logit models were developed to analyze frequency and severity of crashes. The study concludes that rear-end and side-swipe crashes are more likely to cause fatalities in work zones compared to non-work zones. According to FARS data from NHTSA, fatal front-to-rear crashes occurred at an average rate of 150 per year in US work zones during the period from 2014–2018, representing 22.5% of work zone fatalities.

Safety Effects of Queue Warning Systems in Work Zones

Texas Case Study

The Texas Department of Transportation (TxDOT) deployed a QWS consisting of speed sensors, PCMS, and portable rumble strips to mitigate rear-end crashes in a major widening project on I-35 (Ullman et al. 2016). Speed sensors were deployed at the merging taper and at 0.5, 1.5, and 2.5 miles upstream of the taper as shown in Figure 3.



Ullman et al. (unknown original source document), Texas A&M Transportation Institute

Figure 3. TxDOT layout of QWS

A PCMS was placed at 3.5 miles upstream of the taper. Four additional speed sensors were deployed every 1 mile upstream (3.5, 4.5, 5.5, and 6.5 miles) and a PCMS was deployed at 7.5 miles upstream, when longer queues were anticipated.

The deployment of QWS in the 96-mile long work zone varied as required during the different stages of the project, and over 200 nights of lane closures had been completed before the QWS was deployed. Therefore, Texas A&M Transportation Institute (TTI) used a treatment-control approach. The nights during which the QWS was not in place were considered the control group, and the nights during which the QWS was deployed were considered as the treatment group. To perform the safety analysis, the crashes that occurred in control and treatment approaches were compared to the expected number of crashes if there were no work zone. The entire corridor was divided into discrete homogenous segments for the purposes of analyses. The expected number of crashes for each segment without a work zone were computed using the Enhanced Interchange Safety Analysis tool (ISATe). Finally, the expected number of crashes without work zones were compared to the actual observed crashes in the treatment and control groups, and the results are shown in Table 1.

Table 1. Summary of QWS safety results

Parameter	Control (without QWS)	Treatment (QWS)
Total nights of lane closures analyzed	234	216
Total miles of lane closure segments analyzed	829	1,290
Total number of crashes expected if no work zone present	10.4	10.2
Total number of crashes that actually occurred	19	13

Source: Ullman et al. 2016

Both the control and treatment groups had a greater number of crashes than the expected number of crashes without a work zone. However, the control group had 46% more crashes compared to the treatment group. To quantify the impact of the QWS on safety, a crash modification factor (CMF) was computed using the expected and observed numbers of crashes. The CMF was found to be 0.559, which was significant.

Illinois Case Studies

The Illinois Department of Transportation (IDOT) deployed QWS on two interchange projects in rural Illinois (Ullman and Schroeder 2014). The I-70/I-57 interchange project was expected to have low and erratic queues while the I-57/I-64 interchange project was expected to have queues between 3 and 4 miles. Each project followed different approaches in terms of the equipment used.

The I-57/I-64 project used an iCone portable traffic monitoring system with 32 iCones placed on all four approaches, 15 PCMS, and a website portal to monitor the devices and the messages. While no crash evaluation data were included in the report, IDOT staff had positive experiences with the system and believed the system was helpful in reducing queues and managing traffic by encouraging some traffic to divert to alternate routes.

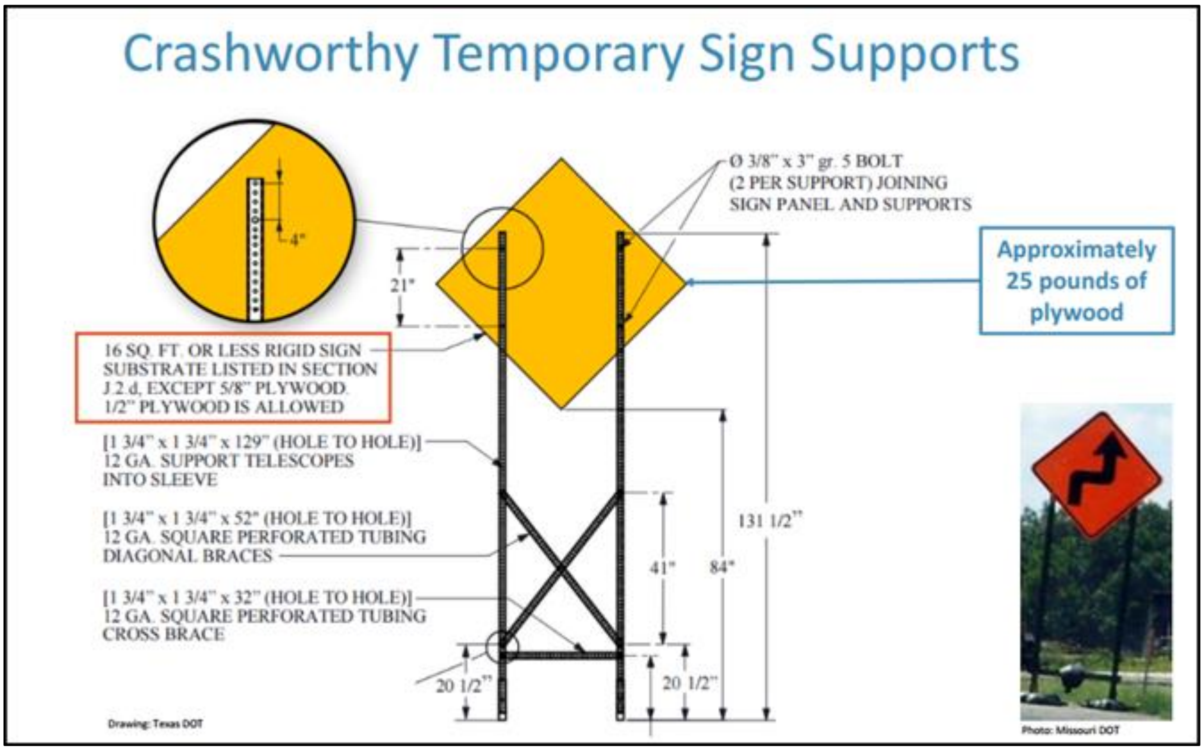
The I-70/I-57 project used 25 portable Wavetronix speed sensors, 25 PCMS, 20 remote video cameras, and a central base station to link all of them. Analysis showed that the QWS improved safety significantly on this project. Queuing crashes decreased by 14% and injury crashes decreased by 11%, despite a 52% increase in the number of days when lane closures were implemented.

CHAPTER 3. DESIGN OF LOW-COST QUEUE WARNING SYSTEM

This chapter describes the iterative process and various revisions involved in the development of the sign support hardware system and sign legend for the low-cost QWS. The University of Wisconsin-Madison's Traffic Operations and Safety Laboratory (TOPS Lab) partnered with TAPCO in this effort.

Design 1

The research team identified a potential crashworthy support system in the proposal submitted to the Smart Work Zone Deployment Initiative (SWZDI), as shown in Figure 4.

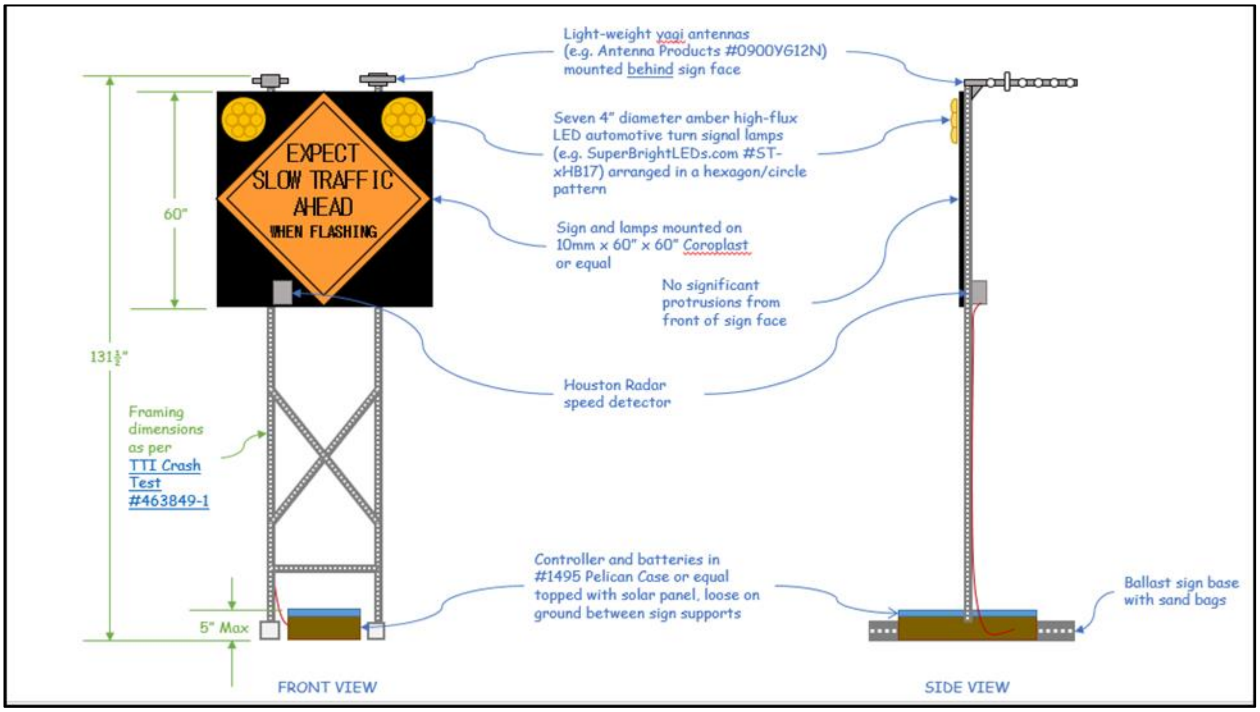


Schematic drawing on left from TxDOT 2017; sign image on right from Keith Smith 2013 (https://epg.modot.org/index.php/File:616.19.2.2.4_4.jpg) on MoDOT Engineering Policy Guide online

Figure 4. TxDOT NCHRP Report 350-approved temporary work zone sign system

The dual leg temporary sign support was developed for TxDOT and had been successfully crash tested to National Cooperative Highway Research Program (NCHRP) Report 350 criteria (Ross et al. 1993) by TTI. The results of the crash test, number 463849-1 and 2, were reported in 2009 by TTI in their research report, On-Going Evaluation of Traffic Control Devices (Carlson et al. 2010). The temporary sign system consists of dual legs made with perforated steel square tube (commonly referred to as Telespar tubing) with a 16 ft^2 (48 in. × 48 in. sign), 5/8 in. plywood sign mounted 7 ft off the ground. The sign support system was not crash tested with any warning beacons.

Weight is one of the significant issues with sign support crash testing, and the low-cost QWS project will require beacons and communication hardware mounted to the sign. Therefore, ways to reduce the overall weight were examined to keep the weight in the range of the TxDOT system. A lighter-weight sign material made with Coroplast was proposed, as well as lightweight amber light-emitting diode (LED) beacons mounted to the sign face, communication antennas, and a radar speed detector. The SWZDI low-cost QWS system will require a computer controller, battery for computer power and flashing LED lights, and solar panel for recharging the battery. These relatively heavy components were proposed to be located on the ground between the sign supports. A sketch of the individual low-cost QWS assembly is shown in Figure 5.



TAPCO

Figure 5. Preliminary design of low-cost QWS based on TxDOT's NCHRP Report 350-approved sign support system

The low-cost QWS sign assembly design concepts were discussed at the SWZDI technical advisory committee (TAC) project kickoff meeting. Ten different potential sign message legends were also discussed. Based on the TAC feedback, the 10 initial draft sign legends were reduced down to two, SLOW TRAFFIC AHEAD WHEN FLASHING and PREPARE TO STOP WHEN FLASHING.

TAPCO staff calculated the weight estimates of various components needed for several alternative designs under consideration, as well as a bill of materials for the number of components needed for the project. The weight estimates are shown in Figure 6.

Low-Cost Back-of-Queue Warning System			
Component Weight Estimates			7/27/2016
Wig-Wag Beacon - As Proposed	**Quan**	**Unit Weight**	**Weight**
		lbs	**lbs**
Beacons	2	7.0	14.0
30W Solar Panels	2	7.0	14.1
Solar Panel Brackets	2	0.5	1.0
Tapco Yagi Antenna	2	3.1	6.2
Antenna Brackets	2	0.2	0.4
Houston Radar w/Enclosure	1	1.0	1.0
Primary Sign (1/2 inch Plywood)	16	1.4	22.4
Secondary Sign (1/2 inch Plywood)	6	1.4	8.4
Total			**67.5**
Maximum			22.4
Excess			**45.1**
Single Beacon - As Proposed	**Quan**	**Unit Weight**	**Weight**
		lbs	**lbs**
Beacons	1	7.0	7.0
30W Solar Panels	1	7.0	7.0
Solar Panel Brackets	1	0.5	0.5
Tapco Yagi Antenna	2	3.1	6.2
Antenna Brackets	2	0.2	0.4
Houston Radar w/Enclosure	1	1.0	1.0
Primary Sign (1/2 inch Plywood)	16	1.4	22.4
Secondary Sign (1/2 inch Plywood)	6	1.4	8.4
Total			**53.0**
Maximum			22.4
Excess			**30.6**
Wig-Wag Beacon - Modified	**Quan**	**Unit Weight**	**Weight**
ASSEMBLY 1		**lbs**	**lbs**
Circle of 7 Four-Inch Automotive LEDs	2	3.2	6.3
Houston Radar w/Enclosure	1	1.0	1.0
Antenna Products Lightweight Yagi	2	0.8	1.6
Antenna Brackets	2	0.2	0.4
Main Sign (10mm Coroplast 5 ft square)	25	0.5	12.5
Total			**21.8**
Maximum			22.4
Excess			**-0.6**
ASSEMBLY 2 (in Pelican case loose on ground)			
30W Solar Panels	1	7.0	7.0
Solar Panel Brackets	1	0.5	0.5
Batteries	??	??	??
Total			**??**
Effective size of diamond sign	42.4	inches	

Figure 6. Weight estimates for the preliminary low-cost QWS options

The weights far exceeded the weight of the system crash tested by TxDOT. The largest crash test issues dealt with the extra sign weight, and height of the case for the controller, battery, and solar panel if a vehicle could not override the case. These issues led to discussions on whether crash testing of the low-cost QWS would have to be conducted to assure the system was as safe as the TxDOT crash tested and approved system.

Design 2

Following the issues with Design 1, TAPCO and the TOPS Lab developed a new sign design using a standard 48 in. diamond-shape plywood warning sign in lieu of a 5 ft^2 sign, and two alternative warning light systems. The first alternative warning light design incorporated LED edge lighting in lieu of beacons to notify motorists of the active condition of slow traffic ahead. LED edge lighting is referred to as "Blinkerstop" lighting by TAPCO. This alternative is shown in Figure 7.

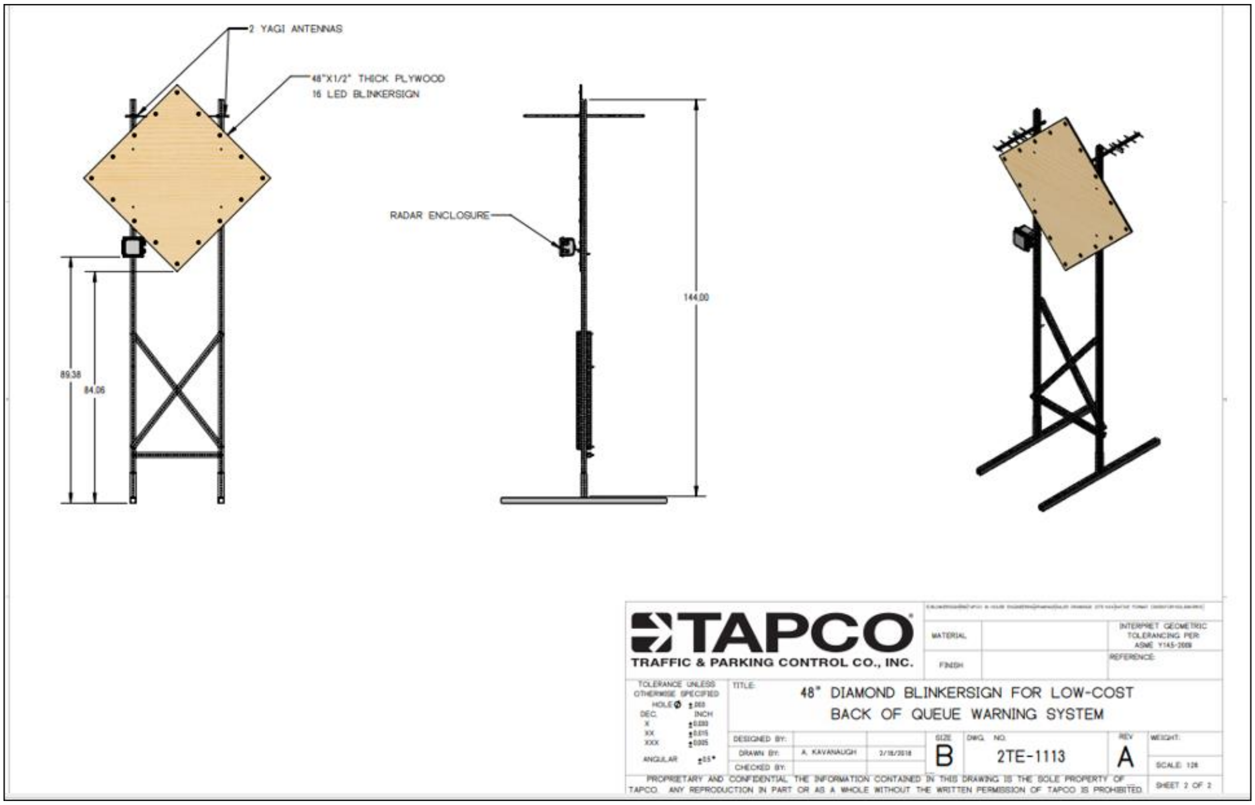


Figure 7. Design 2, alternative #1 LED edge lighting on TxDOT sign support system

The second alternative warning light design proposed to use conventional 8 in. flashing light beacons, shown as Figure 8.

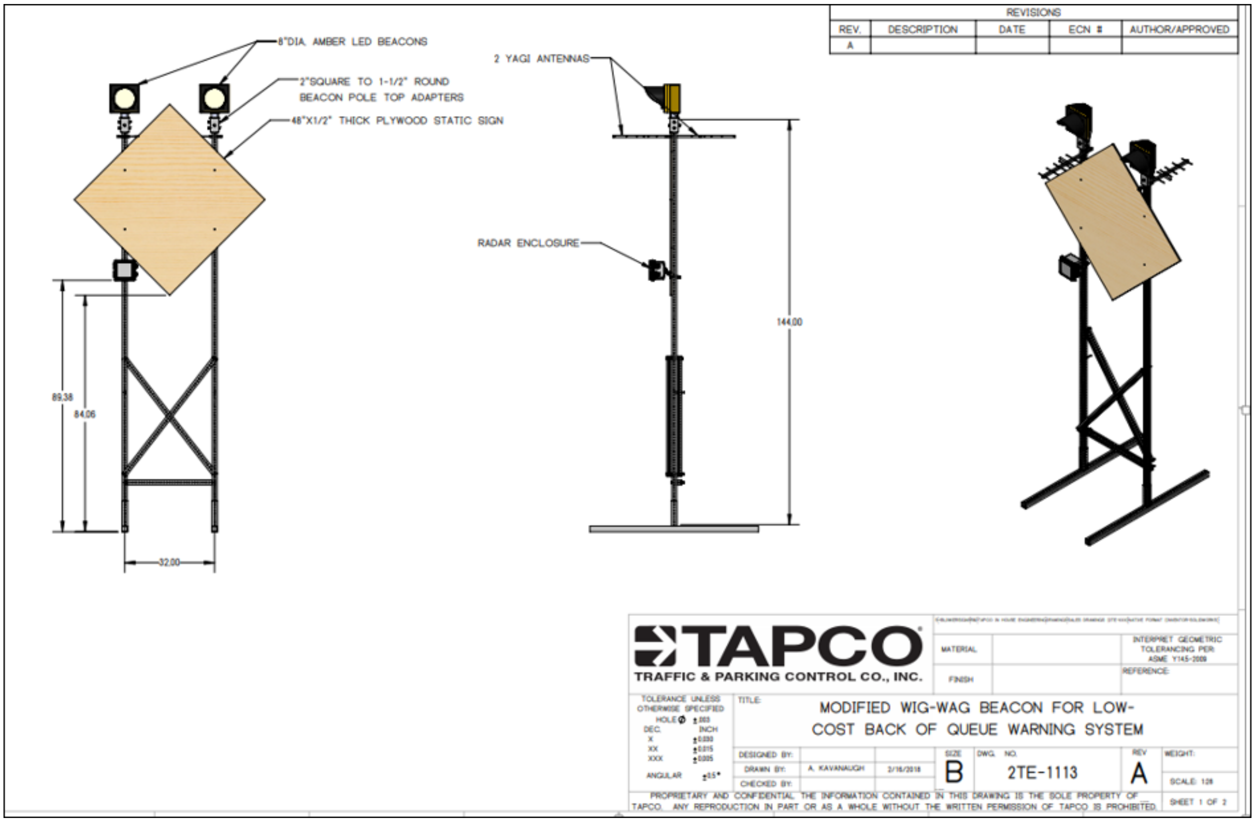


Figure 8. Design 2, alternative #2 conventional 8 in. beacons on TxDOT sign support system

Both of these low-cost QWS designs proposed to use the original TxDOT, NCHRP Report 350-approved, sign support system.

The 48 in. × 48 in. diamond-shaped plywood warning sign with the two alternative warning light system designs were presented to the TAC, as well as the two proposed legend alternatives. While Alternative 1 with edge lighting would reduce the weight, the compatibility with the Manual on Uniform Traffic Control Devices for Streets and Highways (FHWA 2009) was a concern that needed further review. The 2009 edition of the MUTCD uses warning beacons (Section 4L.03) to actuate WHEN FLASHING, and beacons are defined as 8 in. or 12 in. lights. Section 2A.07 discusses use of LED lights in the border of signs for conspicuity of the sign. The MUTCD does not mention using edge lighting LEDs to replace beacons. The FHWA does allow for experimenting with new devices and application of hardware, but MUTCD experiments must be approved by FHWA following a Request to Experiment procedure in advance of testing. Since the testing would require evaluating whether edge lighting performs similar to conventional warning beacons, this would add additional testing beyond the scope of this project.

The research team had a conference call with FHWA's MUTCD team, which confirmed that the research team will need to submit a Request to Experiment before using LED edge lighting in lieu of beacons. The decision was made to withdraw the LED edge lighting alternative for application on this project, and use conventional warning beacons. The FHWA MUTCD team also raised a concern pertaining to the proposed use of the TxDOT sign support design, because that design has not been crash tested with a warning beacon.

Design 3

An investigation was reinitiated to find an approved crash tested sign support system that included a warning beacon and resulted in developing Design 3. A Minnesota sign support, with a flashing light beacon and a 48 in. × 48 in. aluminum diamond-shaped warning sign, was identified. The system had been successfully crash tested in 2007 by the Midwest Roadside Safety Facility (MwRSF) to NCHRP Report 350 criteria (Polivka et al. 2007), as shown in Figure 9. Minnesota NCHRP Report 350-approved 48 in. × 48 in. sign support light attached to the signFigure 9.

Polivka et al. 2007, Midwest States' Regional Pooled Fund Research Program

Figure 9. Minnesota NCHRP Report 350-approved 48 in. × 48 in. sign support light attached to the sign

Design 3, which incorporates the Minnesota support structure design with the low-cost QWS hardware, is shown in Figure 10.

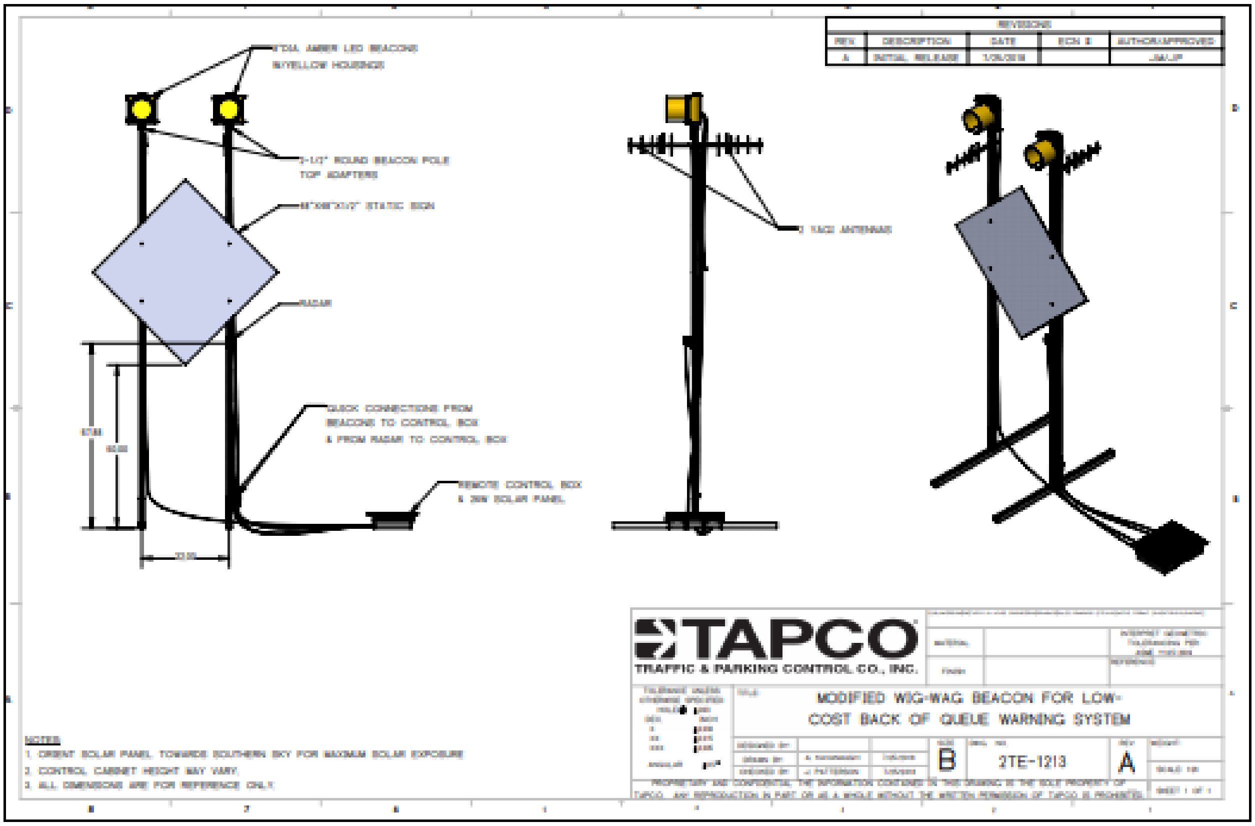


Figure 10. Design 3 low-cost QWS based on Minnesota NCHRP Report 350-approved sign support system

The proposed Design 3 of the low-cost QWS sign support system was sent to the TAC members for their comments and request for approval to proceed, as well as a decision on the sign legend that would be used for the field testing. The TAC members were presented with two proposed legend messages, SLOW TRAFFIC AHEAD WHEN FLASHING and PREPARE TO STOP WHEN FLASHING. Feedback from the TAC members was unanimous for using the legend, SLOW TRAFFIC AHEAD WHEN FLASHING.

However, there was strong concern expressed in feedback at this time from several of the TAC members regarding the proposed use of an NCHRP Report 350 (Ross et al. 1993) system in lieu of an American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware- (MASH-) approved system. The AASHTO/FHWA Joint Implementation Agreement for MASH (January 7, 2016 memorandum from Thomas Everett and Michael S. Griffith, directors of Office of Program Administration and Office of Safety Technologies) specifies temporary work zone devices manufactured after December 31, 2019, must have been successfully crash tested to MASH criteria. However, the Agreement does allow devices manufactured before December 31, 2019, and successfully tested to NCHRP Report 350, to continue to be used throughout their normal service lives.

The rationale for selecting an approved NCHRP Report 350 sign support system initially was the lack of approved MASH systems early in this project development. If the low-cost QWS prototype proof-of-concept system is successful, the project team recognizes additional development work will be required, including MASH criteria crash testing with the low-cost QWS hardware, before the low-cost QWS is considered ready for widespread use. However, there was reluctance by TAC members to field test this low-cost QWS based on a NCHRP Report 350 design. Based on the TAC comments, the research team conducted a new search to identify a possible design for the prototype low-cost QWS project that would satisfy MASH requirements.

Design 4

A 2009 SWZDI report titled Analysis of Existing Work Zone Devices with MASH Safety Performance (Schmidt et al. 2009) gives various support system parameters the “chance of failing MASH.” The report was authored by Jennifer Schmidt, University of Nebraska, a leading national expert on crash testing sign support systems, and she was contacted to help expand the project team’s search. Schmidt referred the project team to a recently completed research project from TTI titled, MASH Evaluation of TxDOT High Mounting Height Temporary Work Zone Sign Support System, (Dobrovolny et al. 2017). Several design options were tested, and the successfully MASH crash tested nonproprietary Option C design in the report was selected by the research team as a new prototype sign support system for use on the low-cost QWS project, for use on projects located on conventional highways with a maximum of 55 mph.

The Option C design has a single vertical post, made from two individual pieces. The bottom vertical support piece is fabricated from an 82 in. long, 1¾ in. 12 gauge (0.105 in.) thick perforated square steel tubing containing 7/16 in. diameter holes on 1 in. spacing on all four sides (Telespar tubing). The bottom vertical support is mounted to an H-shaped base measuring 48 in. × 51 ½ in. comprised of three 48-in. long sections of 1¾ in. Telespar tubing. Junctions of the three-piece base and lower section of the vertical support post are joined with fillet welds. Two 40 lb sandbags are placed on top of the H-shaped base, one at the midpoint of each outrigger. The upper section of the vertical support is comprised of a 48 in. long 1½ in. Ttelespar tubing. This upper section is inserted approximately 4 9/32 in. into the bottom section of 1¾ in. Telespar tubing to form a slip joint. The upper section rests on a ⅜ in. diameter × 2¼ in. long smooth pin located in the holes 4 ½ in. below the top end of the lower section and is welded to one side. The top of the bottom section is 83 ¾ in. above grade.

The sign panel for the Option C design measures 36 in.^{2} and is fabricated from 0.100 in. thick aluminum. The sign is mounted in a diamond configuration with a tip-to-tip distance of 49 ⅛ in. as a result of each corner having a 2 in. radius. The sign is attached to the upper section of the vertical support with two ⅜ in. diameter × 2½ in. long Society of Automotive Engineers (SAE) standards grade 5 hex bolts, nuts, and flat and lock washers. Photographs of the Option C sign support system prior to a crash test are shown in Figure 11.

Dobrovolny et al. 2017, Texas A&M Transportation Institute

Figure 11. Option C crash test design

The approximate total weight of the crash tested assembly was 57 lb (16 lb sign panel, 17 lb sectional posts, and 24 lb three-piece base) exclusive of the two 40 lb sandbags. The bottom and top of the sign panel were 84 ½ in. and 133 ⅝ in. above grade, respectively.

The prototype low-cost QWS system will use the sign legend SLOW TRAFFIC AHEAD WHEN FLASHING. However, the MASH approved TxDOT sign is only 36 in. × 36 in. Therefore, the legend is too long to fit on this size sign with an acceptable font letter height of 6 in. minimum required per the MUTCD in Section 2C-03 for this type of message on a sign used on a conventional highway with maximum speeds of 55 mph. This will require the use of a supplemental sign plaque for the WHEN FLASHING portion of the legend. The low-cost QWS prototype will maintain the 84 ½ in. height to the bottom of the supplemental plaque. The SLOW TRAFFIC AHEAD legend will have 6 ½ in. letter height on the diamond sign and the WHEN FLASHING legend will have 5 in. letter height on the supplemental plaque, which are acceptable sign heights per the MUTCD Section 2C-03 for use on conventional two-lane highways.

Schmidt shared with the research team that a reasonable assurance of passing MASH could still be made if modifications for the necessary low-cost QWS hardware is limited to approximately 10 lb, and the extra weight is kept above the 84 ½ in. post height. TAPCO reduced the thickness of the aluminum sign sheeting to 0.08 in. to minimize weight, but the estimated weight of the extra height of Telespar for mounting the beacon, extra sign plaque, adding antennas, and radar detector, still resulted in a gain of approximately 14 lb. Design 4 based on the TTI MASH criteria-approved sign support system is shown in Figure 12. Design 4 low-cost QWS using TTI MASH-approved sign support system Figure 12.

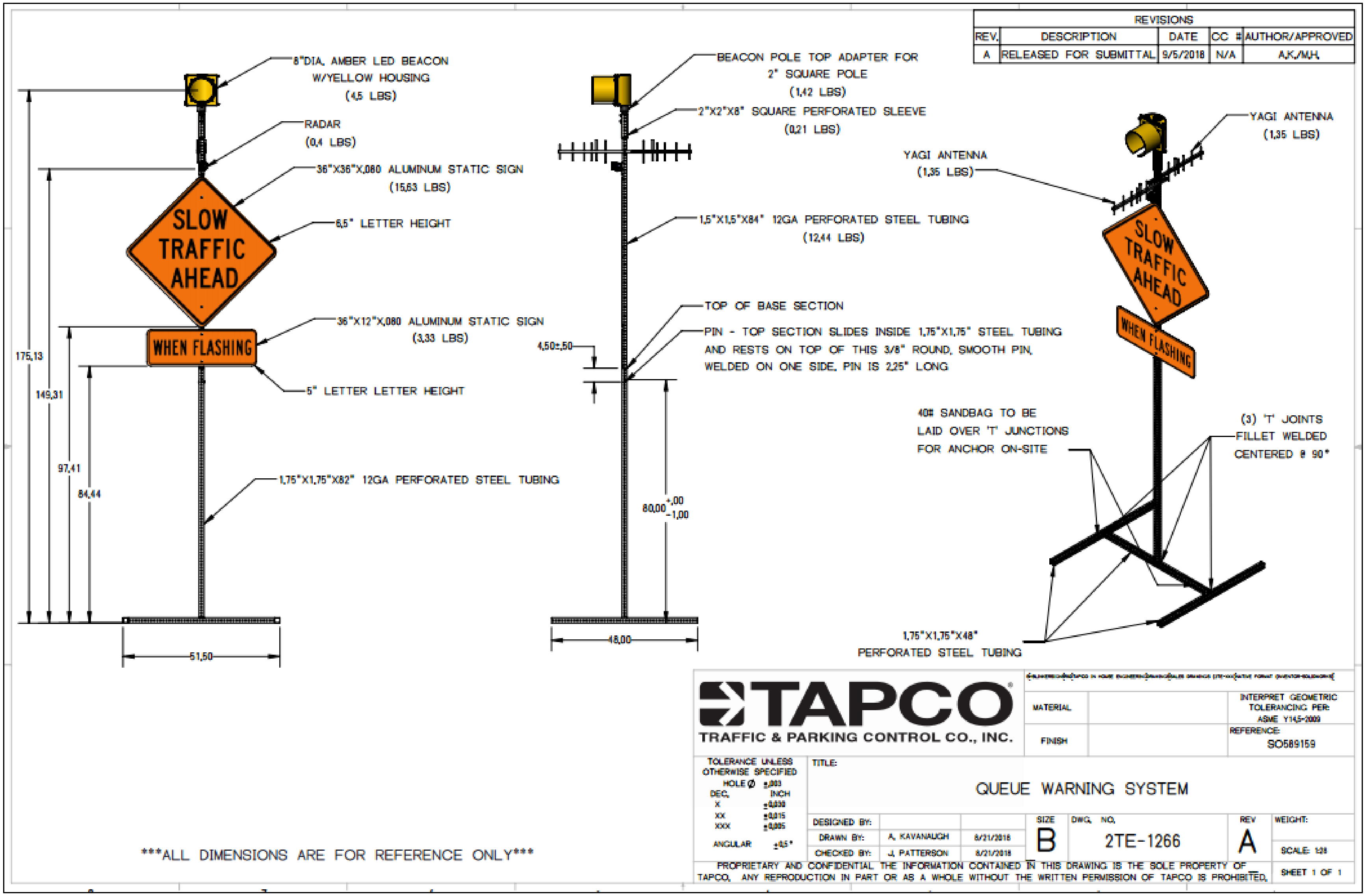


Figure 12. Design 4 low-cost QWS using TTI MASH-approved sign support system

The research team is fully aware of the fact that successfully passing MASH crash testing criteria is required before the low-cost QWS system is ready for adoption for unlimited agency use.

An example prototype low-cost QWS field set-up for collecting and communicating traffic data for determining back of traffic queues, developed by TAPCO, is shown in Figure 13.

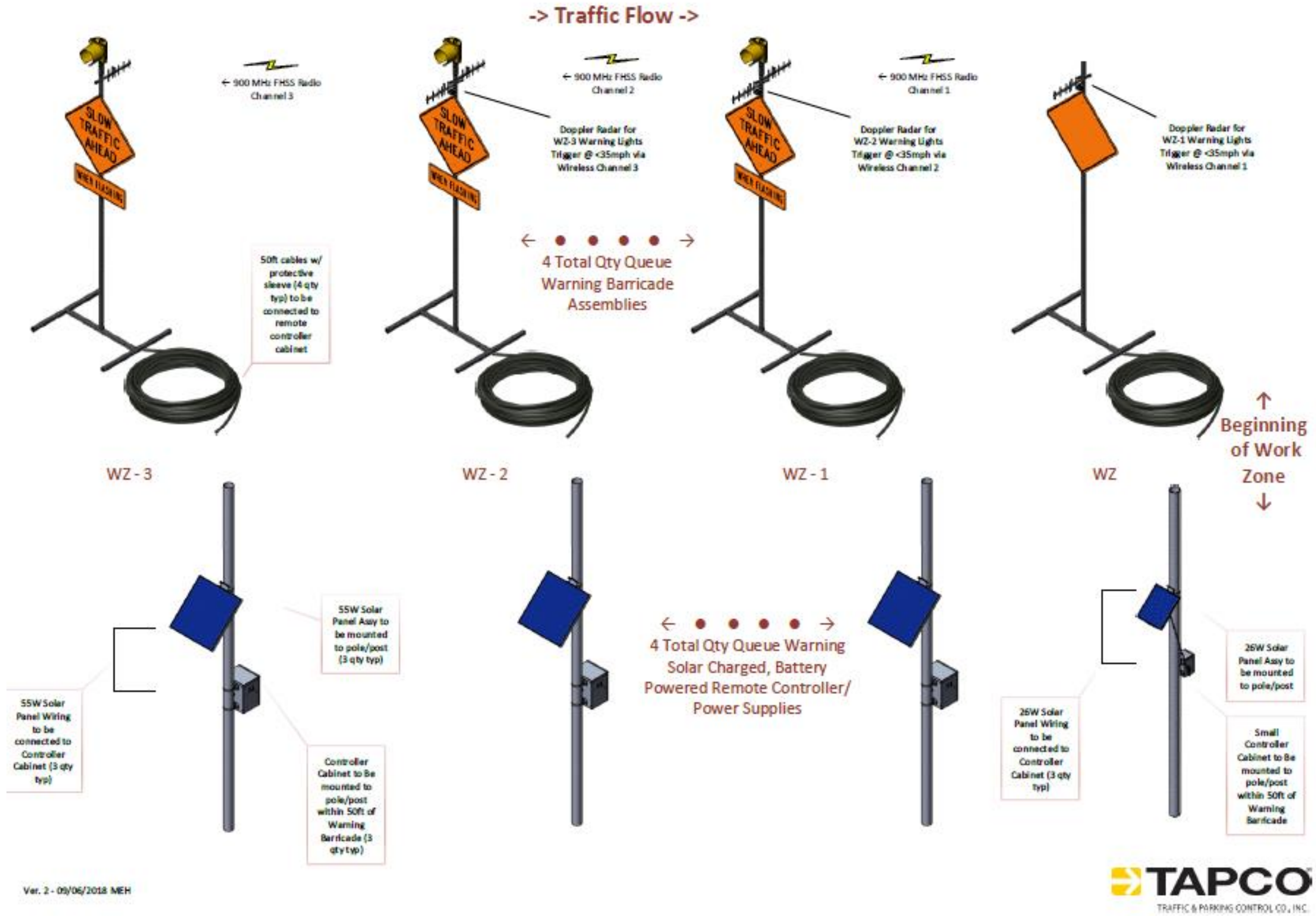


Figure 13. Prototype SWZDI low-cost QWS data collection, communication, and controller equipment locations

This hardware is shown mounted on the proposed Design 4, Option C sign support system. The solar power supply panels and controller cabinets are envisioned to be mounted on poles or posts outside of the clear zone in the vicinity of each warning sign.

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

Safety benefits of queue warning systems in work zones are demonstrated from multiple QWS deployments in work zones. One study estimated a CMF of 0.559, indicating a 44% decrease in crashes when QWS was used. However, a barrier to their widespread deployment has been cost. The proposed low-cost QWS design would cost a fraction of the conventional QWS based on portable changeable message signs. In addition, modular design of the low-cost QWS will allow the system to be extended as far upstream as necessary to provide ample driver notification in high-, medium-, and low-demand situations.

The sign support system for low-cost QWS went through several iterations of design in order to find a design that has been crash tested and approved to MASH standards. The final design of the sign support system is based on a non-proprietary support system crash tested by the TTI for TxDOT. However, the proposed sign support design for the low-cost QWS was not field tested. The most notable reason for not completing the field testing is highway agencies' concern for safety and liability reasons to only use hardware systems that have successfully completed crash testing protocols in accordance to the safety standards in the MASH. To date, only a select few sign support systems have been crash tested to MASH criteria, and none with the type of hardware required for this low-cost QWS prototype design. Therefore, before evaluating a low-cost back-of-queue warning system on conventional highways open to traffic, an investment in funding for crash testing will be required to verify the TxDOT breakaway support system is crashworthy with the low-cost QWS hardware attached. Crash testing to MASH criteria with the final prototype low-cost QWS design is recommended. If a low-cost QWS design for use on expressways and freeways is desired, additional research will be required to develop an acceptable 48 in. × 48 in. size sign capable of successfully passing MASH testing, including the necessary low-cost QWS equipment.

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