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Work Zone Materials for Temporary Signs in High Wind Areas: Final Report

August 31, 2019

By

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16. Abstract

Due to ineffective ballast materials and techniques, temporary signs may easily be knocked down and become invisible to the traveling public, increasing the risk of tort liability. Signs in construction zones must be properly secured to prevent wind from blowing them off posts, and the conditions should be checked periodically to ensure specification compliance. This project's objectives were to understand the need for and concerns surrounding temporary traffic signs in Texas work zones, and conduct a cost/benefit analysis to evaluate the cost-effectiveness of each identified technology or materials. During this project, the research team conducted an intensive literature review and evaluated the techniques and materials that reduce temporary signs from falling over due to high winds, as well as surveying Texas engineers. The team collected field observations in several high-wind Texas regions and conducted a cost-benefit analysis a finite element analysis for different types of temporary signs. Based on the results, the research team proposed a map of recommended signs in Texas and the months to apply. The research team found that there each TxDOT distract has its own most suitable temporary traffic signs for work zones. Based on 25 years mean recurrence interval of fastest mile wind velocity at 33 feet high, there are three types of wind zones in Texas for large traffic signs. Zone 1 is with 90 mph fastest wind, Zone 2 is with 80 mph fastest wind, and Zone 3 is with 70 mph fastest wind. It is recommended that, (1) in Zone 1 during certain specific months, the embedding signs are mandatorily recommended like the *Dual Leg Perforated Square Metal Tubing with Anchor Sign* and three of its updated new versions proposed in the project, while skid signs are not recommended then; (2) in zone 2 during certain specific months, the embedding signs are highly recommended, while skid signs shall be limited for use including (a) the Independent Dual Upright with Leg PSST Skid Sign, and (b) the Dual Leg PSST Skid Support Sign; and (3) both embedding signs and skid signs can be used during all months of the years for Zone 3, and during the rest months of the year for Zone 1 and Zone 2. The wooden signs (such as the Wooden Skid with 2 Wooden Legs Sign, and Wooden long/intermediate-term Single Leg (H-leg) Sign) are also good choices for non-high wind situations. The above recommendations on zones and months to apply are based on wind historical records. In the cases that extremely higher wind is forecasted in any area in Texas, embedding signs shall always be highly demanded.

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RESEARCH REPORT

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Disclaimer

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CHAPTER 1: LITERATURE REVIEW

1.1. Overview

1.1.1 Objective

The objective of this project is to conduct a cost/benefit analysis to evaluate the cost-effectiveness of each identified new technology or materials. The research team will also review and evaluate recent studies on different base designs, materials and techniques used by vendors/DOTs to ballast traffic signs in temporary work zones in Texas and other States that are reliable and efficient under high winds.

1.1.2 Action Items

The following action items will be conducted during the process of this project:

1) Identify the implications, if any, of alternative methods for temporary traffic signs in work zones with high winds;
2) Design warrants of new technologies and materials, and develop detailed policy recommendation and user-friendly standard sheet for new materials and technologies; and
3) Submit preliminary sheet and documentation to RTI Project Manager (PM) and Project Management Committee (PMC) members for review

The MUTCD requires that long-term stationary work zones (more than three consecutive days in one location) use post-mounted advance warning signs, and portable sign mounting is used for work zone applications lasting less than 3 days. The supports shall be crashworthy. Several designs have been approved, but any used in the clear zone shall be crashworthy per the test and evaluation criteria of National Cooperative Highway Research Program (NCHRP) Report 350 or Manual on Assessing Safety Hardware (MASH).

Fabrics, roll-up, and portable signs are popular because they are lightweight and easy to install. However, some designs are too flexible in windy conditions, which may degrade visibility. Flexible base portable signs that do not provide necessary stability in windy situations shall be adequately supported, or work activities must be terminated. The requirements for crashworthiness and adequate visibility shall be met with all work zone signs.

Ballast is often required to maintain position and stability of channelizing devices, and proper placement and type of ballast is important, which follows the following two guidelines:

1) Never place ballast on top of channelizing devices, and keep ballast on the lower part of the device, and
2) Use sandbags or weighted bases, and do not use items such as rocks, broken concrete, etc., for ballasting.

1.2. Facts about Wind Resistance of Traffic Signs in Texas

Thought traffic control signs have been designed to resist high velocity wind according to Manual on Uniform Traffic Control Devices (MUTCD) and Texas MUTCD, a number of wire-suspended traffic signals and large cantilevered sign poles still broke and fell for the landfall of Hurricane Harvey in the Middle Texas coast from August 25 to 29, 2017 (National Weather Service, 2017), imagining what must have happened to the temporary signs in work zones in those particular areas. The Harvey made landfall as a Category 4 storm with maximum sustained winds of 156 mph, leading to enormous damages in Texas (Dolce, 2017). Traffic control signs and devices are one of the most vulnerable facilities to the high-speed storm wind.

In compliance with the Code of Federal Regulations, 23 CFR 6300.1008, a traffic control review team reviews work zone traffic control devices in all 25 districts each fiscal year in Texas and found that one of the most common problems in work zone traffic control devices is temporary signs being knocked down because of wind. The Connecticut Department of Transportation recommended that, signs in construction zones shall be properly secured to prevent wind blowing them off posts and the conditions should be checked periodically to ensure specification compliance (Connecticut DOT, 2017).

Figure 1. A Temporary sign knocked down by the wind on Bellaire Blvd, in Houston, Texas in 2018

Texas is located on a flat area with windy plains and plenty of coast lines. According to the Texas State Energy Conservation Office, Texas already has more than 2,000 turbines. The coast that offers consistent breezes, is quickly gaining ground as more turbines come under construction both on and off shore. A large portion of Texas is set up for success at churning out wind power (Williams, 2014).

Consequently, temporary traffic signs in work zones are frequently knocked down by high wind throughout a year. Figure 2 shows the traffic signs that are typically knocked down by wind, the absence or invisibility of which could increase the risk of tort liability and traffic crashes. The failure of traffic control sign supports has contributed to the total crashes of about 22,500 each year in Texas from 2014 to 2016 (TxDOT, 2016), resulting in a significant amount of fatalities, injuries, and economic loss.

Figure 2. Temporary warning signs in a work zone; and (right) direction signs.

1.3. Functional Requirements on the Design of Temporary Sign Supports for Windy Areas

In addition to being crashworthy, a barricade or temporary sign support including its base should satisfy the various functional requirements of the application. The device should have sufficient structural capacity to withstand anticipated service loads, be durable enough to accommodate frequent handling, and be able to accommodate common variations in site conditions that may exist in the field.

1.3.1 History of Wind Speed Measurement

Admiral Sir Francis Beaufort (1774-1857), an Irish Hydrographer and Royal Navy officer, while serving on the ship “HMS Woolwich”, created one of the first scale to estimate wind speeds and the effects. He developed the scale in year 1805 to help sailors estimate the winds via visual observations. The scale starts with 0 and goes to a force of 12, with a total of 13 scales.

The scale that carries Beaufort's name had a long and complex evolution from the previous work of Daniel Defoe and other Hydrographers to when Beaufort was a Hydrographer of the Navy in the 1830s when it was adopted officially and first used during the voyage of the ship “HMS Beagle” under Captain Robert FitzRoy. He later went on to set up the first Meteorological Office in Britain giving regular weather forecasts. In the early 19th century, naval officers made regular weather observations, but there was no standard scale and so they could be very subjective – one man's "stiff breeze" might be another's "soft breeze". Beaufort succeeded in standardizing the scale. The Beaufort scale is still used today to estimate wind strengths.

1.3.1.1 Beaufort scale

The initial scale of thirteen classes (zero to twelve) did not reference wind speed numbers but related qualitative wind conditions to effects on the sails of a frigate, then the main ship of the Royal Navy, from "just sufficient to give steerage" to "that which no canvas sails could withstand".

The scale was made a standard for ship's log entries on Royal Navy vessels in the late 1830s and was adapted to non-naval use from the 1850s, with scale numbers corresponding to cup anemometer rotations. In 1916, to accommodate the growth of steam power, the descriptions were changed to how the sea, not the sails, behaved and extended to land observations. Rotations to scale numbers were standardized only in 1923. Sir George Simpson, the director of the UK Meteorological Office, was responsible for this and for the addition of the land-based descriptors. The measure was slightly altered some decades later to improve its utility for meteorologists. Today, many countries have abandoned the scale and use the metric system based units, m/s or km/h, instead, but the severe weather warnings given to the public are still approximately the same as when using the Beaufort scale.

Wind speed on the 1946 Beaufort scale is based on an empirical relationship in Equation (1).

$$v = 0.836\ B3/2\ m/s \qquad (1)$$

Where v is the equivalent wind speed at 10 meters above the sea surface, and B is the Beaufort scale number. For example, B = 9.5 is related to 24.5 m/s which is equal to the lower limit of "10 Beaufort". Using this formula, the highest winds in hurricanes would be 23 in the scale. The Beaufort scales for number 0-12 are listed in Table 1.

Table 1. Beaufort wind scale

Beaufort Number	Description	Wind Speed	Land Conditions
0.	Calm	Less than 1mph	Smoke rises vertically
1.	Light Air	1 - 3 mph	Direction shown by smoke drift but not by wind vanes
2.	Light Breeze	4 - 7 mph	Wind felt on face; leaves rustle; wind vane moved by wind
3.	Gentle breeze	8 - 12 mph	Leaves and small twigs in constant motion; light flags extended
4.	Moderate Breeze	13 - 18 mph	Raises dust and loose paper; small branches moved.
5.	Fresh Breeze	19 - 24 mph	Small trees in leaf begin to sway; crested
6.	Strong Breeze	25 - 31 mph	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty
7.	High wind, moderate gale, near gale	32 - 38 mph	Whole trees in motion; inconvenience felt when walking against the wind
8.	Gale, fresh gale	39 - 46 mph	Twigs break off trees; generally impedes progress.
9.	Strong/severe gale	47 - 55 mph	Slight structural damage (chimney pots and slates removed).
10.	Storm, whole gale	55 - 63 mph	Seldom experienced inland; trees uprooted; considerable structural damage
11.	Violent storm	64–72 mph	Very rarely experienced; accompanied by widespread damage
12.	Hurricane force	Above 73 mph	Devastation.

Today, hurricane-force winds are sometimes described as Beaufort scale 12 through 16, very roughly related to the respective category speeds of the Saffir–Simpson hurricane scale, by which actual hurricanes are measured, where Category 1 is equivalent to Beaufort 12. However, the extended Beaufort numbers above 13 do not match the Saffir–Simpson scale. Category 1 tornadoes on the Fujita and TORRO scales also begin roughly at the end of level 12 of the Beaufort scale, but are independent scales – although the TORRO scale wind values are based on the 3/2 power law relating wind velocity to Beaufort force.

The Beaufort scale was extended in 1946, when forces 13 to 17 were added. However, forces 13 to 17 were intended to apply only to special cases, such as tropical cyclones. Nowadays, the extended scale is only used in Taiwan and mainland China, which are often affected by typhoons. Internationally, WMO Manual on Marine Meteorological Services (2012 edition) defined the Beaufort scale only up to force 12 and there was no recommendation on the use of the extended scale.

1.3.1.2 High wind

It could be concluded from several reports and publications related to wind distribution in the United States that, the so-called "high wind" refers to a gust or continuous wind traveling within the range of 32 – 46 mph measured at a certain height to avoid interference. This could occur within a few minutes or for weeks at a stretch or considered high wind at Beaufort 7 and 8. The distribution of wind in Texas is complex because of the land configuration and several environmental elements. There are coastal and land locked districts which are at different altitudes and have different vegetation covers ranging from desert land to pine tree forests, all of which duly affect wind speed/velocity. Figure 3 is the map of Texas with wind velocity zones for road signs, which is based on 25 years' Mean Recurrence Interval of Fastest Mile Wind Velocity at 33 feet height.

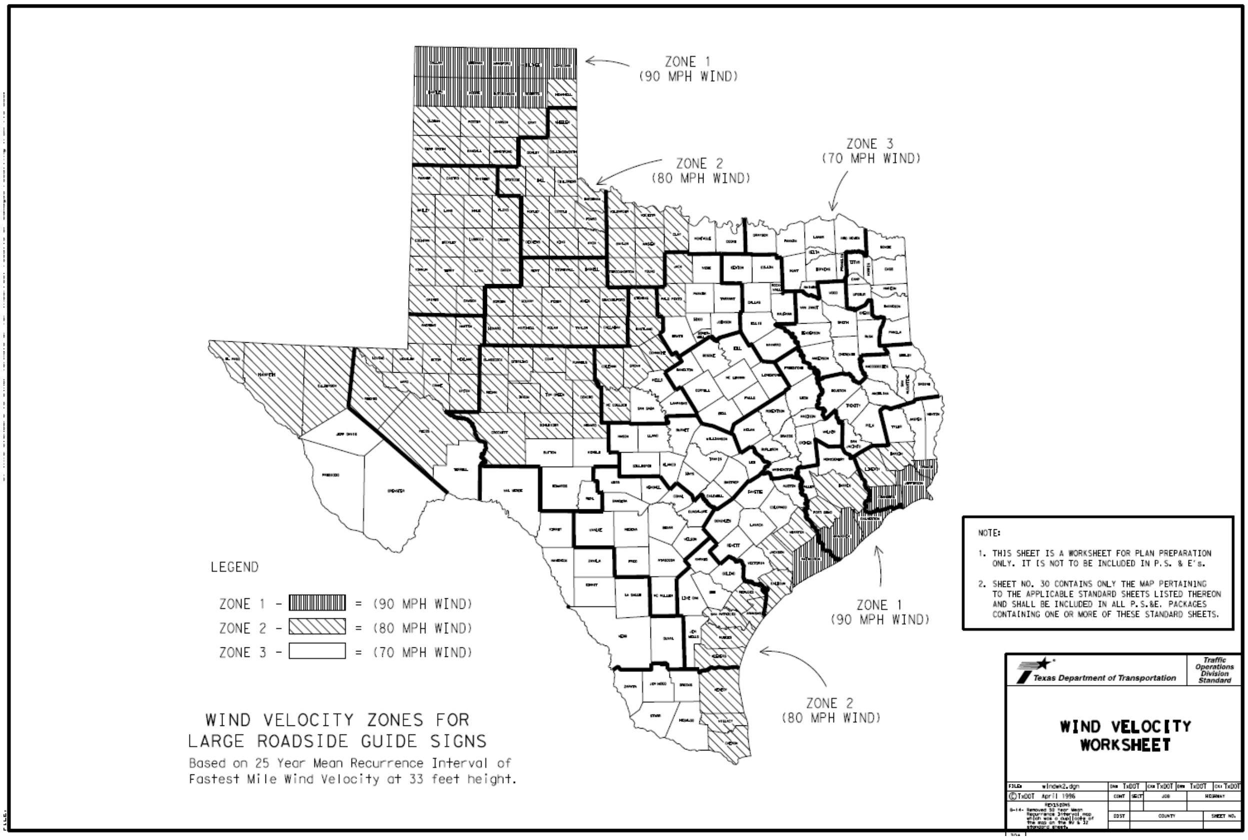


Figure 3. Wind Velocity Zones for Road Signs in Texas (Source; ftp://ftp.dot.state.tx.us/pub/txdot-info/cmd/cserve/standard/traffic/windwk2.pdf).

Based on Figure 3, the wind velocity zone 1 is defined as **90 mph** and above, which includes 9 Counties in Amarillo (AMA) district, 3 Counties in Beaumont (BMT) district, 2 counties in Houston (HOU) district, and 1 county in Yoakum (YKM) County. The "high wind" areas are concentrated in (1) the far north part of Texas, and the north part of coast in Texas along the Gulf of Mexico.

1.3.2 Wind Load Analysis

In American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals, it is described that sign supports need to meet wind load requirements (AASHTO, 2013).

There are currently two acceptable methods in the specification for calculating wind pressures on signs. Section 3 in AASHTO standard of the specification describes the current method, which is an attempt to unify wind load design with that of other structures. However, the legacy method is still considered acceptable for determining wind load values for signs, and is included as Appendix C of the design specification.

One method is not considered more conservative than the other is. Both methods result in similar overall wind pressures, although some differences may exist depending on geographic location.

The design wind pressure is based on the basic wind speed and the life expectancy of the structure. The basic wind speed is associated with the annual probability of 0.02 (or a 50-year mean recurrence interval), and prescribed by isotachs contained in the AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals. Figure 8 shows that the basic wind speed varies with geographical location across Texas, and ranges from 90 mph to 130 mph near the coast.

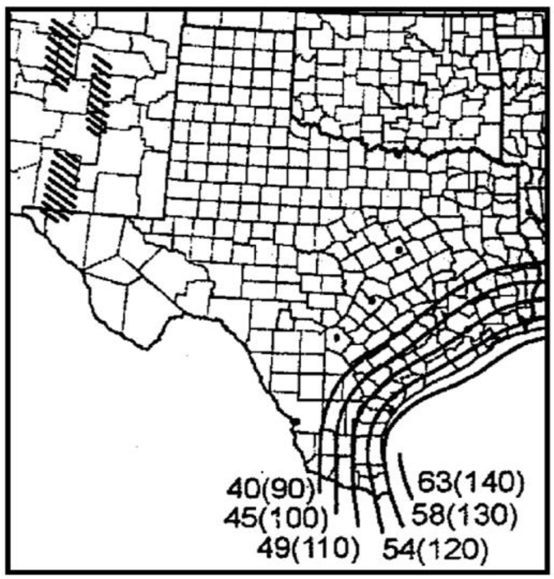


Figure 4. Texas Wind Load Isotachs (AASHTO, 2013).

In Figure 4, a wind speed of 90 mph covers approximately 80% of Texas. A wind speed of 110 mph covers approximately 90 percent of the state. A wind speed of 120 mph covers almost all of the state with the exception of some narrow coastal areas. A wind speed of 130 mph covers all of the state. Since all high wind zones in Texas are located along the gulf coast, a hurricane region, the current wind load calculation method allows for the reduction of wind speed. The resulting wind pressure must equal or exceed the calculated wind pressures for a non-hurricane zone wind speed of 100 mph.

The basic wind speed is modified by an importance factor based on the recommended minimum life expectancy of a structure. The recommended minimum design life for permanent roadside sign structures is 10 years.

Given a design wind speed, the associated wind pressure is computed by Equation (2).

$$P_z = 0.00256\ k_z G (V * C_v)^2 I_r C_d (psf) \tag{2}$$

where,

P_z is design wind pressure in psf,
I_r is wind importance factor,
C_v is velocity conversion factor,
k_z is height and exposure factor, 0.85 is for the sign with 5 m/16.4 ft height or less,
G is gust effect factor, and
C_d is wind drag coefficients, 1.12 is for sign with length/width ratio of 1
V = Basic wind speed in mph from wind chart.

The current method defines permanent sign supports as having a design life of 10 years or less. A **90-mph design** wind speed with a 10-year recurrence interval equates to a wind pressure of 11.5 psf. This represents a total wind load of 1,469 lb when applied to the 128-ft2 sign. A 100-mph design wind speed equates to a wind pressure of 14.2 psf and a total wind load of 1,813 lb. These wind loads can be applied to the resultant height of a sign panel to determine the required number of support posts of a certain size and grade as well as the required amount of ballast needed to prevent a skid-mounted sign support system from overturning when subjected to a design wind event (Roger et al., 2014).

The impact performance evaluation of sign support structures is documented in the AASHTO Manual for Assessing Safety hardware requirements (2009). Besides, there are many factors involved in determining the minimum number and spacing of support posts required, such as sign size, sign mounting height, post size, and post grade (AASHTO, 2013).

1.3.3 Durability

An important consideration when designing any work-zone traffic control sign and device is the ability to accommodate frequent handling, on-site relocation, transportation, and repair. In other words, to be cost effective, the sign base shall be durable. Insight can be gained from contractors, suppliers, and users of these signs and devices regarding the nature of abuse to which temporary traffic signs are subjected in daily use and common problems that are encountered in the field. For example, many suppliers/contractors have a preference for using channelizing drums with rubber bases rather than a ballasted plastic base. They have observed that these devices are typically moved by using the handle on the top of the drum and dragging it on its base. While the rubber bases extend beyond the edges of the drum and protect it from damage, the ballasted plastic bases frequently wear through and require replacement.

Another preference is using plastic horizontal barricade rails, which is over the more commonly used wood. Although the initial cost may be slightly higher, the probability of saving the reflective sheeting (which is often the most expensive part of a barricade) during an impact is greatly improved because the rail members do not fracture. When wood rails are used, they tend to fracture easily even in relatively minor impacts resulting in the loss of both the rail and its reflective sheeting. Further, wooden rails require painting while plastic rails, which can be provided in a white color, do not.

Some suppliers/contractors prefer to use hose clamp–type connectors rather than through bolts to attach rails or sign panels to hollow-profile plastic vertical supports. The barricade rails or sign panels often require slight adjustments in height for relocation. If holes are drilled each time to accommodate through bolts, the support will soon be rendered structurally inadequate. By using the clamps for the connections, the need for drilling holes is eliminated and the life of the support can potentially be prolonged.

Some barricade designs incorporate bracing to enhance transportation, handling, and durability. Use of the vertical braces permits the barricade rails to be preassembled and then attached or detached from the barricade supports as a unit, which assists with transportation and on-site erection. Use of horizontal cross braces can provide more rigidity to the barricade frame when flexible barricade rails (e.g., plastic) are used. This rigidity helps improve handling characteristics and the ability to withstand wind and other service loads.

1.3.4 Site Adaptability

The site conditions encountered in work zones can vary considerably from one job to the next. Ideally, a well-designed work-zone barricade or sign support will be able to accommodate some of the more common variations in site conditions. When barricades are placed on the roadside, for instance, varying degrees of sloped terrain or tall grass are commonly encountered. If the vertical supports of the barricade or sign support are designed to be readily adjustable, accommodating the differential elevation caused by the sloped terrain or increasing the mounting height to position the warning or guide sign above the tall grass is a simple matter. Adjustability can be accomplished by using sleeves into which the vertical supports can be easily inserted and adjusted to the required height.

Barricades or temporary sign stands with fixed, non-adjustable supports and bases lack this type of adjustment and are sometimes raised or leveled on a slope using blocks under the skids or legs. This practice can potentially have an adverse effect on the crashworthiness of the device and its ability to withstand wind loads. Alternatively, the attachment of the sign panel to the uprights can be adjusted provided adequate support for the sign panel is still provided.

1.3.5 Materials on Environmental Effects

Because of the unacceptable impact performance experience with rigid substrates (e.g., plywood) with some sign support systems, many alternative substrates have been evaluated for use as temporary sign panels. The type of substrate used and its means of attachment to the vertical support(s) can affect the functionality of the device. To meet crashworthiness requirements, many devices incorporate lightweight materials such as vinyl/fabric roll-up signs, plastic sheeting, corrugated plastic, fiberglass, and thin-gage aluminum. Most of these materials are very flexible in nature and some, such as the plastic materials, may be susceptible to war page; both of these behaviors can decrease retro-reflectivity and legibility of the warning or guide sign.

Bracing can be used to reduce this behavior, but the effects of the bracing on the impact performance of the device must be carefully evaluated. If a proper combination of support and substrate are selected, some of these environmental design considerations can be accommodated in the design process.

Another concern is the long-term durability of plastics (e.g., PVC, HDPE, polypropylene [PP]) and FRP components used in barricade and temporary sign support construction. Although admixtures are typically incorporated into these products to enhance their resistance to degradation from ultraviolet rays and other types of environmental attack, their long-term susceptibility and, thus, their life expectancy are not fully known.

1.4. Design of Temporary Signs for Work Zone

1.4.1 Base Design

The material “wood” is often used for sign bases as an economical alternative to steel (Impactrecovery.com). The MUTCD does not prescribe the specific species of wood that should be used, but pressure-treated standard lumber pieces are often chosen, as they are infused with anti-rot chemicals to withstand decay for extended periods, even after prolonged exposure to the elements.

Sign bases made of hot rolled steel are considered breakaway supports as long as they weigh less than 3lbs. per linear foot, as a vehicle strike to such a post will cause it to bend, break, or uproot (Impactrecovery.com). The post should be buried no deeper than 42" underground, and installers should avoid using concrete to secure the base, as this will interfere with breakaway considerations.

If heavier-weight steel is used, the sign base should have a stub post installed at ground level to enhance breakaway. Use of a stub post not only enhances safety in case of a vehicle collision, it also makes replacement or repairs a simpler process. Figure 5 shows a long / intermediate and regulatory sign mounting (left), and a short-term duration sign mounting (right).

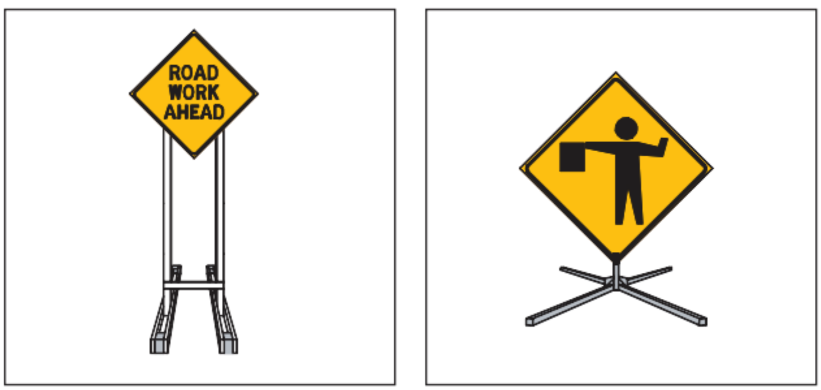


Figure 5. (Left) Long and/intermediate and regulatory sign mounting; (Right) Short-term duration sign mounting (TxDOT, 2017)

To resist heavy winds, there are some specific standards for temporary traffic control signs that are mentioned in Chapter 6 of MUTCD for work zone areas. For instance, the faces of the Automated Flagger Assistance Devices (AFAD)'s STOP/SLOW signs may include louvers to improve the stability of the device in windy or other adverse environmental conditions. Steps should be taken to minimize the possibility of cones being blown over or displaced by wind or moving vehicular traffic. On high-speed expressways or in other situations where barricades may be susceptible to overturning in the wind, ballasting should be used to increase their weight.

For the high frequent wind events in Texas, more specific standards and requirements are documented in TMUTCD. For instance, in Chapter 6 of TMUTCD section 2A. 21, it is required that sign posts, foundations, and mountings shall be so constructed as to hold signs in a proper and permanent position, and to resist swaying in the wind or displacement by vandalism. Post-mounted sign supports shall be crashworthy (breakaway, yielding, or shielded with a longitudinal barrier or crash cushion) if within the clear zone (TMUTCD, 2011 edition).

Long-term/intermediate-term work zone signs shall be installed in accordance to manufacturer's instructions. In no case shall the height of the non-breakaway portion of the support (i.e., stub) extend higher than 4 inches from the ground (TxDOT, 2017). There are a few designs of portable sign supports, taking into wind conditions. For instance, for the Wood Dual Leg, skid design (H-leg) in Figure 6(a), its skid length shall be at least 60 inches in length. The skid length may be increased for wind conditions if space permits. Another example is FRP pipe with dual-purpose base, as is shown in Figure 6(b).

The sign support shown in Figure 7(a) has an H-shaped base with a single center upright. The central member of the H-shaped base is welded to the center of each skid. A short sleeve is then welded to the center of this cross member. An upright is inserted and bolted into the sleeve. The rigid sign panel is then mounted to the single upright using a minimum of two bolts. Assembly and disassembly of this design are faster because there is only one upright with a single bolt or pin to insert or remove. However, signs mounted on single vertical supports will be more susceptible to flutter in windy conditions. This design does not possess any side-to-side or front-to-back adjustability.

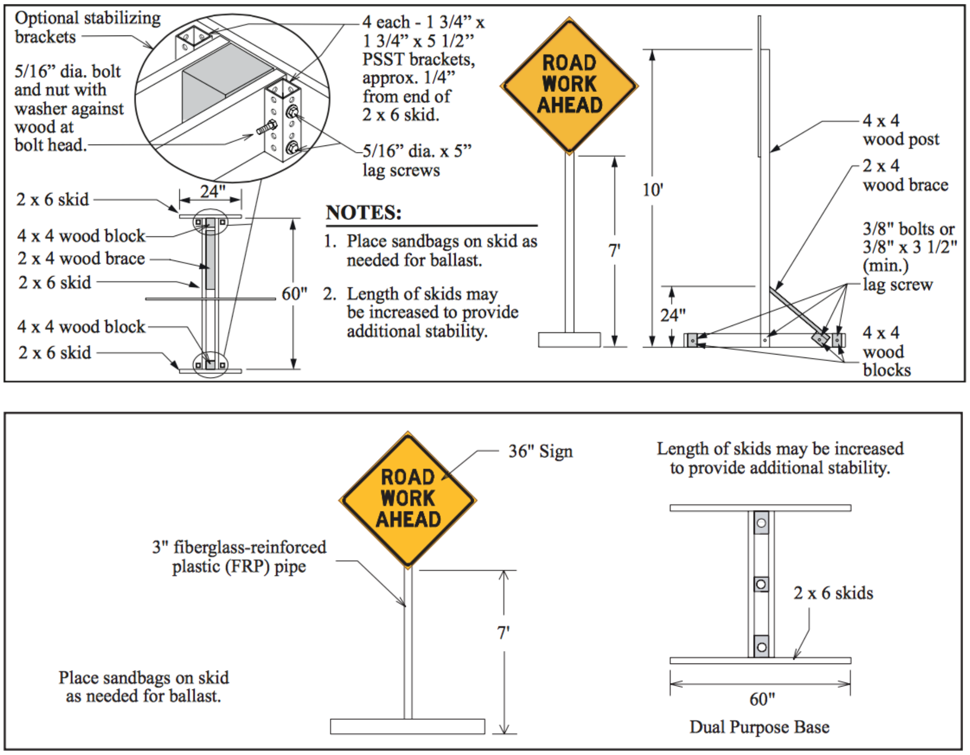


Figure 6. (Top) Wooden long/intermediate-term single leg (H-leg) sign support; and (bottom) Com's long/intermediate-term single leg (H-leg) sign support (TxDOT, 2017).

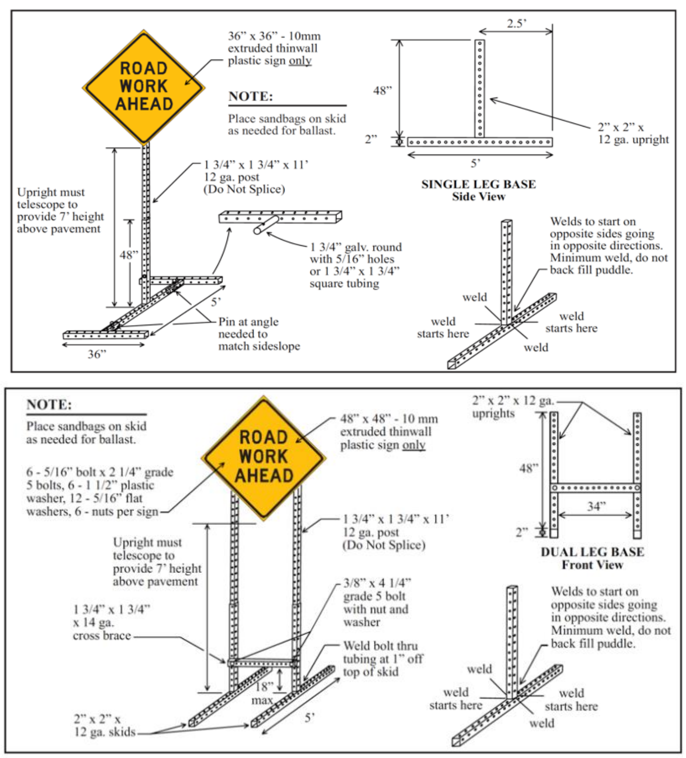


Figure 7. (Top) H-base single upright with leg PSST skid sign support; and (down) Independent dual upright with leg PSST skid sign support (TxDOT, 2017).

Figure 7(b) show an H-base with independent dual uprights. The sign support uses two identical but independent uprights to support the plywood sign panel. The use of two uprights improves the torsional stability of the sign panel. Short sleeves are welded to 1.2-m (4-ft) long skids. Uprights are inserted and bolted into the sleeves. The rigid sign panel is then bolted to the uprights with a minimum of two bolts in each. The sign panel serves as the cross bracing for the system. Transportation and erection is facilitated by the removal of bolts connecting the uprights to the skids. While the design is simple, there is only minimal adjustability to account for varying terrain considerations. Although it may not be needed, there is no front-to-back tilt adjustment to accommodate vertical grade. If the sign support is placed on the roadside, horizontal slope can be accommodated by adjusting the height of the downhill upright by either extending the tube out of the sleeve and/or lowering the attachment points to the sign panel. Figure 8 is a dual leg PSST skid support for various substrates (7-foot mounting height), Figure 9 is the perforated square metal tubing with anchor, and Figure 10 is the wood & HPPL short-term/short-duration H-leg sign support (1-foot mounting height).

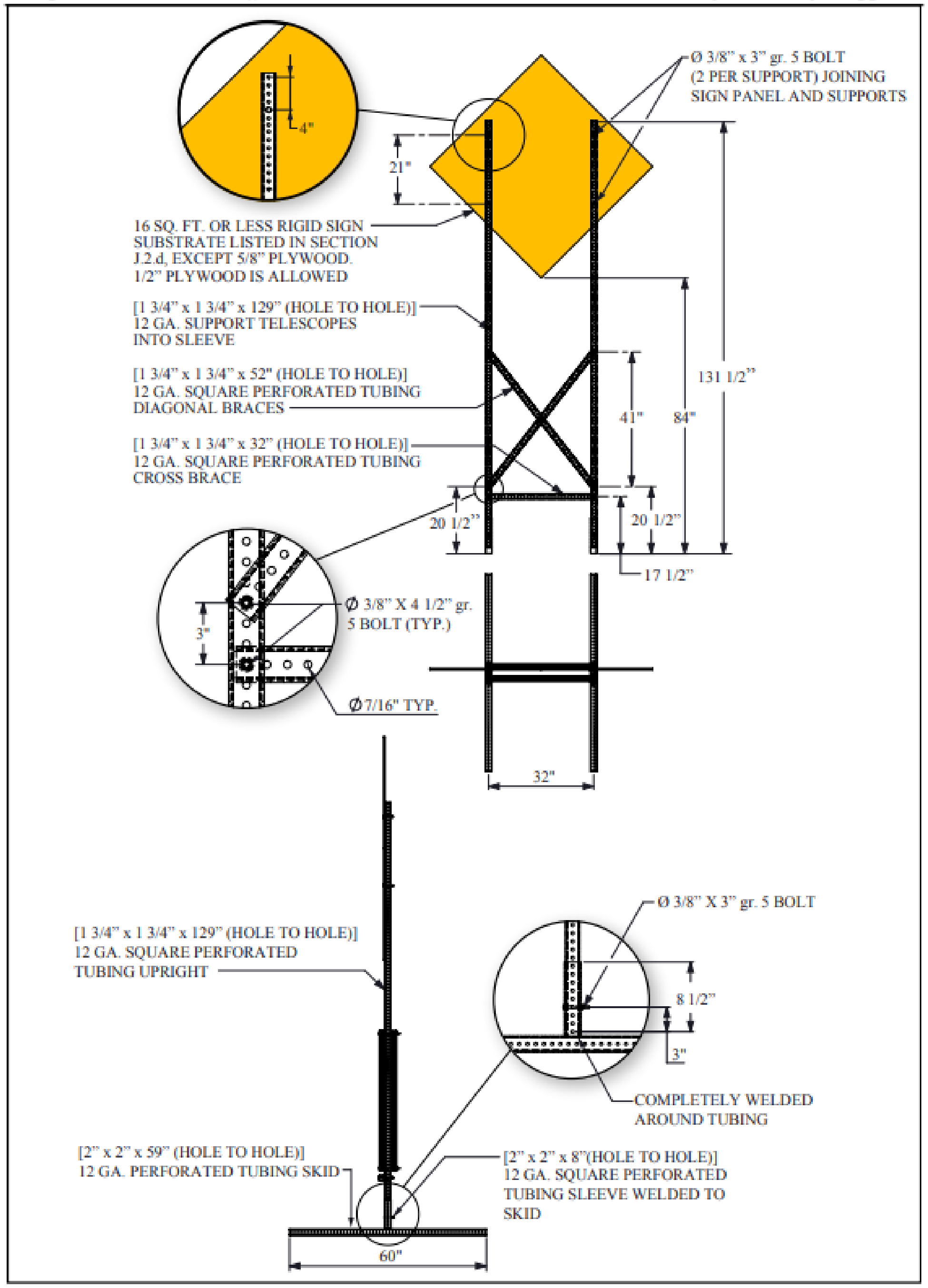


Figure 8. Dual Leg PSST skid support for various substrates (7-foot mounting height) (TxDOT, 2018)

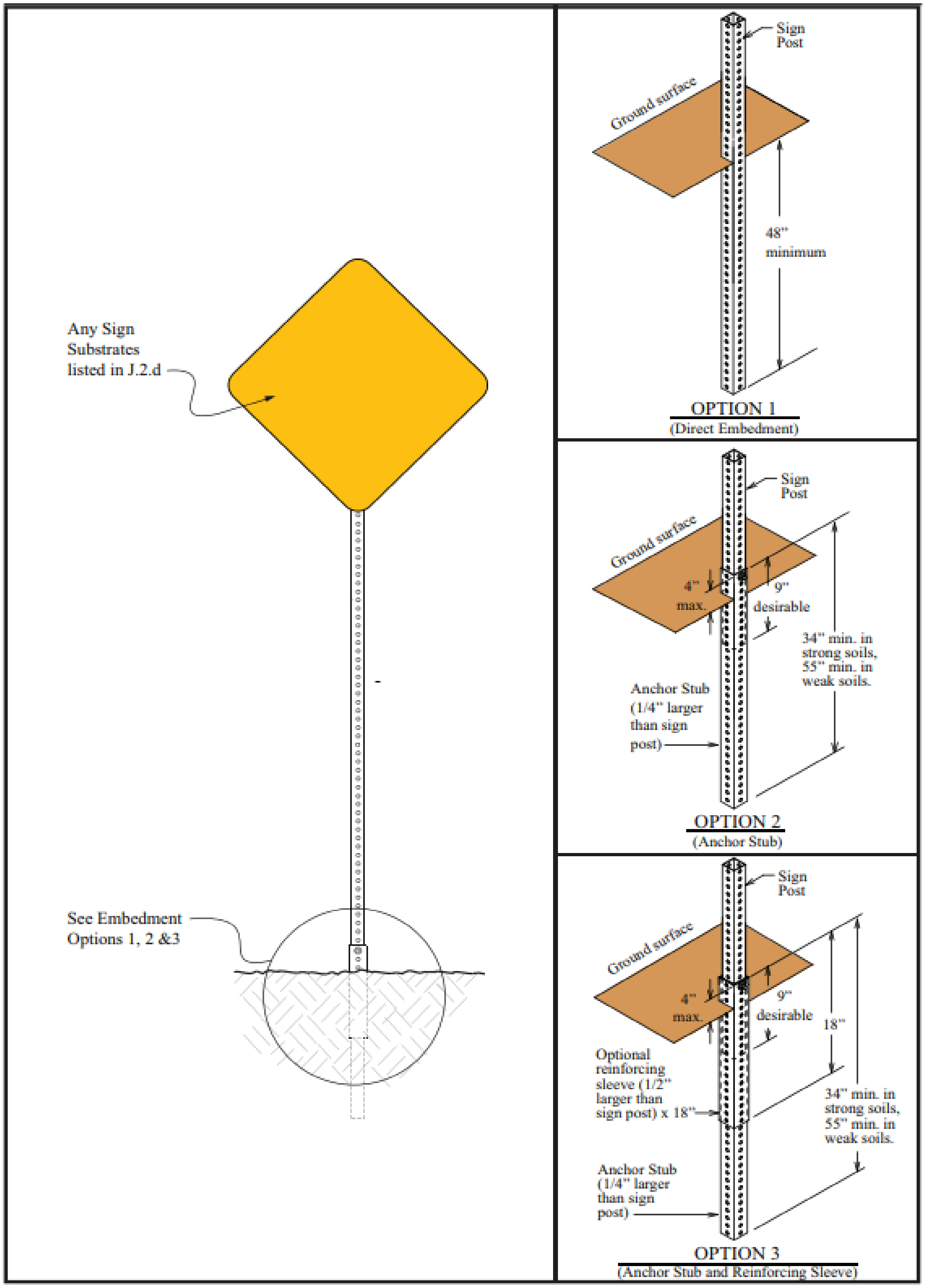


Figure 9. Perforated square metal tubing with anchor (TxDOT, 2018)

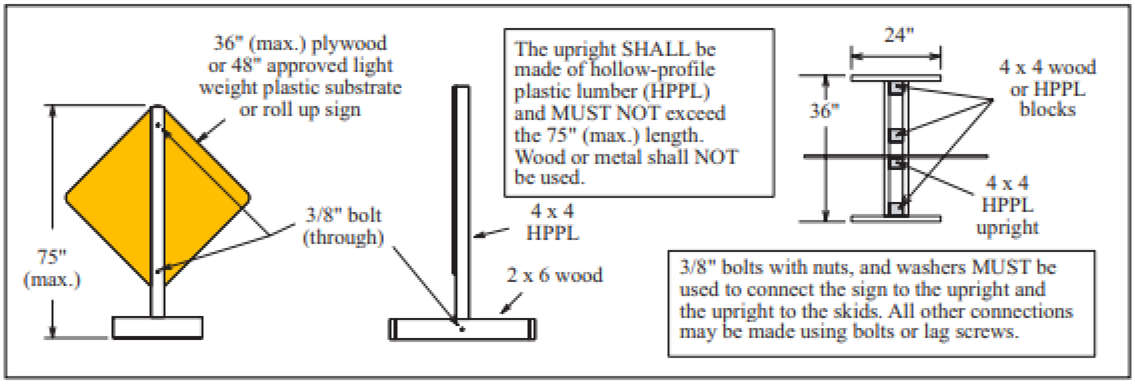


Figure 10. Wood & HPPL short-term/short-duration H-leg sign support (1-foot mounting height) (TxDOT, 2018)

Unlike the independent dual upright, pivoting dual uprights incorporates some front-to-back adjustability by using pin plates at the base of each upright. These adjustment plates can be either welded or bolted to the skids. The plates are used to attach the 305-mm (12-in) long sleeves to the skids. The uprights insert and bolt into the sleeves. The rigid sign panel is then bolted to the uprights with a minimum of two bolts in each vertical member.

To tilt the sign panel to the front or back, the upper adjustment bolt/pin is removed and reinserted after aligning the sleeve with one of the other holes in the plate. As with Design independent dual upright, side-to-side adjustment can be accommodated by telescoping of one of the vertical members inside its sleeve or adjusting the attachment of one of the uprights to the sign panel. The top adjusting pin on each plate can be removed to lay the sign down for easy transport as a single unit. If desired (for ease of repair, etc.), the sign panel and uprights can be readily detached from the base by removing the bolts through the sleeves. Figures 11-13 are X-base with single upright, JB Witt PVC sign support, and Hwy Com's short-term H-leg sign support, (1-foot mounting height), respectively.

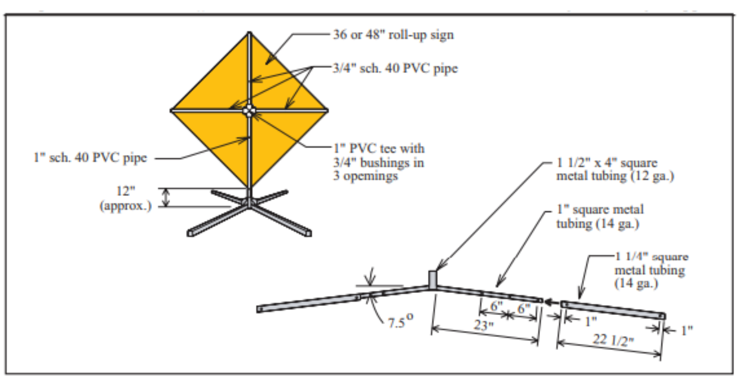


Figure 11. X-base with single upright (TxDOT, 2018)

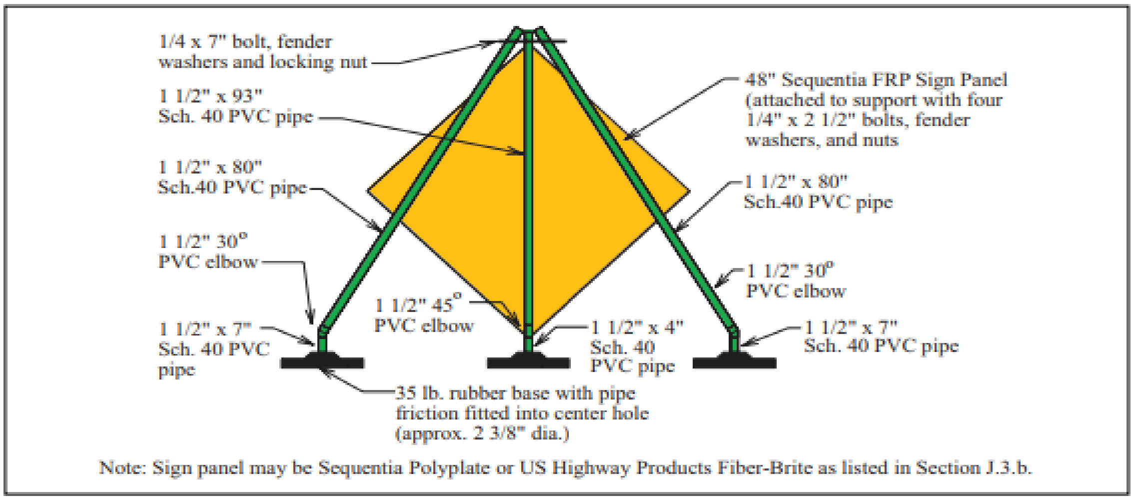


Figure 12. JB Witt PVC sign support (TxDOT, 2018)

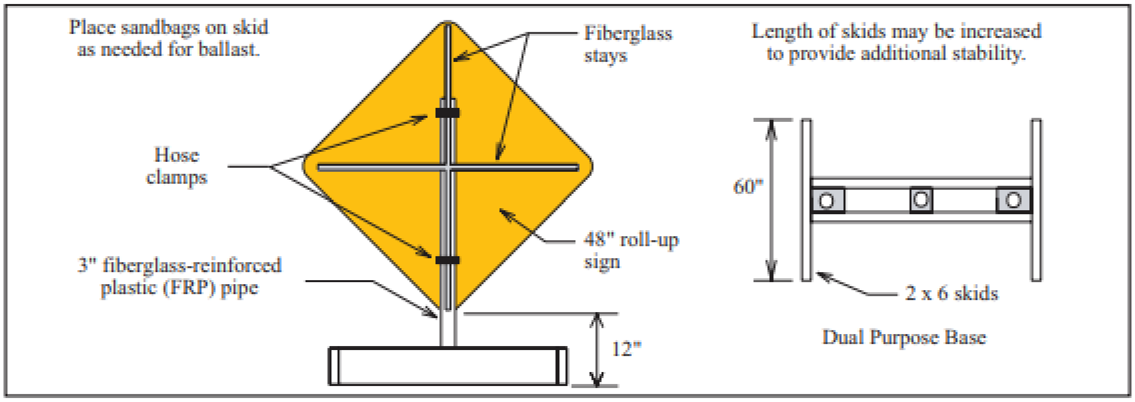


Figure 13. Hwy Com's short-term H-leg sign support (1-foot mounting height) (TxDOT, 2018)

The H-base is a combination of Designs independent dual uprights and H-base with single upright. It uses the H-base in combination with two uprights. The cross member can be attached to the skids using sleeves as shown or by direct welding. This design uses a little more material and requires a little more welding than Design H-base with single upright, but should be more stable and eliminate flutter. As with Design H-base with single upright, the H-base with dual uprights does not have side-to-side or front-to-back adjustability. Moreover, the bases have been designed to X shape (Figure 11) and adjustable tripod, and HDPE/wooden.

1.4.2 Base Materials and Ballast

Figure 14. Sandbags on skid as ballast to resist high speed wind forces

A base is designed to secure the pavement with an adhesive or rubber weight to minimize movement caused by a vehicle impact or wind gust. The most popular technique is to use sandbags placed on skid as needed for ballast to resist high speed wind force, as shown in Figure 14.

The ballast requirement is able to prevent overturning during a wind event. The researchers performed an overturning analysis to determine the amount of ballast required for the skid-mounted temporary sign support system for different wind speeds. Using the calculated wind pressure applied to the sign panel, the maximum overturning moment can be computed (Bligh et al., 2014), which determines the amount of ballast (in the form of 40-lb sand bags) placed on the skids to prevent overturn of the sign support system during a design wind event. For example, for a 8-ft*16ft sign panel mounted at 7 ft, the 11 and 60 bags of ballasts are required for the wind speed of 41.6 and 97 mph, respectively (Bligh et al., 2014).

Instead of sandbags, a traffic sign base could be stabilized by increasing its weight via materials. The traffic sign base could be made of angle steel, metal, and rubber, to increase its weight for stability. Figure 15 illustrates the type of temporary traffic sign bases designed, which could resist wind force.

(a) WindMaster stand

(b) Cast iron base for a STOP sign

(C) Portable sign base

(d) Rubber base for a STOP sign

Figure 15. The type of temporary traffic sign bases designed, which could resist wind force (source: my parking sign.com)

In Figure 15a, the WindMaster stand applies the mechanism of vertical supports to prevent from being knocked, which is easily moved or relocated on the job site as necessary to accommodate work zones. However, the stand doesn't have a ground-mounted foundation; proper ballast should be provided to prevent overturn from occurring in a strong wind event. Metal traffic sign base design shown in Figure 7b directly increases the weight of the base to minimize its mobility.

The metal sign base is usually made of cast iron with about 37 lbs in weight. Meanwhile, the 37 lbs base increases the difficulty in movement by workers as well. Another base design can overcome this difficulty, which is a portable sign base shown in Figure 14c. The base is built in wheels and fills with water or sand for 35 lbs of ballast.

To meet the needs of heavy weight and easy movement, rubber sign base is designed and shown in Figure 15(d). The rubber sign bases are made from recycled tires in about 71 lbs, which are the heaviest of the bases. Besides, the heaviest base is more portable. Its round shape design could be easily rolled into place. Further, the rubber sign bases last the longest and no maintenance is required.

1.4.3 Other Post-Type and Sign Supports

1.4.3.1 Rectangular-timber sign posts, No. 2 SYP or equivalent, 4 x 4 or 4 x 6

If a 4 x 6 post is used, 1-1/2 inch weakening holes shall be drilled through the wide face at 4 and 18 inches above the ground. The wide face of the post shall be installed parallel with traffic. No more than 2 posts shall be mounted within a 7-foot span. The post shall be embedded into the ground a minimum of 36 inches. This support may be used in both weak and strong soils. The post may be directly embedded or may be embedded in pre-mixed concrete, soilcrete, or approved expanding closed-cell polyurethane foam.

1.4.3.2 Quick-Punch® 14-gauge 2-inch square tubing with 7/16-inch die-cut knockouts on 1-inch centers

This support may be directly embedded a minimum of 48 inches in both weak and strong soils. As an option, an anchor stub may be use. The anchor stub is the next larger size tubing (2-1/4 inch). Additionally, an 18-inch reinforcing sleeve made from the next larger size tubing (2-1/2 inch) may be used. The optional anchor stub, when used, shall be embedded at least 34 inches in strong soils or 55 inches in weak soils with approximately 1 inch protruding above the ground (Figure J-5). Both systems may also be set in concrete, soilcrete, or approved expanding polyurethane foam. No more than 2 posts shall be installed within a 7-foot span.

1.4.3.3 Square metal tubing with 7/16-inch holes punched on 1-inch centers

This support may be directly embedded a minimum of 48 inches in both weak and strong soils (Option 1). As an option, an anchor stub may be used. The anchor stub is the next larger size tubing (Option 2). Additionally, an 18-inch reinforcing sleeve made from the next larger size tubing may be used (Option 3). The optional anchor stub, when used, shall be embedded at least 34 inches in strong soils or 55 inches in weak soils with approximately 1 inch protruding above the ground. Both systems may also be set in concrete, soilcrete, or approved expanding polyurethane foam. The posts may be mounted according to the following table. Any approved sign substrate from Section J.2.d may be used on square metal tubing supports when embedded.

1.5. Functional Performance Evaluation

In the NCHRP report 553 (2006), a rating scheme was developed to evaluate the functional performance of a work zone barricade or sign support in windy areas. Wind resistance, durability, handling, fabrication/repair, and site adaptability are primarily concerned in the rating. The rating scale for each area was “high,” “average,” and “low.”

The rating of wind resistance reflects the strength and stiffness of the support member and sign substrate. For example, support systems that incorporate vinyl roll-up signs are generally rated as average because of their propensity to lean and deflect in the wind thus reducing legibility and retro-reflectivity. Rigid substrates (e.g., aluminum, plywood) with sufficiently strong support members are generally rated as high due to their ability to retain their shape and orientation in windy conditions.

The durability rating primarily reflects the durability of the materials used in the construction of the sign support. Systems composed of steel, aluminum, and wood are generally rated as high for their resistance to environmental attack. Systems with vinyl sign substrates and plastic or fiberglass components are generally rated as average based on uncertainty regarding the long-term susceptibility of these materials to degradation from environmental attack, such as the exposure to strong winds.

The handling assessment is to rate general ease of handling, transportation, and erection of the device. A rating of high generally reflects the device’s ability to be readily assembled and disassembled for ease of transportation and to minimize exposure during on-site deployment. A high rating is also generally indicative of durable connections and a reasonable weight that enables the device to be moved short distances as an assembled unit during on-site handling. More bulky assemblies or units that cannot be readily disassembled or folded would be rated as average or low.

The fabrication/repair rating provides a general assessment of the cost and availability of materials used to construct and repair the device. Units that use readily available materials that can be easily cut to length, drilled, etc. (e.g., wood, steel tubing, or hollow profile plastic) would be given a higher rating than devices that require specially molded parts or are constructed from more expensive materials such as fiberglass. The fabrication/repair rating is also based on the types of connections and ease of assembly of the device. Devices composed of components that are easily nailed, bolted, or pinned together would rate higher than those that require welding or more labor-intensive fabrication.

The rating on site adaptability refers to the degree of adjustment that a device has to accommodate variations in field conditions. For example, a device with a reasonable range of height adjustment and/or an ability to adjust to uneven terrain would be given a site-adaptability rating of high. A telescoping or sleeved system that allows height adjustment of the sign and its support would receive a high rating. Of course, the device would need to be crashworthy for the range of heights to which it might be adjusted in the field. A few devices have a tilt adjustment on the mast/support, which enables the sign to be plumb when the base is placed on a sloping roadside or otherwise unleveled terrain. Such a feature would warrant a high site adaptability rating.

Devices with fixed supports and bases that are not adjustable would be given a rating of average or low depending on the features of the design. The overall rating assesses the overall functionality of each device and sign, which is an average of the wind, durability, handling, fabrication/repair, and site-adaptability ratings.

1.6. Practices of Temporary Traffic Sign Supports

Temporary traffic sign supports are typically free-standing systems that have sign panels mounted at various heights with a base. High-mounting-height, portable sign stands are typically fabricated with larger support members. If the supports do not readily fracture or release upon impact, they may yield around the front of the impacting vehicle and carry either the sign panel and/or top of supports into the windshield. As with low-mounting-height sign stands, rigid sign panel substrates are more problematic with collisions of this nature. Remedial measures for these types of problems have involved weakening the supports at or near bumper height, installing breakaway mechanisms at bumper height, or providing sign panel release mechanisms. Sometimes combinations of these design modifications are incorporated. As mentioned previously, the configuration of the sign stand and selection of an appropriate sign substrate are equally important in the design of a portable sign support system. Several generic sign stands with various sign substrates including plywood, aluminum, FRP, and corrugated plastic have been successfully tested. However, further work is needed to develop additional generic sign stand alternatives that can be used with rigid or semi-rigid sign substrates at different mounting heights.

A review of the existing portable sign support systems for the work zone areas in the United States is summarized as following observations (NCHRP report 553, 2006).

- A large number of the devices are proprietary.
- Most proprietary support devices are fabricated from square steel or aluminum tubing and are available with both rigid and non-rigid sign substrates.
- Many of the proprietary X-base supports are adjustable for varying site conditions.
- A small portion of the proprietary supports are fabricated from various plastics.
- Generic supports are mostly fabricated with wood or plastic lumber, perforated steel tubing, and/or PVC pipe and are generally not well suited for varying site conditions.
- Generic rigid sign substrates are generally fabricated with sign-grade plywood or aluminum.
- Proprietary rigid sign substrates include laminated composites and extruded plastics.
- Portable sign supports with signs mounted at 1.5 m (5 ft) or higher experience more favorable results in crash tests when some type of fracture or release of the support occurs near bumper height of the impacting vehicle or when early release of the sign panel is achieved.

CHAPTER 2: DETERMINING NEEDS, CONCERNS AND EXPECTATIONS

2.1. Overview

This chapter summarizes the survey conducted to relevant engineers in Texas, and the field observations in areas with high wind within Texas.

2.1.1 Objective of Chapter 2

The objective is to determine the needs, concerns, and expectations of TxDOT on the techniques and materials for temporary traffic signs on work zones during high winds. In this chapter, different base designs, materials, and techniques used by TxDOT to ballast traffic signs in temporary work zones in high wind are analyzed.

2.1.2 Action Items

The actions in this chapter include:

- Designed a survey form placed on SurveyMonkey.com and distributed it to TxDOT personnel in areas with high winds to determine needs, concerns, and expectations of the temporary signs at work zone areas. This included to:
    - Collect information on existing technologies and materials that engineers are using
    - Collect information on the performance of currently used technologies and materials
    - Collect information on practical and specific safety issues that engineers have encountered in their own district;
    - Collect information on new technologies and materials available; and
    - Evaluate new technologies and materials for ballasting temporary signs
- District Selection
    - The Houston district was initially selected as the test bed for field observation. During the research progress meeting in Austin on February 4, 2019, the Project Management Committee (PMC) suggested adding three other districts (SJT, AMA, and LBB) for field observations. The reason was that, the high wind in Houston district normally happens during hurricane season, which might beyond the duration of this project, while during spring season in those added three districts (SJT, AMA, and

LBB), high winds are often observed affecting the temporary traffic signs in work zones.

- Field Observation (Apply the new technologies or materials and observe while using cameras and wind speed detectors)
- Evaluation Rating (Work with vendors to determine the costs of the identified new technologies or materials)
- Overturning Check (Conduct an overturning check to test the reliability)
- Evaluation Reporting

2.2. Survey TxDOT Engineers

2.2.1 Survey Design

Survey was conducted by administering a well-prepared questionnaire which was used to collect data regarding the impact of high wind on temporary signs in the respondent's location and evaluate all TxDOT's standard temporary signs which are used in work zones based on criteria such as; setup and mobility, performance and safety. This questionnaire was administered to 21 respondents, and the results gathered were properly analyzed. Figure 16 illustrates the survey process.

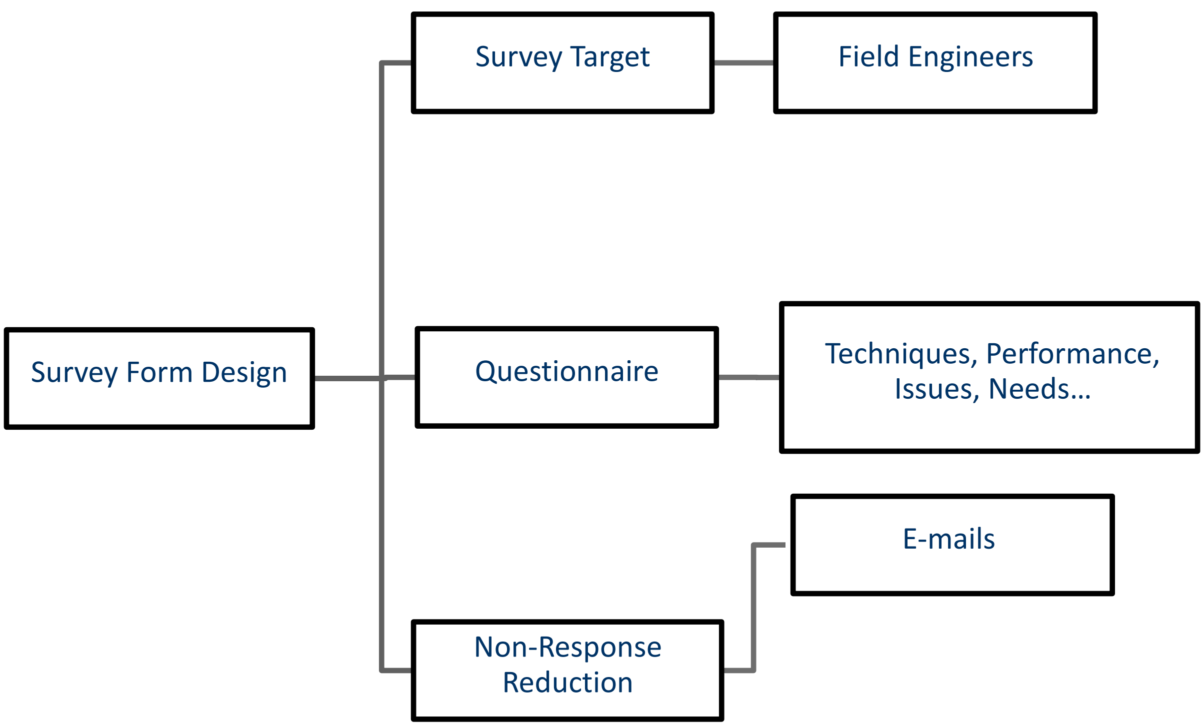


Figure 16. Survey Procedure

With the discussion with and approval from the PMC members, there are 11 signs selected for the survey, as listed below.

- Sign 1000: Wooded skids with 2 wooden legs
- Sign 1001: Wooden long/intermediate-term single leg (H-leg) sign
- Sign 1002: Com's long/intermediate-term single leg (H-leg) sign
- Sign 1003: H-base single upright with leg PSST skid sign
- Sign 1004: Independent dual upright with leg PSST skid sign
- Sign 1005: Dual leg PSST skid support for various substrates (7-foot mounting height)
- Sign 1006: Perforated square metal tubing with anchor
- Sign 1007: Wood & HPPL short-term/short-duration H-leg sign support (1-foot mounting height)
- Sign 1008: X-base with single upright
- Sign 1009: JB Witt PVC sign support
- Sign 1010: Hwy Com's short-term H-leg sign support (1-foot mounting height)

The survey form includes three major parts: (1) basic information; (2) sign evaluation; and (3) information on new tech and materials.

The survey was designed on October, 2019, revised on November 2018, distributed on December 2019, and followed up on January 2019. The survey was placed on SurveyMonkey.com with the website: https://www.surveymonkey.com/r/KQLRS6B.

2.2.2 Survey Results

2.2.2.1 Respondents' Distribution

There were seven respondents from six districts in Texas, as was marked in red triangles in Figure 17.

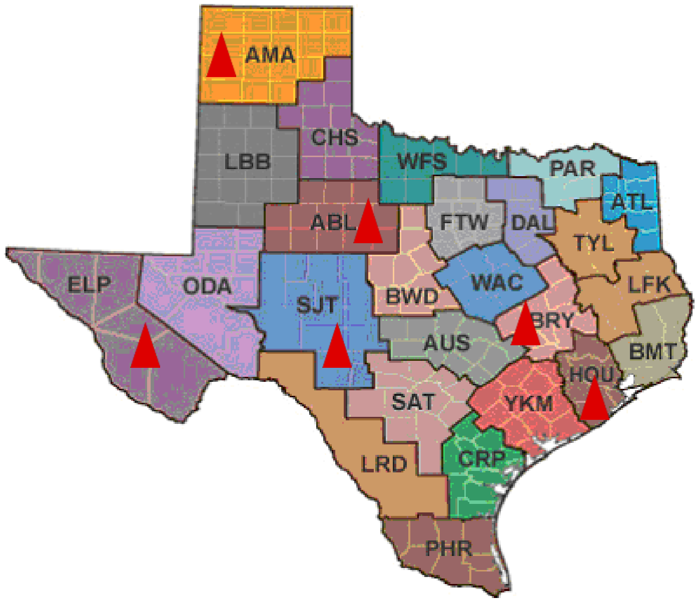
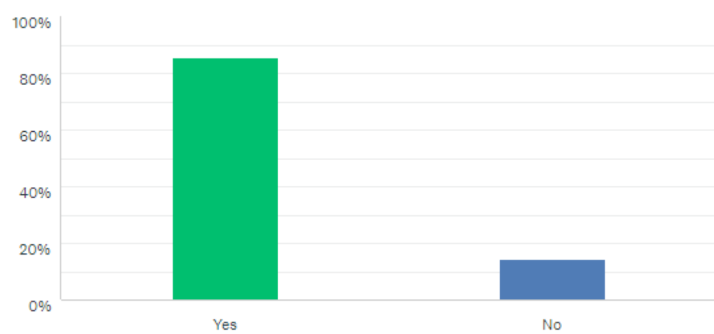


Figure 17. Respondents' Geolocation Distribution in Six TxDOT Districts as were marked in Red Triangles.

2.2.2.2 On the Experience of High Wind

The majority (85.71%) of the respondents experience high wind in their districts, as were shown in Figure 18.

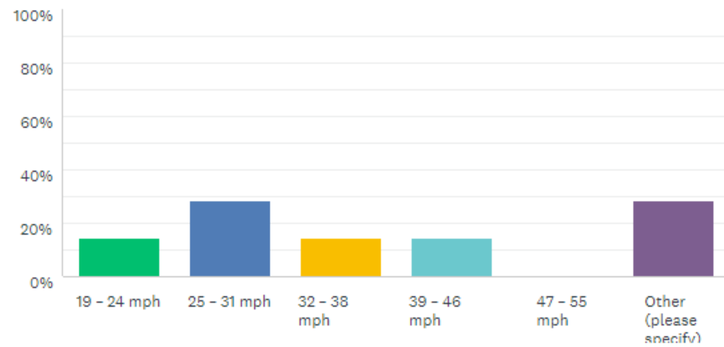


ANSWER CHOICES	RESPONSES	
Yes	85.71%	6
No	14.29%	1
Total Respondents: 7		

Figure 18. A total of 85.71% of the Respondents Experienced High Wind in their Districts.

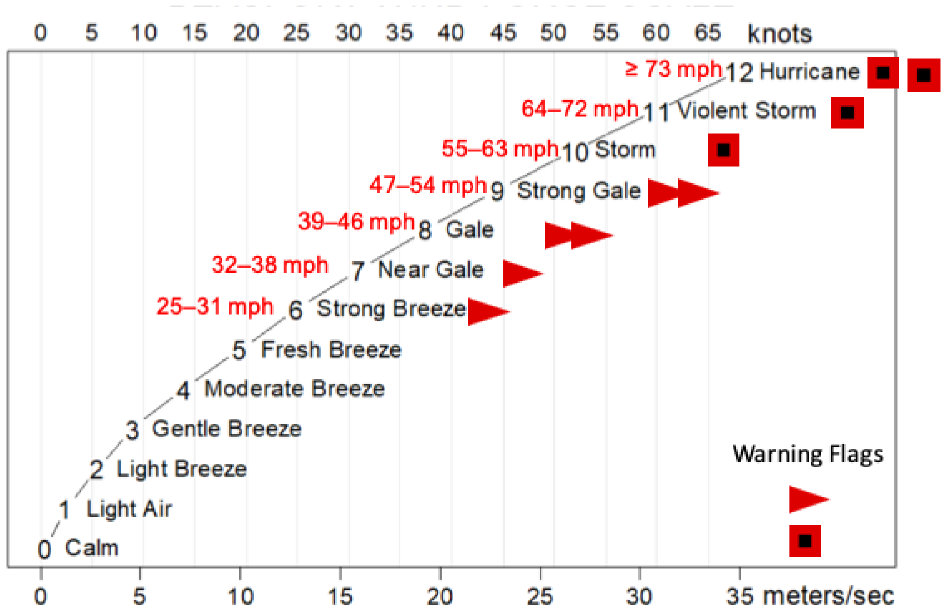
2.2.2.3. On the Definition of High Wind

The responses regarding the definition of high wind varied across all responded districts (Figure 19). The most common range of High Wind from the survey was 25-31 mph. This is within scale 6 of the Beaufort Wind Scale, which is illustrated in Figure 20. A wind with scale 6 is called “Strong Breeze”, which is also a level that needs “Warning Flags” on.



ANSWER CHOICES		RESPONSES	
19 – 24 mph		14.29%	1
25 – 31 mph		28.57%	2
32 – 38 mph		14.29%	1
39 – 46 mph		14.29%	1
47 – 55 mph		0.00%	0
Other (please specify)	Responses	28.57%	2
TOTAL			7

Figure 19. The Definition of High Wind from the Survey Results.



Beaufort Wind Scale

0	1	2	3	4	5	6	7	8	9	10	11	12
Calm	Light Air	Light Breeze	Gentle Breeze	Moderate Breeze	Fresh Breeze	Strong Breeze	Near Gale	Gale	Strong Gale	Storm	Violent Storm	Hurricane Force
Light Winds						Advisory-force		Gale-force		Storm-force		Hurricane-force
<1 mph <1 knot <0.3 m/s	1–3 mph 1–3 knots 0.3–1.5 m/s	4–7 mph 4–6 knots 1.6–3.3 m/s	8–12 mph 7–10 knots 3.4–5.5 m/s	13–18 mph 11–16 knots 5.5–7.9 m/s	18–24 mph 17–21 knots 8.0–10.7 m/s	25–31 mph 22–27 knots 10.8–13.8 m/s	31–38 mph 28–33 knots 13.9–17.1 m/s	39–46 mph 34–40 knots 17.2–20.7 m/s	47-54 mph 41–47 knots 20.8–24.4 m/s	55–63 mph 48–55 knots 24.5–28.4 m/s	64–72 mph 56–63 knots 28.5–32.6 m/s	≥73 mph ≥63 knots ≥32.7 m/s

Figure 20. The Beaufort Wind Force Scale

2.2.2.4 The Months Experiencing High Wind

The most respondents experience high wind in March to June, as is illustrated in Figure 21.

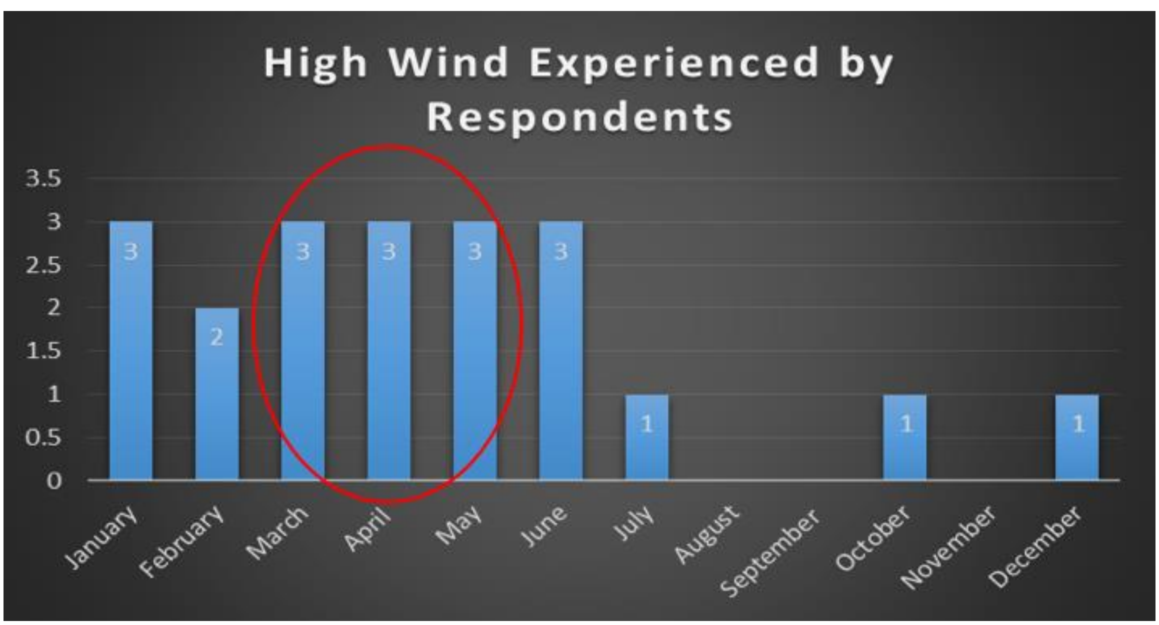


Figure 21. The Months Experiencing High Wind

2.2.2.5 If High Wind Affects Ballasted Temporary Signs in Work Zone

All respondents (100%) found that, the high wind affected ballasted temporary signs on work zones in their districts.

2.2.2.6. Evaluation of the 11 Signs from Survey

The evaluations of the 11 signs in the survey were based on three criteria in the survey: (1) Setup and mobility; (2) Performance; and (3) Safety. The evaluation results are listed in Figures 22-32, respectively.

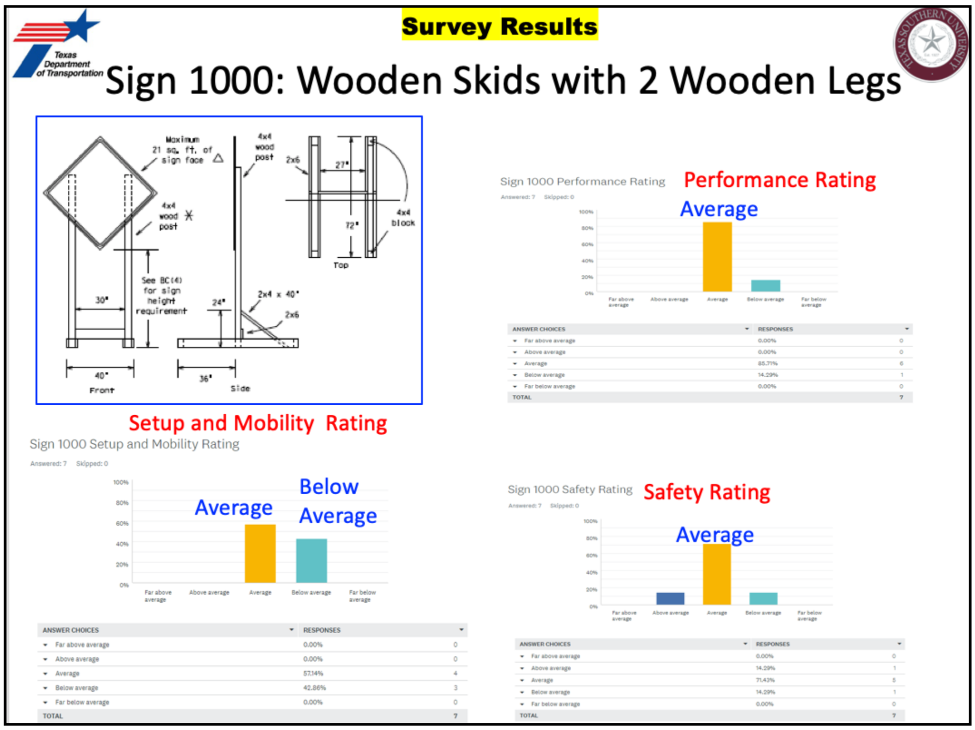


Figure 22. Evaluation Results on Sign 1000 from Survey

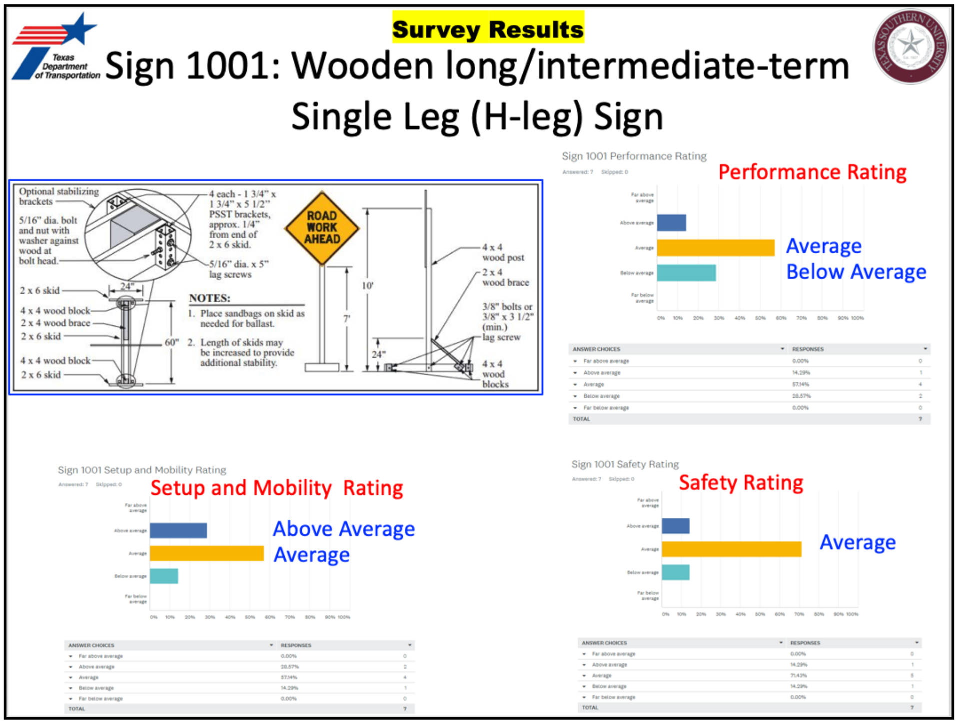


Figure 23. Evaluation Results on Sign 1001 from Survey

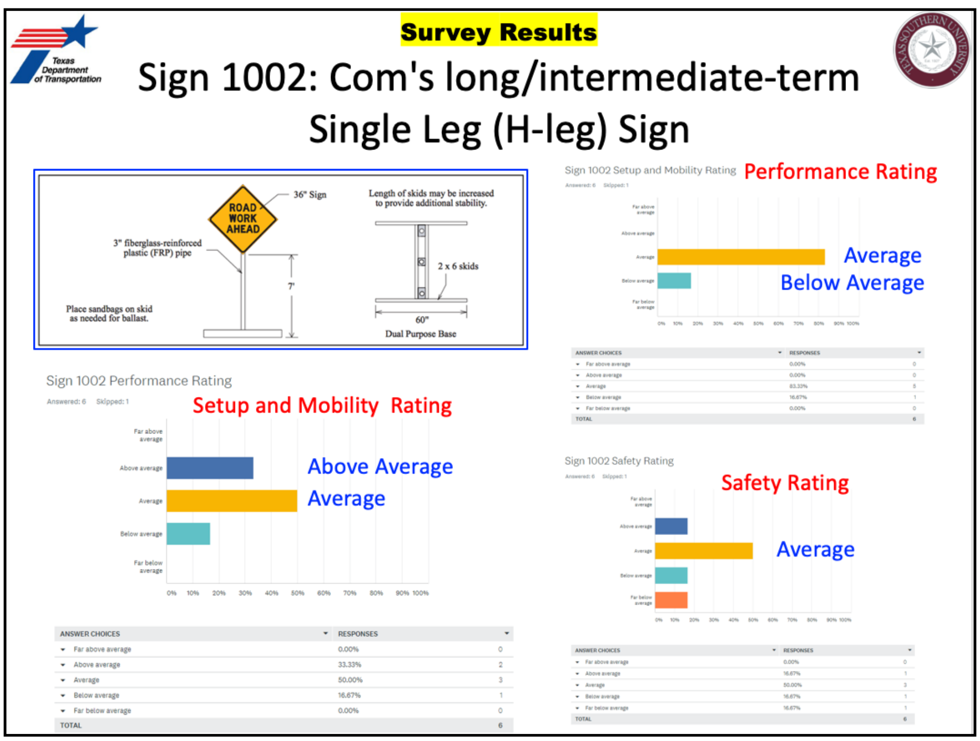


Figure 24. Evaluation Results on Sign 1002 from Survey

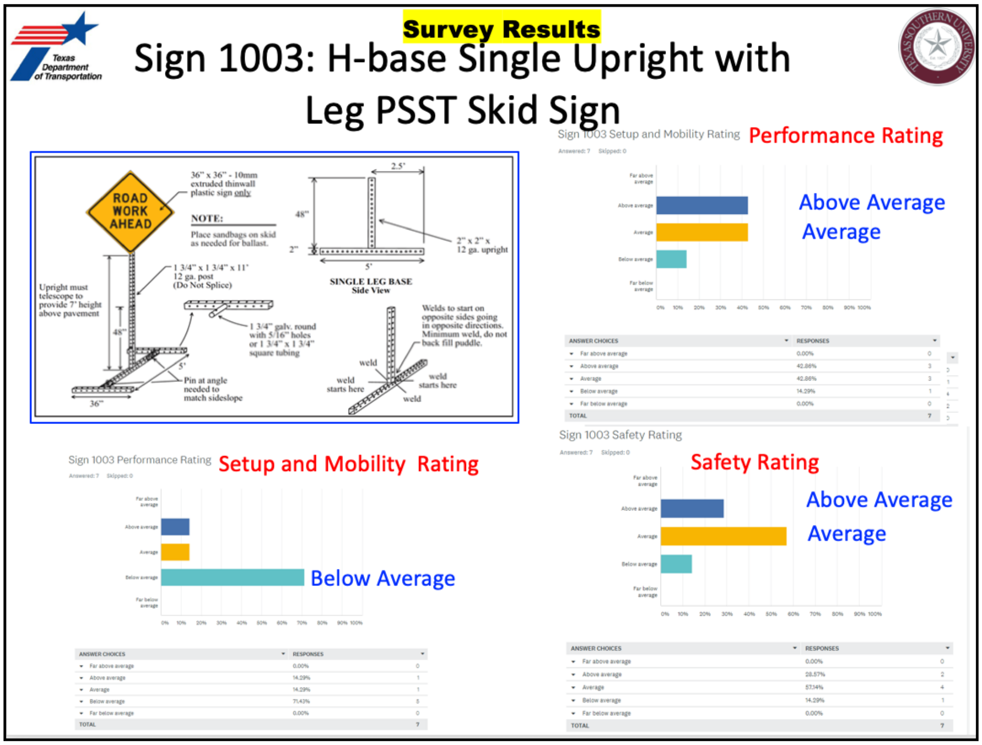


Figure 25. Evaluation Results on Sign 1003 from Survey

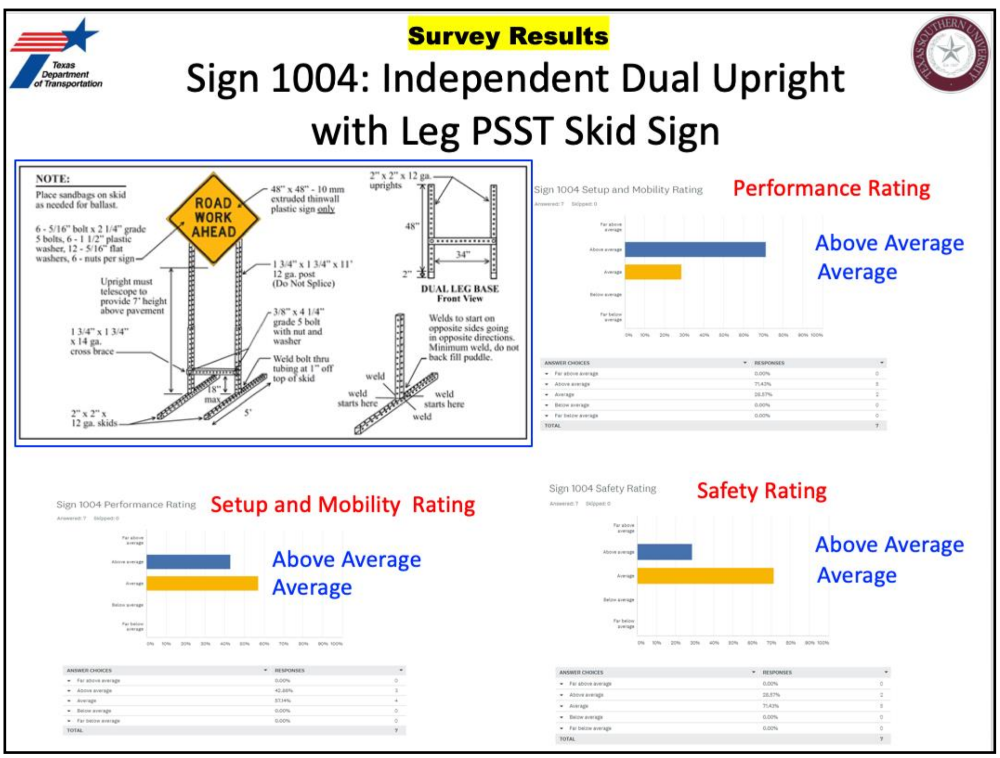


Figure 26. Evaluation Results on Sign 1004 from Survey

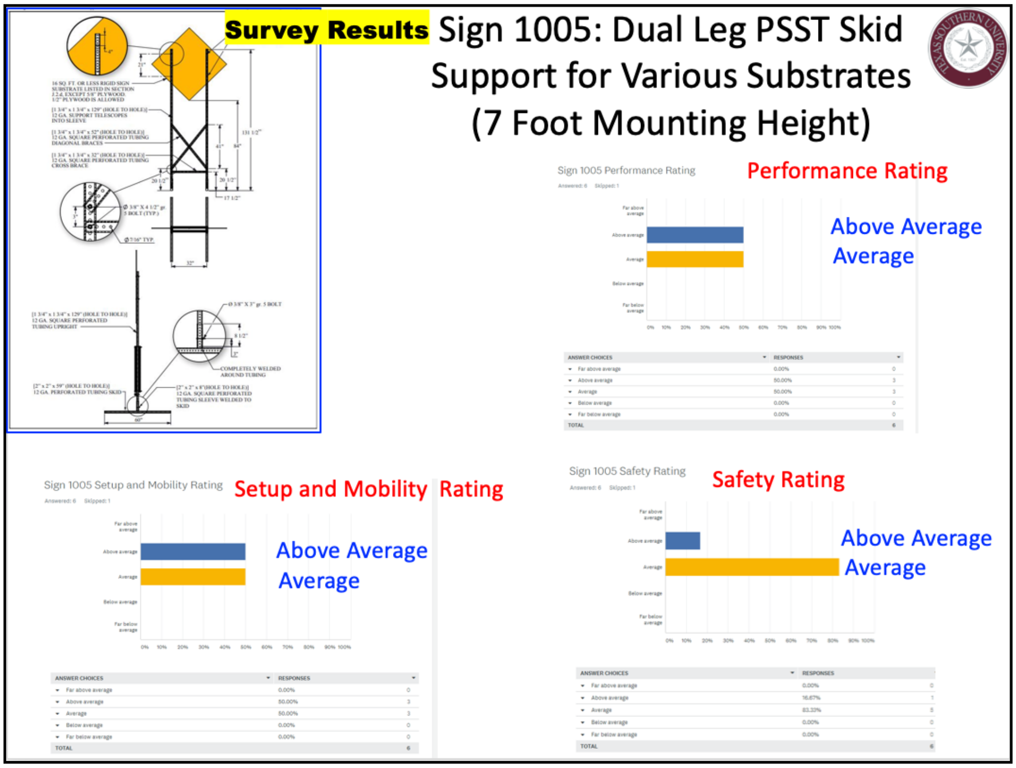


Figure 27. Evaluation Results on Sign 1005 from Survey

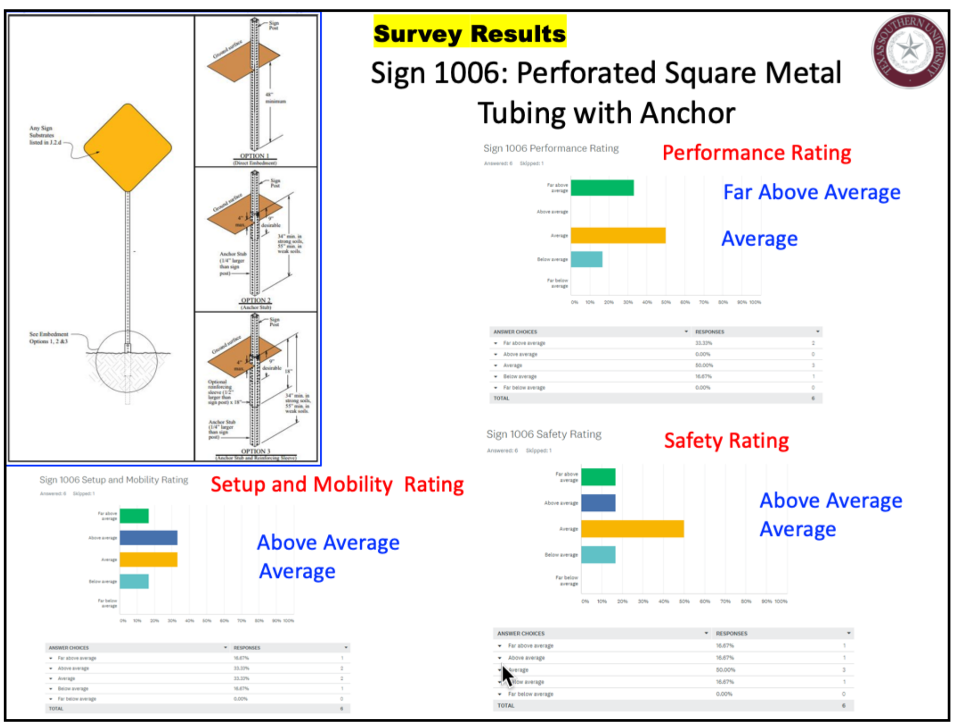


Figure 28. Evaluation Results on Sign 1006 from Survey

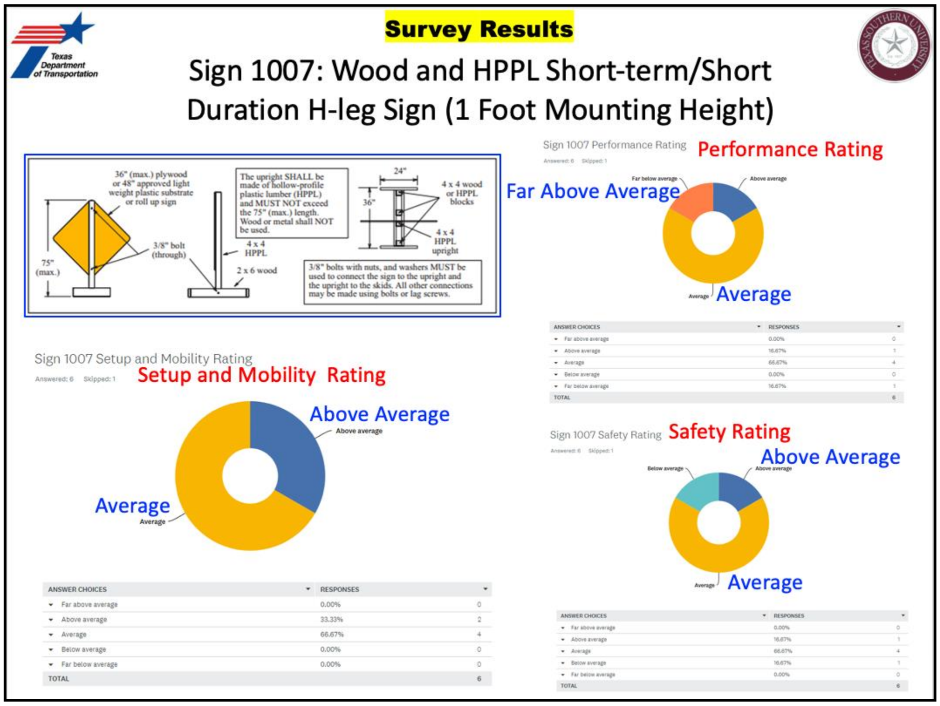


Figure 29. Evaluation Results on Sign 1007 from Survey

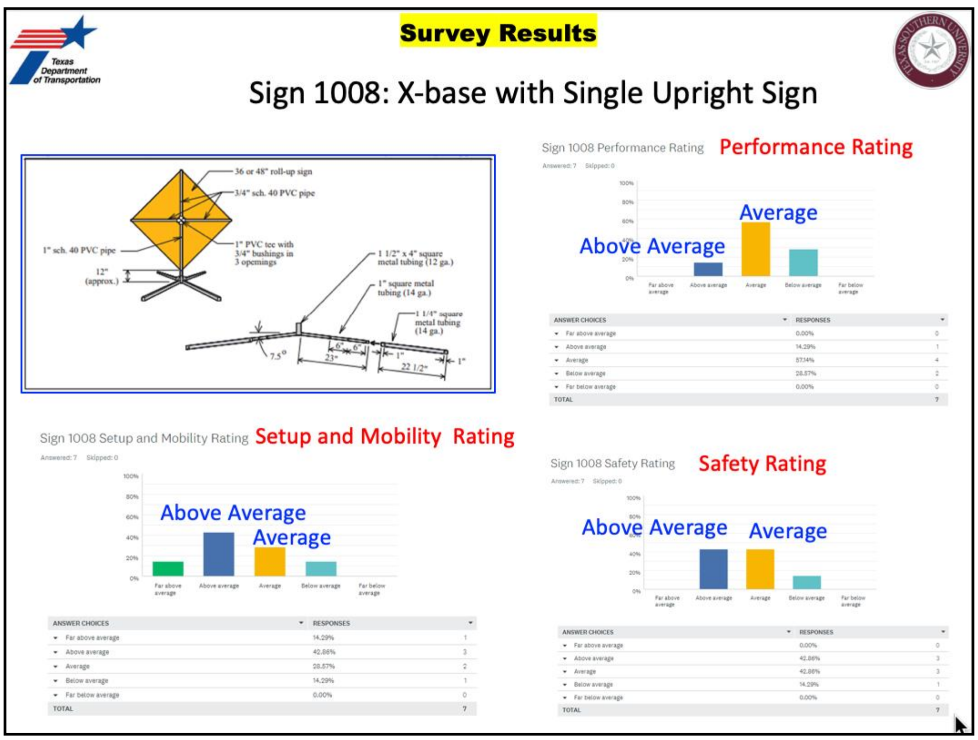


Figure 30. Evaluation Results on Sign 1008 from Survey

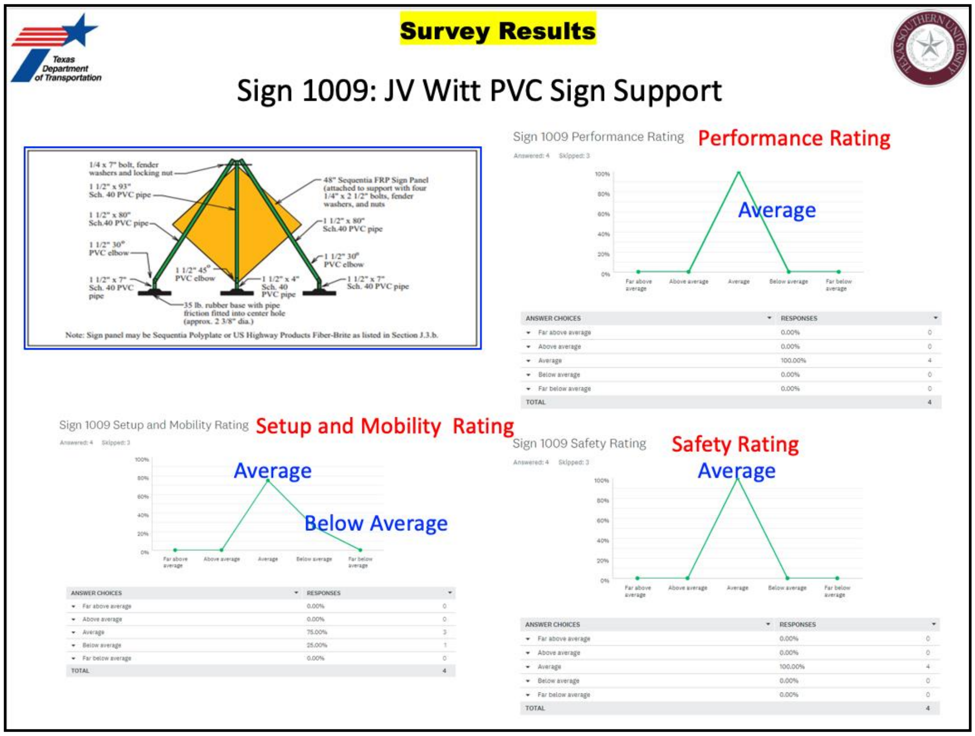


Figure 31. Evaluation Results on Sign 1009 from Survey

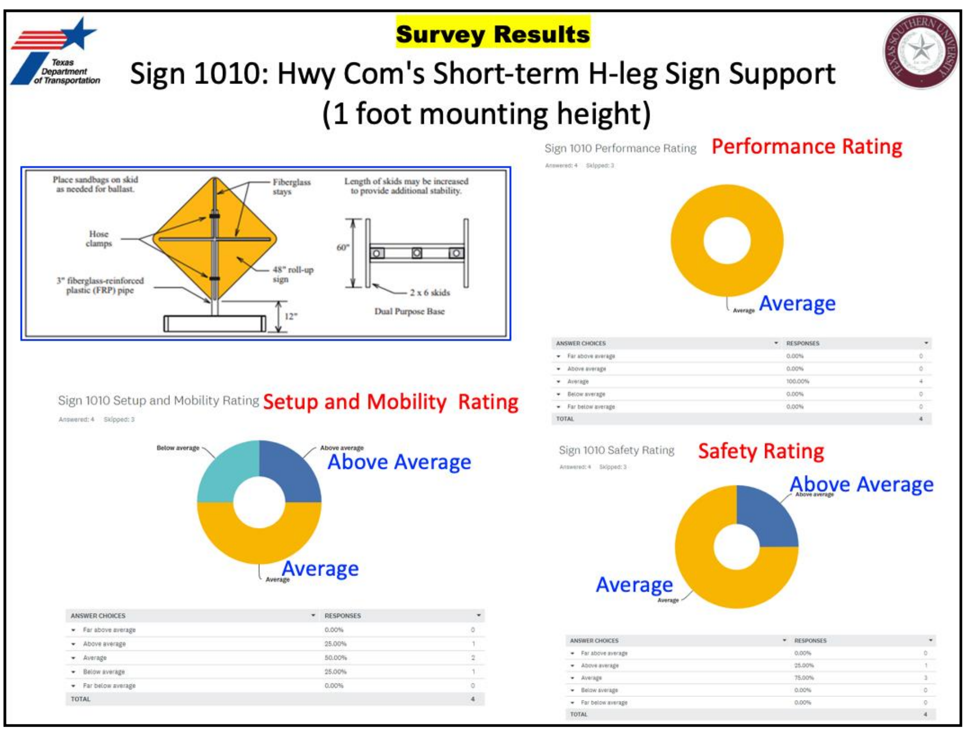


Figure 32. Evaluation Results on Sign 1010 from Survey

2.2.2.7 Methods to Modify Work Zone Sign Supports

The methods suggested from the engineers to modify work zone sign supports include:

(1) Restricting the use of certain supports in high wind districts (6/7)

(2) Using modified sign supports in work zones (5/7)

(3) Using more sandbags/ballasting (4/7)

2.2.2.8 New Technology and/or Materials in Temporary Sign Support Currently Not in Use by TxDOT

Based on the survey, there was one respondent is aware of technology/materials in temporary sign supports currently not in TxDOT, which is the half circle cuts to allow wind to pass through.

2.2.3 Survey Analysis

The evaluation scores in section 2.2.2 were summarized and further calculated in Table 2.

Table 2. Sign Evaluation Results from Survey

Sign Code	Sign Name	Set Up and Mobility Rating	Performance Rating	Safety Rating	Average
1000	Wooden Skids with 2 Wooden Legs	2.57	2.86	3.00	2.81
1001	Wooden long/intermediate-term Single Leg (H-leg) Sign	3.14	2.86	3.00	3.00
1002	Com's long/intermediate-term Single Leg (H-leg) Sign	3.17	2.83	2.67	2.89
1003	H-base Single Upright with Leg PSST Skid Sign	2.43	3.29	3.14	2.95
1004	Independent Dual Upright with Leg PSST Skid Sign	3.43	**3.71**	**3.29**	**3.48**
1005	Dual Leg PSST Skid Support for Various Substrates (7 Foot Mounting Height)	**3.50**	**3.50**	3.17	**3.39**
1006	Perforated Square Metal Tubing with Anchor	**3.50**	**3.50**	3.33	**3.44**
1007	Wood and HPPL Short-term/Short Duration H-leg Sign (1 Foot Mounting Height)	3.33	2.83	3.00	3.06
1008	X-base with Single Upright Sign	**3.57**	2.86	3.29	**3.24**
1009	JV Witt PVC Sign Support	2.75	3.00	3.00	2.92
1010	Hwy Com's Short-term H-leg Sign Support (1 foot mounting height)	3.00	3.00	3.25	3.08

The results from the evaluation of all 11 TxDOT temporary signs showed that, there are four signs being the most reliable ones with the highest average scores. They were selected for further practical evaluation, and these signs are: Sign 1004, Sign 1005, Sign 1008, and Sign 1006.

Though the team would continue to evaluate the perforated steel supports which happens to be the top ones rather than include one of the wooden sign supports by swapping (Sign 1008: X-base with single upright) for a wooden sign to have good base line which further validate the work, as the wooden signs would fail miserably in some districts, such as those in the northern part of Texas.

2.3. Field Observation

The field observation shall be formally conducted once the modified contract is in effect, and the high wind comes to any of the candidate districts. The performing agency has prepared a test plan, which was approved by the PMC and the Project director already.

2.3.1 Test Plan

2.3.1.1 Testing Objectives

- Evaluate existing ballasting technologies or materials
- Apply the newly suggested technologies or materials and observe while using cameras and wind speed detectors
- Overturning check (Conduct an overturning check to test the reliability)

2.3.1.2 District Selection

TxDoT Districts selected for the field observation were considered and picked at the project progress meeting on February 4, 2019, between the TSU project team and the TxDOT PMC. Figure 33 illustrates the wind distribution in Texas, where the highest average wind speed occurs in middle and northern part of Texas. The newly added three districts (SJT, AMA, LBB) are all within such high wind regions (Figure 34).

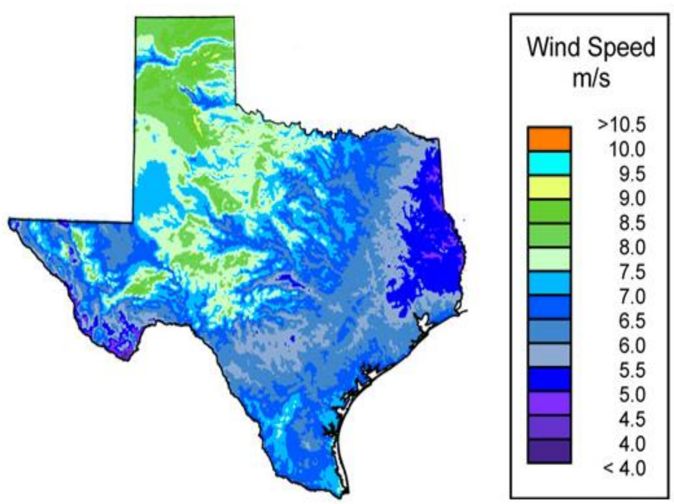


Figure 33. Texas Annual Average Wind Speed Distribution

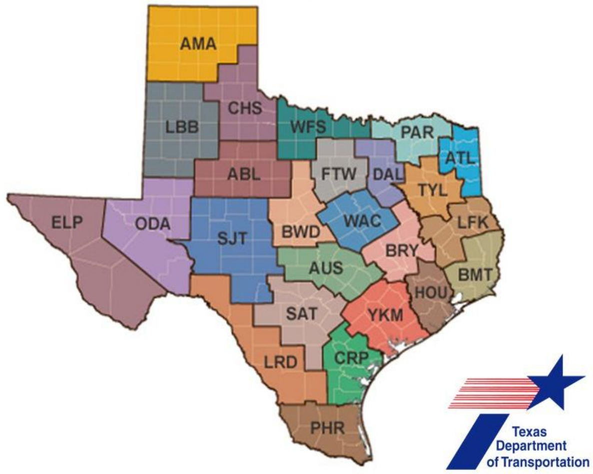


Figure 34. TxDOT Districts, where SJT, AMA, and LBB districts are within the High Wind Regions in Figure 33.

The site observation is to be carried out by the performing agency TSU with the helps from the performing agency TxDOT.

2.3.1.3 Testing Activities

Based on the testing objectives, the performing agency designed a test plan in three TxDOT districts (SJT, AMA, and LBB). Besides, the performing agency shall watch the weather report and find suitable high wind days to conduct similar tests in HOU district.

As the high wind in relevant districts might be intermittent and do not typically last for several days, the research team designed two schedule plans in Tables 3 and 4. Table 3 is the schedule plan to conduct all tests via one travel; while Table 4 is another schedule plan to conduct all tests via two travels (one for SJT district only, and the other one for AMA and LBB districts).

Table 3. Test Schedule Plan to Conduct all Tests through one Travel

Date	TSU Team Activities	Note
Day 1	Departure from Houston	
Day 2	Arriving at San Angelo	
Day 3	Visit SJT Engineers Visit the Test Site/Open field Setup Signs and Other Equipment Initiate Performance Test of signs in high wind in SJT district	Leave signs on test site(s) through the night
Day 4	Performance Test Continues Take Down Signs and Equipment	
Day 5	Departure from San Angelo to Amarillo	
Day 6	Visit AMA Engineers Visit the target field and signs in AMA district Initiate Performance Test of signs in high wind in AMA district	Leave signs on test site(s) through the night
Day 7	Continue field test in AMA district	
Day 8	Continue field test in AMA district	
Day 9	Continue field test in AMA district Take Down Signs and Equipment	
Day 10	Departure from Amarillo to Lubbock Visit LBB Engineers Visit the target field and signs in LBB district Initiate Performance Test of signs in high wind in LBB district	Leave signs on test site(s) through the night
Day 11	Continue field test in LBB district	
Day 12	Continue field test in LBB district Take Down Signs and Equipment	
Day 13	Departure from Lubbock	
Day 14	Arriving at Houston	

Table 4. Test Schedule Plan to Conduct all Tests through two Travels

	Date	TSU Team Activities	Note
Trip 1	**Day 1**	Departure from Houston	
	Day 2	Arriving San Angelo	Leaving signs on test site(s) through the night
	Day 3	Visit SJT Engineers Visit the Test Site/Open field Setup Signs and Other Equipment Initiate Performance Test of signs in high wind in SJT district	
	Day 4	Performance Test Continues Take Down Signs and Equipment	
	Day 5	Departure from San Angelo and back to Houston	
Trip 2	**Day 1**	Departure from Houston	
	Day 2	Arriving Amarillo Visit AMA Engineers Visit the target field and signs in AMA district Initiate Performance Test of signs in high wind in AMA district	Leaving signs on test site(s) through the night
	Day 3	Continue field test in AMA district	
	Day 4	Continue field test in AMA district Take Down Signs and Equipment	
	Day 5	Departure from Amarillo to Lubbock Visit LBB Engineers Visit the target field and signs in LBB district Initiate Performance Test of signs in high wind in LBB district	Leaving signs on test site(s) through the night
	Day 6	Continue field test in LBB district	
	Day 7	Continue field test in LBB district Take Down Signs and Equipment	
	Day 8	Departure from Lubbock	
	Day 9	Arriving at Houston	

2.3.1.4 Equipment to Prepare

The package of testing equipment to prepare shall include:

- Wind speed meter

- Video camera, tripods, and accessories (batteries and memory cards)
- Phone chargers
- Construction hard hat and safety vest
- Laptop for recording tests data

2.3.1.5 Candidate Signs to Test

Four types of signs are selected to test, as are illustrated in Figure 35, which are:

- Sign 1004: Independent dual upright with leg PSST skid sign
- Sign 1005: Dual leg PSST skid support for various substrates (7-foot mounting height)
- Sign 1006: Perforated Square Metal Tubing with Anchor
- Sign 2000: Portable sign stand

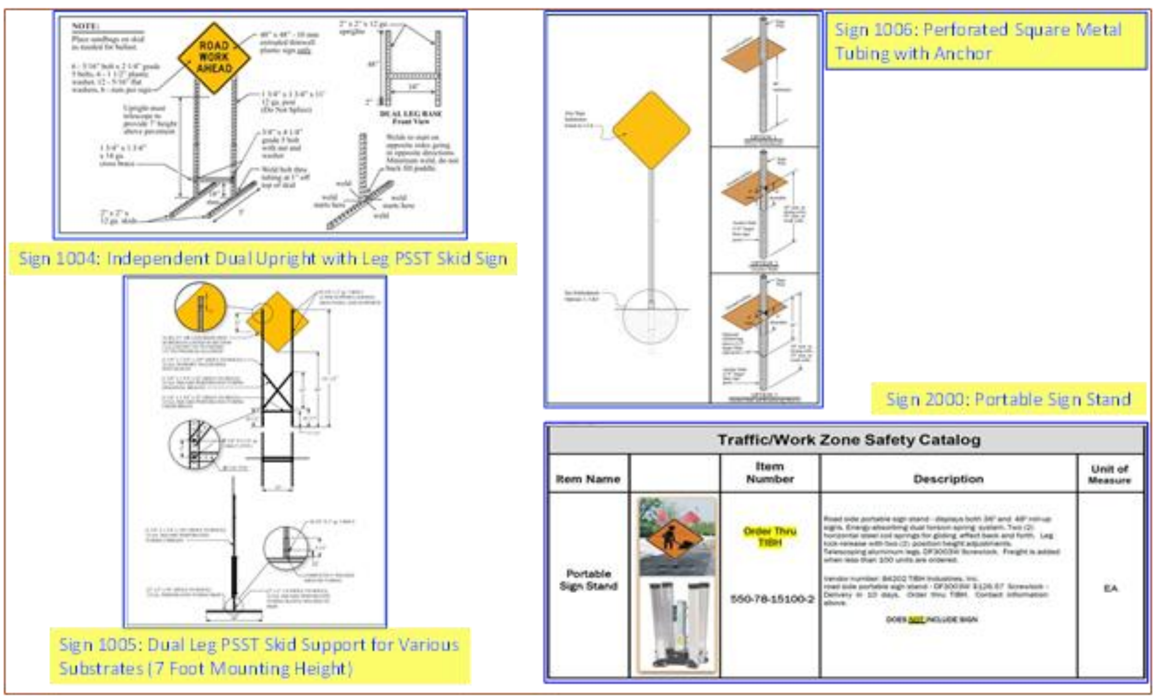


Figure 35. Illustration of Candidate Signs to Test

2.3.2 Field Observation in Texas

Field observation in Texas is introduced in the following eight sections, including: (1) candidate signs to observe, (2) site selection, (3) chasing the high wind, (4) equipment preparation of field observation, (5) observation process of temporary traffic signs, (6) performance check of temporary signs, (7) on-site interview with traffic engineer, and (8) other popular temporary signs.

2.3.2.1 Candidate Signs to Observe

Based on the survey and discussion with the project PMC members, four types of temporary traffic signs have been spotted out. These four kinds of temporary traffic signs are what we should pay more attention to in field observations and cost evaluations, which are:

1) Sign 1004: Independent Dual Upright with Leg PSST Skid Sign (shown in Figure 36);
2) Sign 1005: Dual Leg PSST Skid Support Sign (shown in Figure 37);
3) Sign 1006: Perforated Square Metal Tubing with Anchor Sign (shown in Figure 38);
4) Sign 1008: X-base with Single Upright Sign (shown in Figure 39).

Figures 36-39 indicate the structure, material, size, and installation guidance of the four relevant temporary traffic signs.

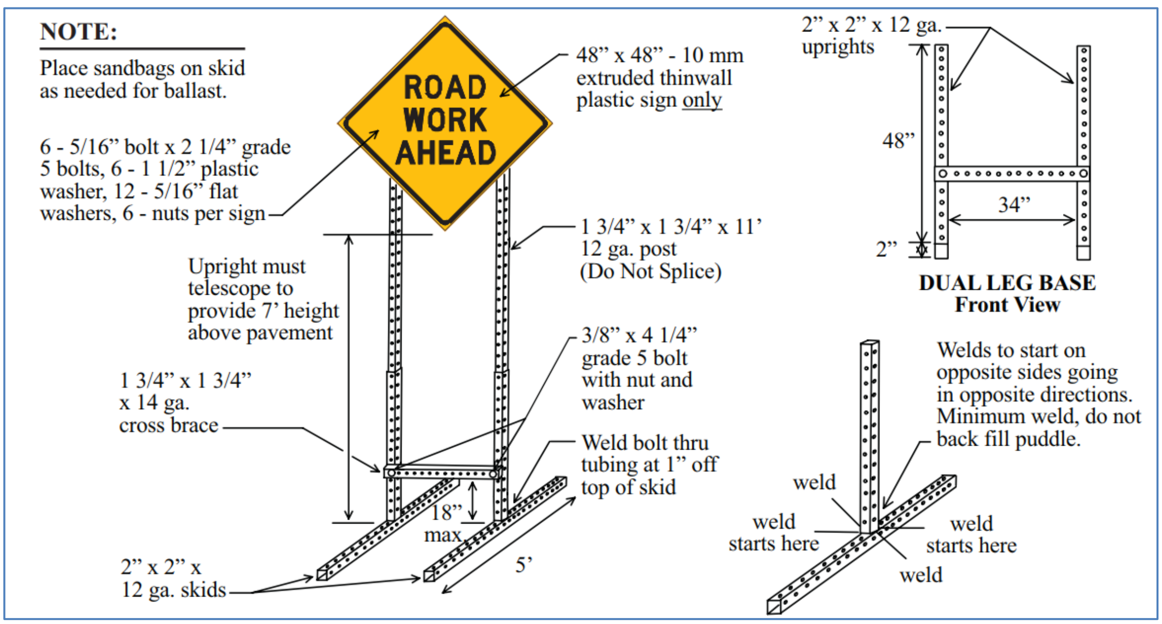


Figure 36. Sign 1004: Independent Dual Upright with Leg PSST Skid Sign

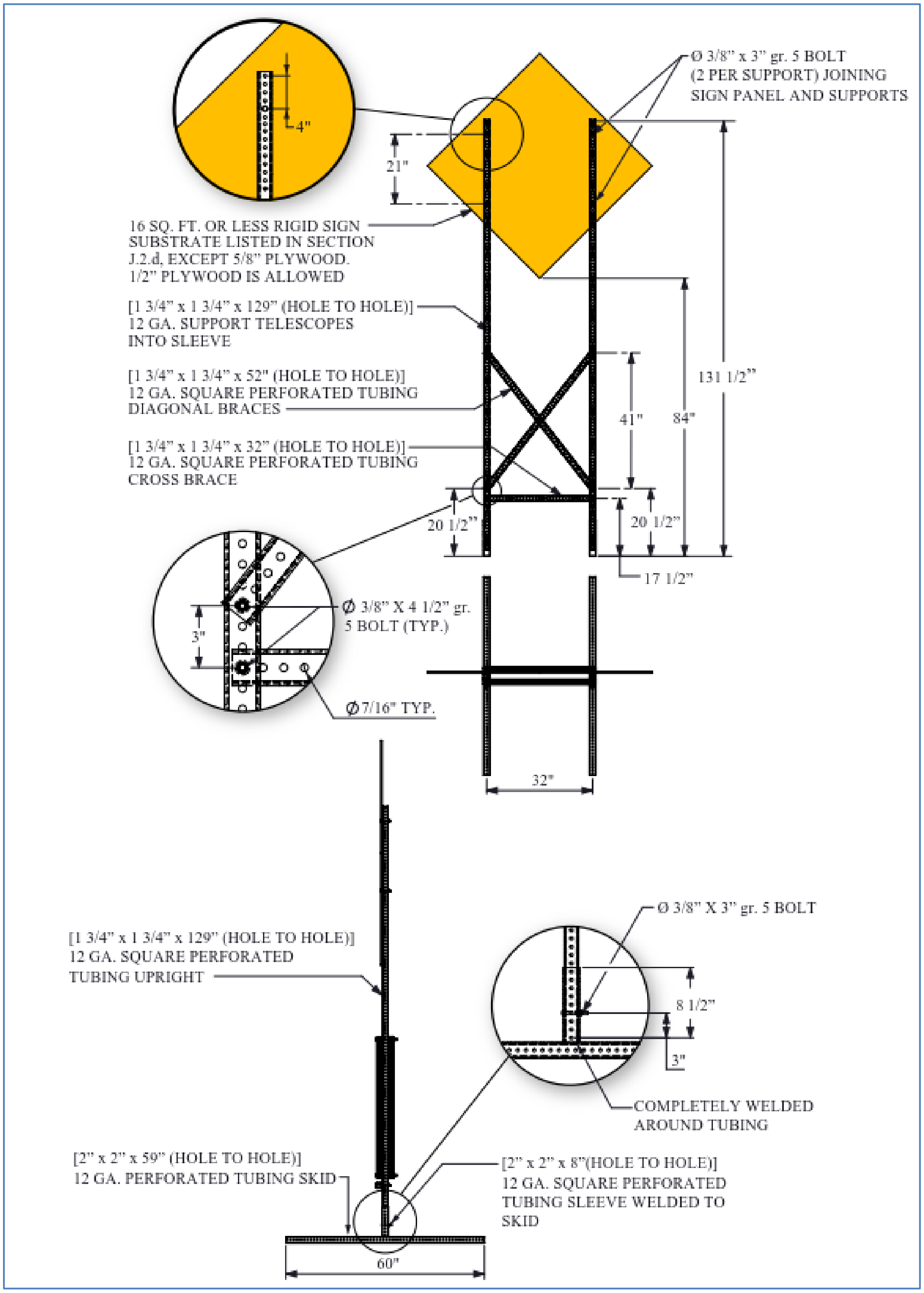


Figure 37. Sign 1005: Dual Leg PSST Skid Support Sign

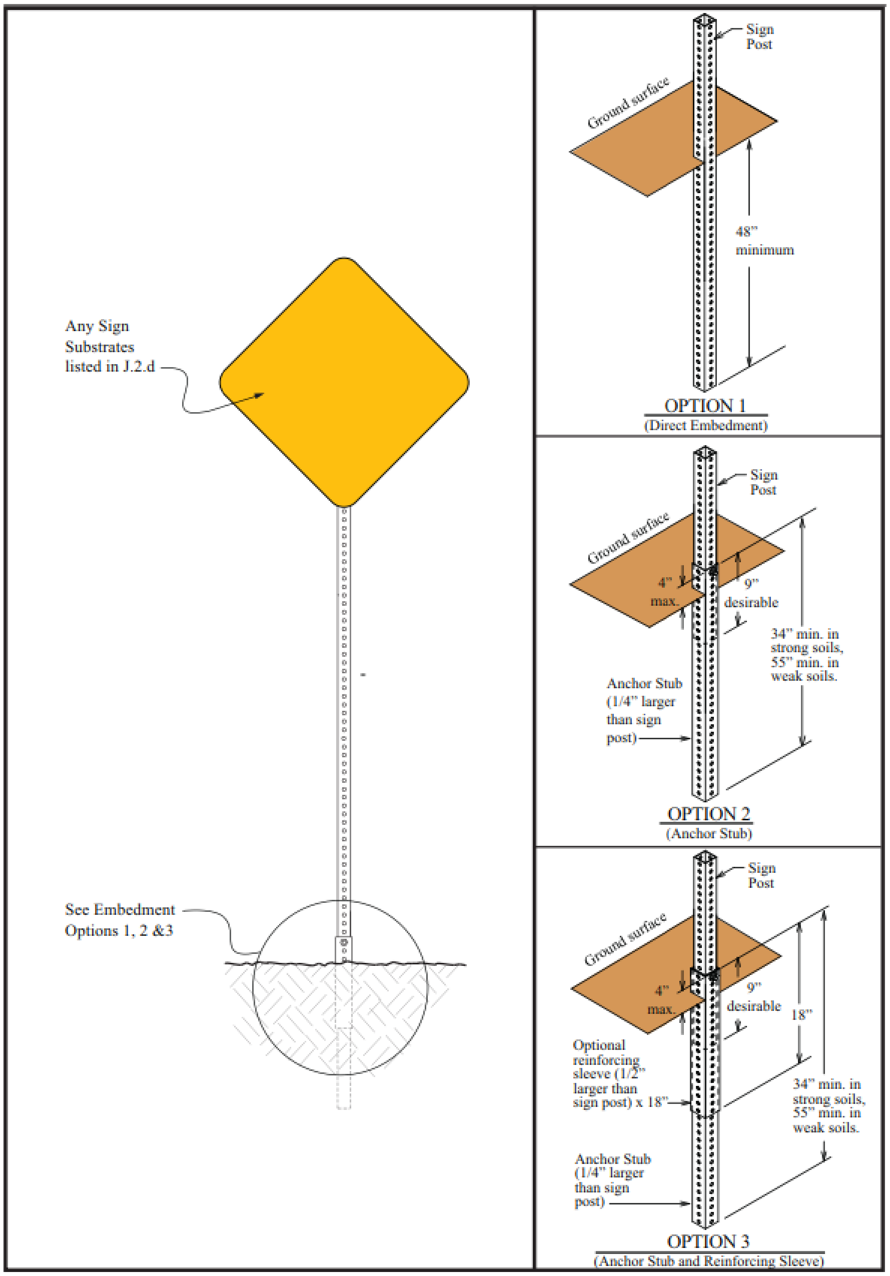


Figure 38. Sign 1006: Perforated Square Metal Tubing with Anchor Sign

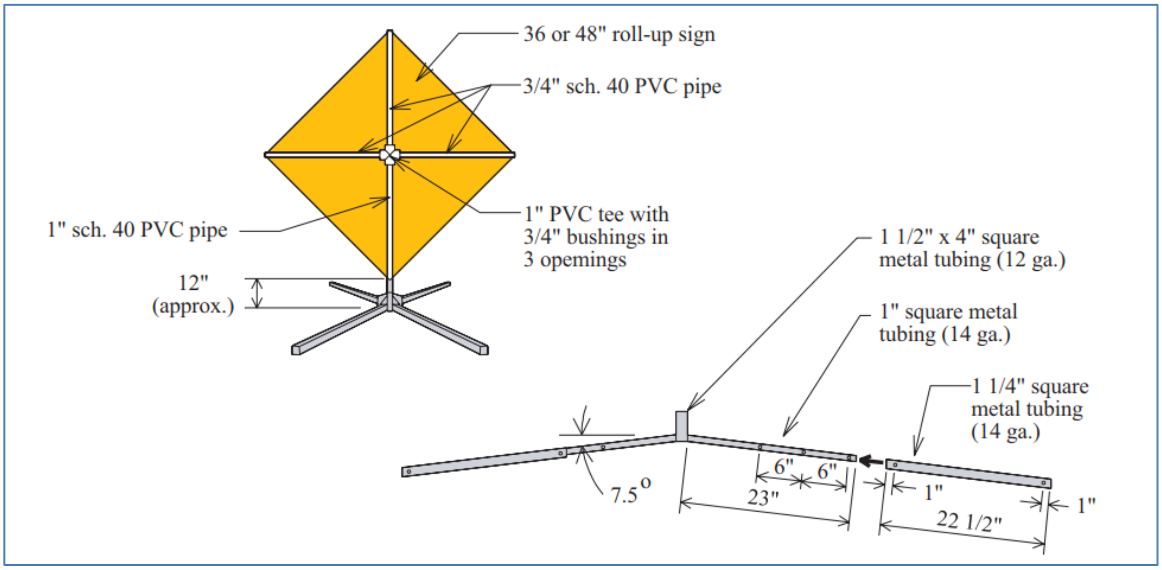


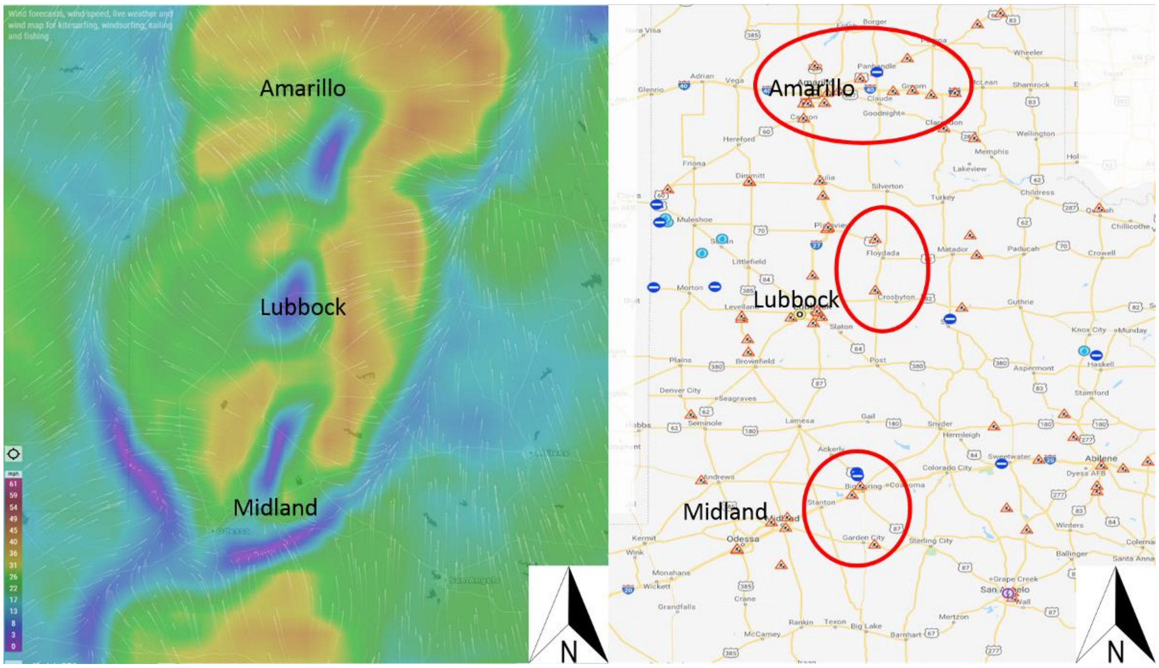
Figure 39. Sign 1008: X-base with Single Upright Sign

2.3.2.2 Site Selection

An idea site for field observation should include two conditions: (1) with high wind, and (2) with work zones. The wind forecast is referred from the website https://www.windfinder.com/#7/32.8150/-100.6787, where wind forecast is provided four times a day at 5:30am, 11:30am, 5:30pm, and 11:30pm.

The Texas work zone information is obtained from the website: https://drivetexas.org/#/7/32.340/-99.500?future=false, which illustrates the active construction areas in Texas. An area with both high wind and work zone is selected as a test site for observation.

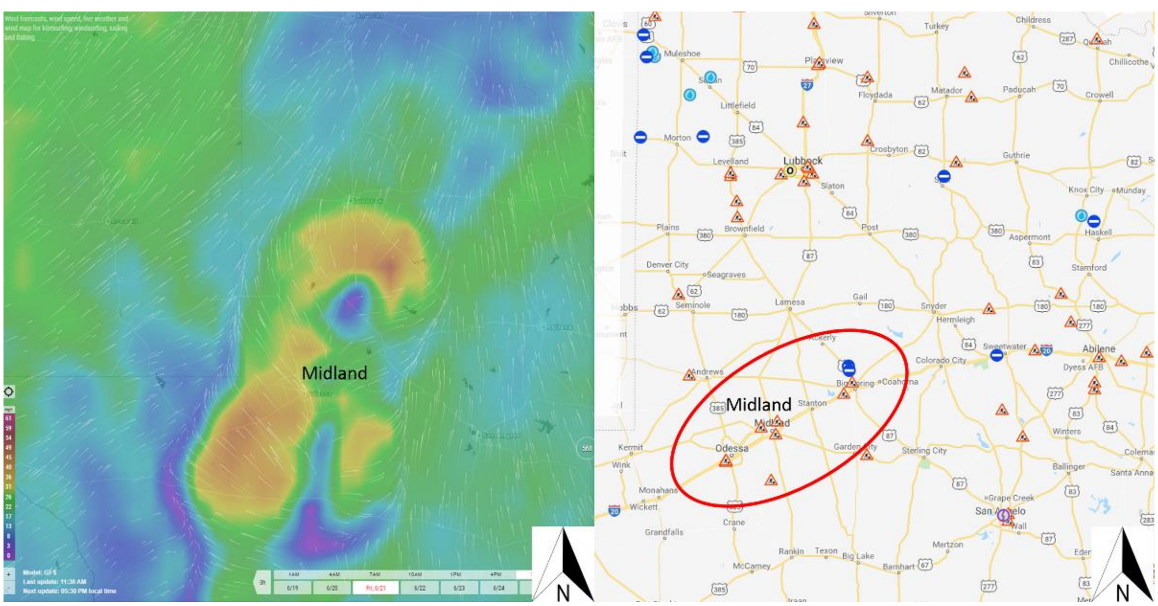
For instance, the yellow and orange color areas (east and west part of Midland, east of Lubbock, and north and east of Amarillo) in Figure 40(a) are with higher wind (>30 mph) at the moment that this wind map is forecasting, while the triangular areas in Figure 5(b) are active work zones in the relevant areas. Both Figure 40(a) and Figure 40(b) were retrieved at 4:00pm of June 18, 2019, with the wind forecast for 7:00pm, June 21, 2019.



a. Wind Forecast Map b. Work Zone Map

Figure 40. One Exemplary Site for Observation with both High Wind and Work Zones are matched in Midland, Lubbock, and Amarillo within State of Texas

Another case is illustrated in Figure 41(a) which was recorded at 4:00pm of on June 19, 2019, with the wind forecast for 7:00pm, June 21, 2019. The relevant work zones selected for testing from Figure 41(b) are in the north, west and southeast parts of Midland, Texas.



a. Wind Forecast Map b. Work Zone Map

Figure 41. Another Exemplary Site for Observation with both High Wind and Work Zones are matched in Midland, State of Texas

It should be pointed out that, the wind forecast map is always changing. It can only predict the approximate trajectory of high winds. Sometimes, the research team followed the forecasting high wind to have almost reached the target work zone, but the wind forecasting changed it prediction a couple hour before the wind is coming. So, the research team often had to chase the high wind, sometimes with additional 80-100 miles driving during the last a couple of hours, so as to catch it in a work zone.

2.3.2.3 Chasing the High Wind in Texas

The wind forecast web updated every 6 hours. The high wind forecasts in Figure 40(a) or Figure 41(a) were actually changed in their next rounds of forecasts. Sometimes, the areas with high wind are not associated with active construction zones. All these issues impacted the field observations of work zone temporary traffic signs. Therefore, what we could do was to frequently check the wind forecast website and the work zone map, by chasing the high wind.

Based on the Wind Forecast and Texas Work Zone Map, performance observations of temporary traffic signs were conducted in Midland, Dallas, Fort Worth, Big Spring, San Angelo, San Antonio, Waco, and Houston. Such field observations were conducted through two journeys:

(1) Trip one with the route as: Houston → Midland → Big Spring → Fort Worth → Dallas → Waco → Houston, started on June 20, 2019 and end with June 23, 2019. The travel route map is shown in Figure 42.

2.3.2.4 Equipment for Field Observation

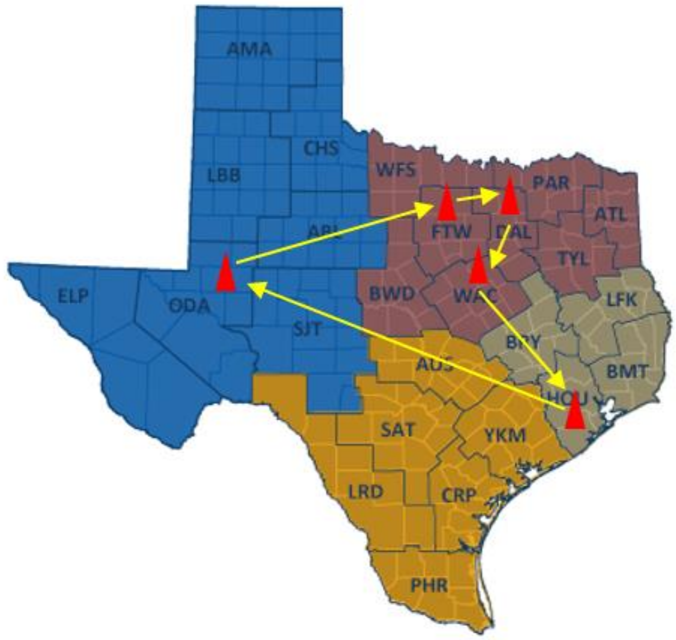


Figure 42. Travel Route of Trip One

(2) Trip two with the route as: Houston → Midland → San Angelo → San Antonio → Houston, started on June 24, 2019 and end on June 26, 2019. The travel route map is shown in Figure 43.

Figure 43. Travel Route of Trip Two

In field observations, the main equipment we used includes:

1) Wind speed meter and smart phone in Figure 44(a);
2) Video camera set in Figure 44(b);
3) Construction helmet in Figure 44(c); and
4) Laptop in Figure 44(d).

Among these equipment, the wind speed meter was used to measure the wind speed associated with the smart phone. A particular app named “Wind & Weather Meter” were downloaded in the smart phone. The video camera set includes video camera, SD cards, tripod, extra batteries, and other accessories. The video camera and smartphones were used to film and/or take pictures of the trembling of temporary traffic signs when the high winds were blowing on the traffic signs. The construction helmet was used to present any potential damage to human head during high winds. The laptop was used to record and arrange data collected from field observations.

a. Wind Speed Meter & Smart Phone

b. Video Camera Set

c. Construction Helmet

d. Laptop

Figure 44. Equipment for Site Observation

2.3.2.5 Observation Process of Temporary Traffic Signs

Every time we got a test site, the first thing was to visit and check the target field and temporary traffic signs within the target site before the high wind came. In field observations, two observers took part in the field test, including the project supervisor and his research assistant. When the high wind come, the team wore the construction helmets and prepared all relevant equipment (wind speed meter, smart phone, camera…). The wind speed meter and smart phone were placed in higher place for airs to flow through. The wind speed measurements would then show on the smartphone app. The performance of traffic signs in high winds were filmed by the video camera and pictured by smartphones. The stabilities of temporary traffic signs were the main performance that the research team observed. Various kinds of temporary traffic signs pictures in the test fields were token by the mart phone and camera. When the high wind passed, filed observations in a target field would then be completed.

After all the field observations in different test sites were conducted, the videos and pictures were processing and analyzed using laptops.

Table 5 indicates detailed day-to-day works of field observations.

Table 5. Test Diary to Observe performances of Temporary Traffic Signs with High Winds through two Trips

	Date	Activities	Note
Trip 1	6/20/2019	• Departed from Houston to Midland • Arrived at Midland, TX at 10:00pm (ODA District)	
	6/21/2019	• Visited the target field and signs in Midland, TX (at the east feeder of TX-250 North @ TX-349, and at TX-191 eastbound to the west side of TX-250) • Performance tested of signs before high winds arrive at Midland, TX • Performance tested of signs with high winds in Midland, TX	Wind speed was around 20-30 mph with some gust more than 30 mi/hr.
	6/22/2019	• Departed from Midland, TX to Fort Worth, TX where high wind was forecasted to be high • Visited the target field and signs in FTW and DAL districts • Performance tested of signs with high winds in FTW and DAL districts	Conduct field test in FTW district firstly, and then DAL district secondly
	6/23/2019	• Departed from Dallas, TX to Waco, TX • Arrived at Waco, TX • Visited the target field and signs in WAC district • Performance tested of signs with high wind in WAC district • Departed from Waco, TX to Houston, TX • Arriving at Houston, TX	

	Date	Activities	Note
Trip 2	6/24/2019	• Departed from Houston, TX to San Angelo, TX • Arrived at San Angelo, TX, and then moved to Bronte, TX, then to Midland, TX to catch the changed high wind locations • Arriving at Midland (9:00pm) • Visit the target field and signs in Midland, TX (ODA District) • Performance tested of signs with high wind in Midland, TX	High wind moved from San Angelo, TX to Bronte, TX, then to Midland, TX
	6/25/2019	• Departed from Midland, TX to Junction, TX (SJT District) • Arrived at Junction, TX • Visited the target field and signs in SJT district • Performance tested of signs in high wind in SJT district • Interviewed traffic engineer in Junction Area Office of SJT District • Departed from Junction, TX to San Antonio, TX • Arrived at San Antonio, TX (SAT District)	
	6/26/2019	• Visited the target field and signs in SAT district • Performance tested of signs in SAT district • Departed from San Antonio, TX to Houston, TX • Arrived at Houston, TX	

All kinds of temporary traffic signs appeared in the various field observation location showed as Figure 45(a) to (l), which is more than four types of main traffic signs. All these temporary traffic signs were usually used to be placed on the sides of street roads and highways.

(a) Sign 1005 in Midland, TX

(b) Sign 2000 in Midland, TX

(c) Sign 1003 in Midland, TX

(d) Sign 1008 in Big Spring, TX

(e) Sign 1004 in Midland, TX

(f) Sign 1008 in San Antonio, TX

(g) Sign 1003 in Fort Worth, TX

(h) Sign 1006 in Dallas, TX

(i) Sign 1001 in Waco, TX

(j) Sign 2000 in Dallas, TX

(k) Sign 1000 in Junction, TX

l. Sign 1005 in Houston, TX

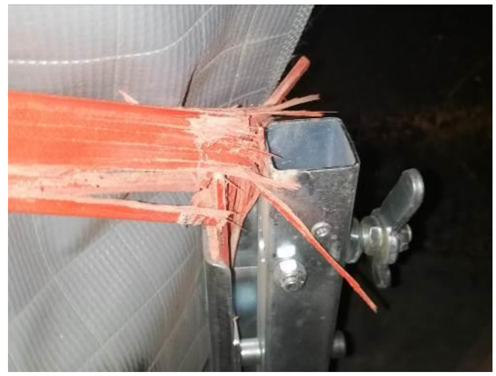
Figure 45. Tested Temporary Traffic Signs in Various Work Zones in Texas

2.3.2.6 Performance check of Temporary Signs

The stability and wind resistance ability are the most important factor in the process of performance check of temporary traffic signs. There are many performances that traffic signs appeared with high winds in field observations, which includes main body trembling, partial damage like traffic sign broke and loosen nut, main body broke, etc.

Figure 46(a) and 46(b) indicate the damages caused by a high wind in Midland, TX (along the Westbound of highway TX-191, about one mile away from the west of North TX-250). Figure 46(a) displays that, a traffic sign (code: 1008) fell down due to the high wind. Figure 46(b) displays location where the main body of sign 1008 was broken.

(a) Traffic Sign 1008 Fall Down



(b) Traffic Sign 1008 Main Body Broke

Figure 46. Performance Check of Traffic Signs in Midland

Figure 47(a) and 47(b) indicate the damages caused by high winds on the way to the Junction, TX along freeway I-10. Figure 47(a) displays the wood traffic sign fallen down due to the high wind, while Figure 47(b) illustrates the partial picture of this wood traffic sign. The fallen down of the wood traffic sign partially because of the inadequate sandbag and the uneven ground surface where the wood traffic sign was placed.

(a) Wood Traffic Sign Fallen Down

(b) The Partial Wood Traffic Sign

Figure 47. Performance Check of Traffic Signs on the way to the Junction, TX

Figure 48(a) and 48(b) indicate the damages caused by high winds on the way to the Dallas, TX. Figure 48(a) displays that traffic sign 2000 fell down due to the high winds, while Figure 48(b) illustrates the main body broke of this traffic sign by high winds.

(a) Traffic Sign 2000 Fallen Down (b) Traffic Sign 2000 Main Body Broken

Figure 48. Performance Check of Traffic Signs on the way to the Dallas, TX

Figure 48(a) and 49(b) indicate the damages caused by high winds on the way to the Ozona, TX. Figure 49(a) displays that the traffic sign 2001 fell down due to the high wind. Figure 49(b) illustrates the partial damage of the surface of this traffic sign by high winds.


(a) Traffic Sign 2001 Fallen Down (b) Traffic Sign Partial Damage

Figure 49. Performance Check of Traffic Signs on the Way to the Ozona, TX

Figure 50(a) and 50(b) indicate the damages caused by high winds on the way to the Ozona, TX. Figure 50(a) displays the hole on the ground caused by the constant trembling of the post of this traffic sign. The hole will get larger and larger, and the traffic sign will fall down finally if no any other treatment applied. Figure 50(b) displays the loosen nut damage resulted from constant trembling traffic sign. The nut will get looser and looser, in the end, traffic sign will get fallen.

a. The hole (the gap between the metal post and the earth) caused by the constant traffic sign trembling

b. The loosened nut resulted from the constant trembling of the supported traffic sign

Figure 50. Performance Checks of Traffic Signs in Midland, TX

Figure 51 indicate the wood traffic sign damages. This kind of rot damage was caused not only by high wind but also by sun, rain, and the property of the wood itself.

Rot Damage of a wood traffic sign in San Antonio, TX

Figure 51. Performance Check of Traffic Signs in San Antonio, TX

2.3.2.7 On-site Interview with Traffic Engineer

The research team conducted an on-site interview with one TxDOT traffic engineer (actually a sign inspector) in Junction, TX of San Angelo District on June 25, 2019. Several questions were proposed during the interview, including:

- Which temporary traffic sign is easy to be blew down?
- Which temporary traffic sign have better wind resistance ability?
- What other traffic signs are often used to be placed in the work zone?
- How about the damage degree of the traffic signs?
- How to repair and deal with the broken traffic signs?

Based on the interactive talks with the engineer, the research team have learned that:

- When the high wind came, almost types of traffic signs in San Angelo got fallen, but the wood traffic signs performs the best.

- Wood temporary traffic signs have better wind resistance ability due to their heavy body weight. In usual cases, sign 1005 also have good wind resistance ability.
- In the areas of San Angola, especially on freeway I-10 where speed limit is 80 mil/hr and big trucks normally generate higher wind effects to traffic signs, most temporary traffic signs placed in the work zone are wood traffic signs.
- The most common damages of temporary traffic signs caused by the high wind could be:
  - The temporary traffic sign fell down;
  - The main body of the traffic signs may get broken;
  - The partial broken of traffic signs;
  - The ballast that used to prevent the traffic signs from falling like sandbags and waste tires would get broken;
  - The nuts on the traffic sign get loosen;
  - The constant trembling traffic signs make the holes on the ground being larger and larger.
- The contractors would check the traffic signs frequently. Once they found the falling traffic signs or other damages, they will pick them up and repair or replace them. Sometimes, the main body of the traffic signs may get broken, the contractors need to replace them with new traffic signs or substitute part of them. Besides, the ballast that are used to prevent the traffic signs from falling like sandbags and waste tires would get broken as well. The contractors should frequently check and replace them, too. The loosen nuts on traffic signs would result in the falling of a sign, so reinforcing the loosen nuts is also important. The hole on the ground caused by the constant trembling of traffic signs could cause falling as well. Filling in the hole in time is essential to maintain the proper standing of temporary traffic signs.

2.3.2.8 Other Popular Temporary Signs

In this field observation, except from the four main temporary traffic signs mentioned earlier, there are still several other types of temporary traffic signs in Texas work zone areas, which include:

1) Sign 1000: Wooden Skid with 2 Wooden Legs Sign (shown in Figure 52);
2) Sign 1001: Wooden long /intermedia-term Sigle Leg (H-Leg) Sign (shown in Figure 53);
3) Sign 1003: H-base Single Upright with Leg PAAT Skid Sign (shown in Figure 54);
4) Sign 2000: Dual Leg Perforated Square Metal Tubing with Anchor Sign (shown in Figure 55).

Figures 52-55 indicate the structure, material, size, and installation guidance of the relevant temporary traffic signs.

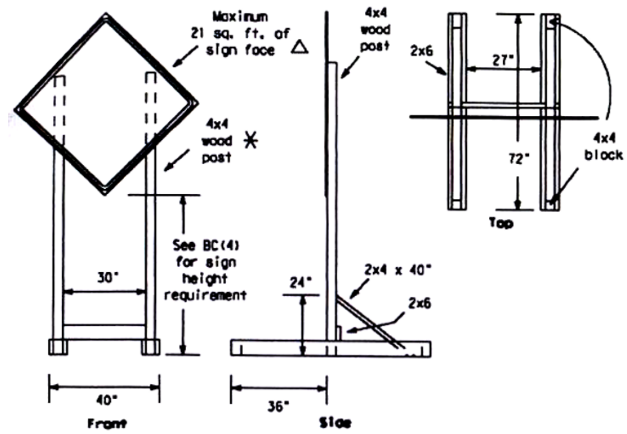


Figure 52. Sign 1000: Wooden Skid with 2 Wooden Legs Sign

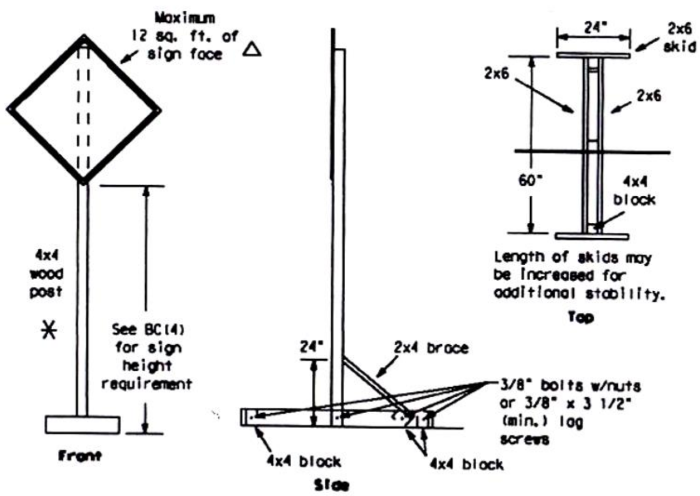


Figure 53. Sign 1001: Wooden long /intermedia-term Sigle Leg (H-Leg) Sign

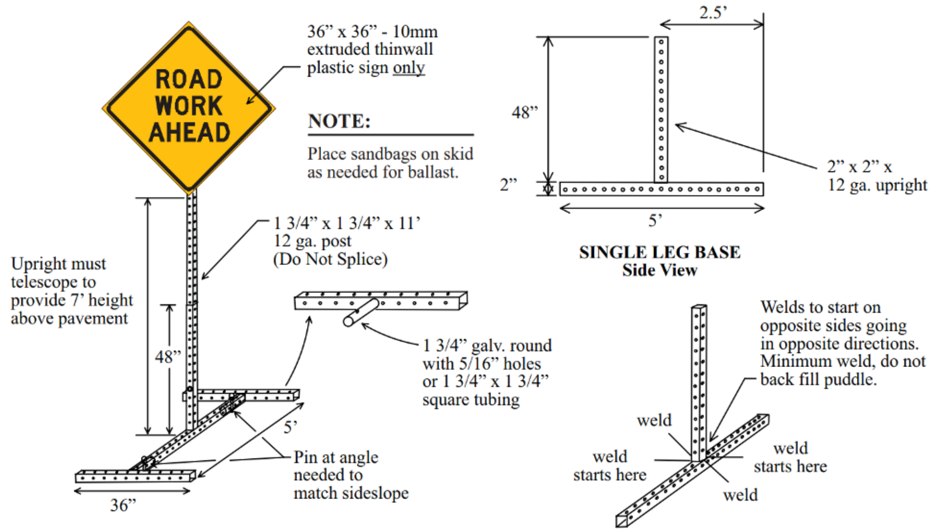


Figure 54. Sign 1003: H-base Single Upright with Leg PAAT Skid Sign

Figure 55. Sign 2000 Dual Leg Perforated Square Metal Tubing with Anchor Sign

2.4. Recommended New Signs Based on Field Observations

Based on the observations in target locations and video analysis, the research team propose three types of new temporary traffic signs with sign codes 2001, 2002, and 2003, all are imbedding signs. All these proposed new temporary traffic signs are based on the update of sign 2000: *Dual Leg Perforated Square Metal Tubing with Anchor Sign* (Figure 56). The recommended new signs are shown in Figure 57, Figure 58, and Figure 59, respectively.

During field observations, the research team felt that, sign 1005 (*Dual Leg PSST Skid Support Sign)* has relatively better trembling resistance than sign 2000. Under high winds, sign 2000 would be easily broken than sign 1005 and sign 1004 (*Independent Dual Upright* *with Leg PSST Skid Sign*). Sign 1005 and sign 1004 had less turning trembling performance in the high wind but gentle trembling forth and back performance. However, sign 2000 was observed with much stronger trembling by moving "forth and back" or with rotations. The proposed new designs of traffic signs 2001, 2002, and 2003 combine the good features of signs 1004, 1005, and 2000, while overcoming their drawbacks.

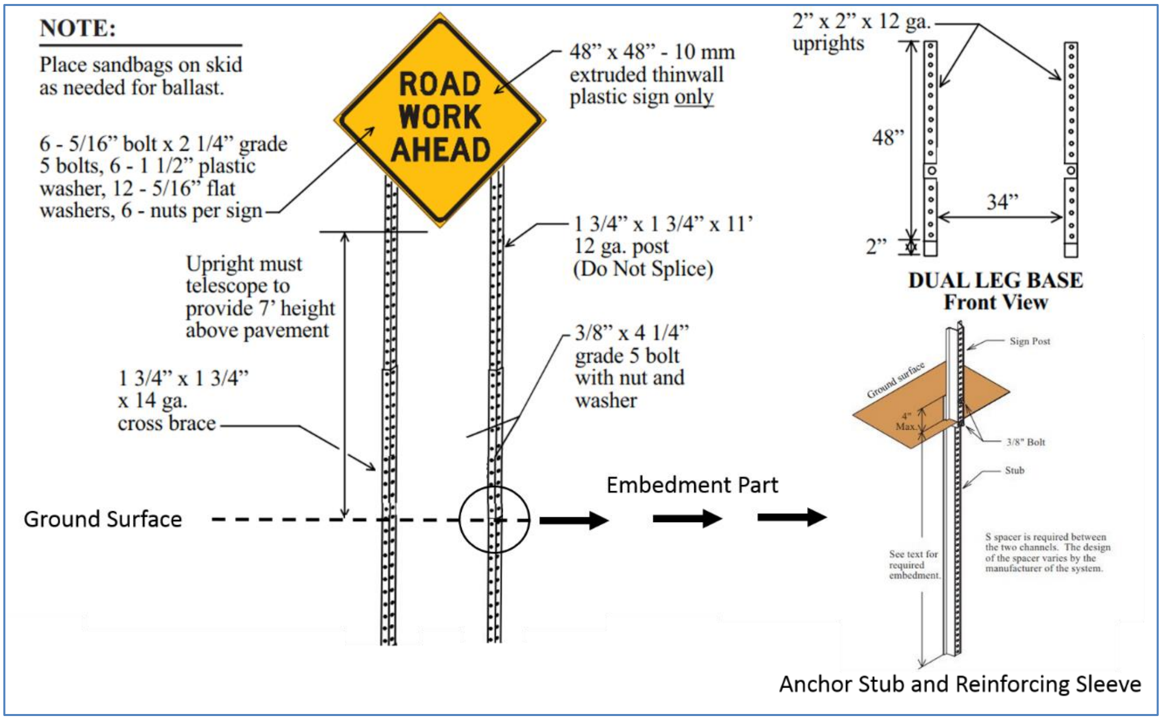


Figure 56. Sign 2000: Dual Leg Perforated Square Metal Tubing with Anchor Sign

The main body structure of sign 2001 in Figure 57 is actually coming from sign 2000. The only change is to have added one horizontal support between its two legs, which would to a certain extent reduce turning trembling of its traffic sign under the high winds. The two legs of sign 2001 are anchored under the ground. This sign is not suitable for locations where the surface ground shall not be damaged.

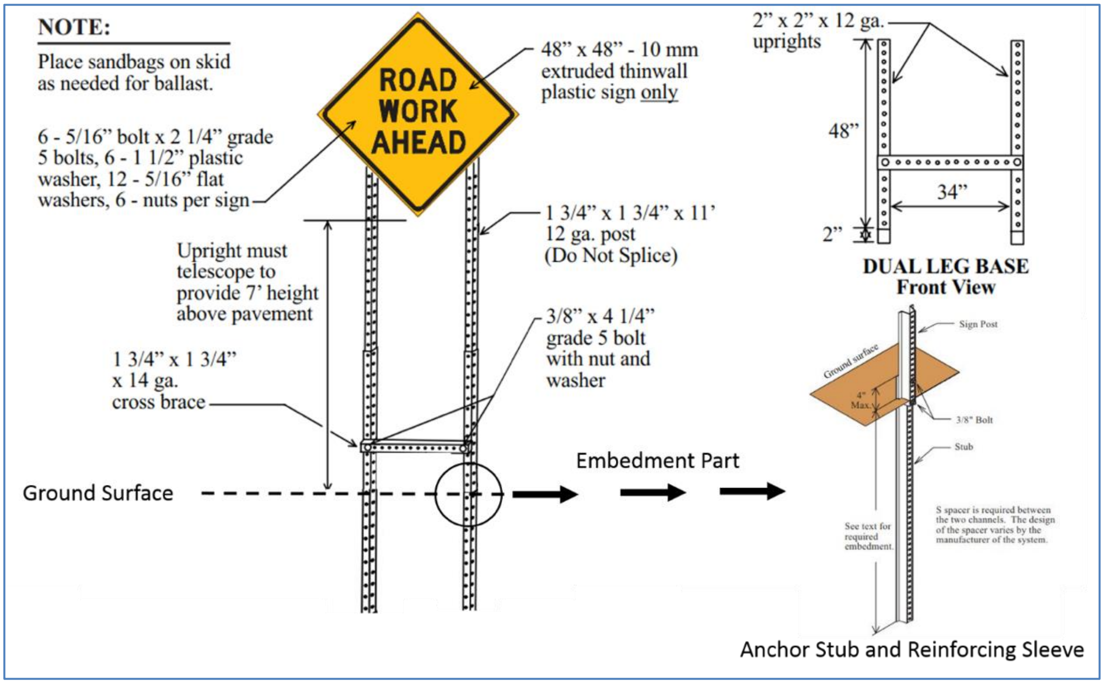


Figure 57. Sign 2001: Dual Leg Perforated Square Metal Tubing with Anchor Sign – Update 1

The main body structure of sign 2002 in Figure 58 is also from sign 2000 with one set of cross support added between its two legs. This can, to a certain extent, reduce turning trembling under high winds. The ability on turning trebling resistance of sign 3001 would be better than sign 2001, but the cost of sign 2002 should be higher as it needs more materials and a little bit more manpower.

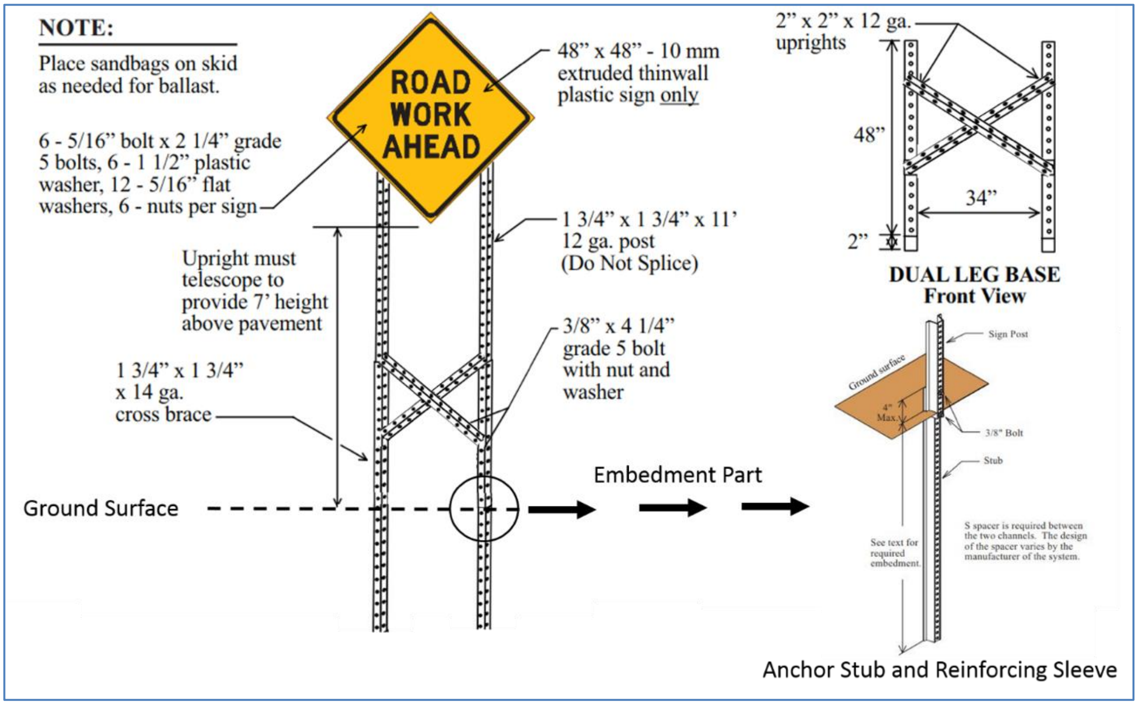


Figure 58. Sign 2002: Dual Leg Perforated Square Metal Tubing with Anchor Sign – Update 2

The main body structure of sign 2003 in Figure 59 is also from sign 2000 with one horizontal support and one set of cross support between its two legs. This can perfectly reduce the turning trembling under high winds. The ability of turning trembling resistance of sign 2003 would be better than both sign 2001 and sign 2002, but its cost shall be also the highest among these three new signs.

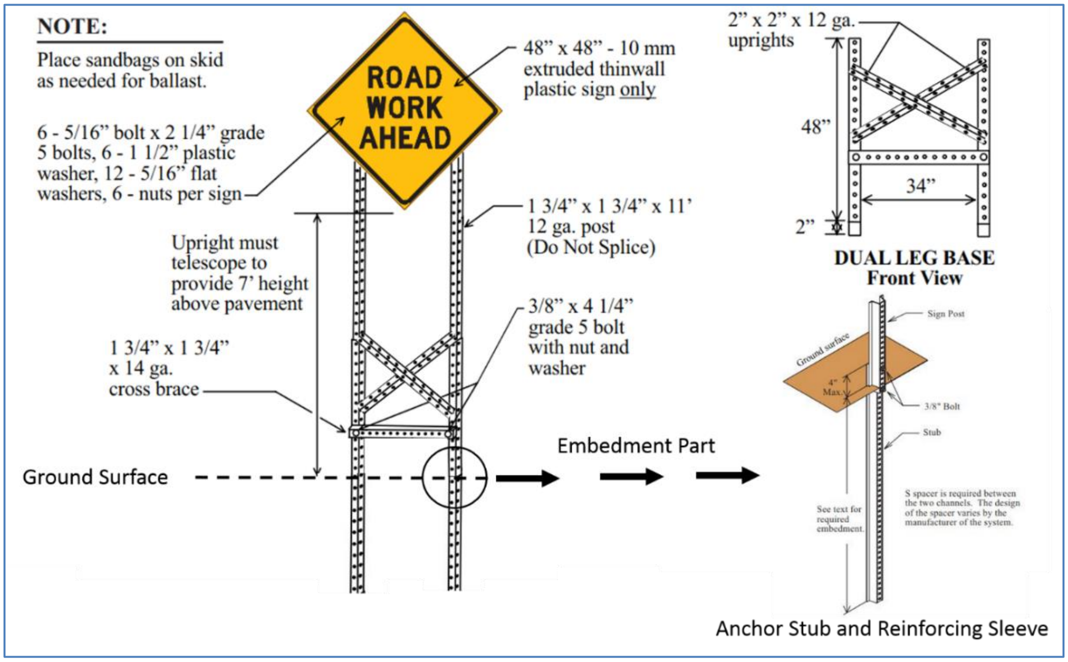


Figure 59. Sign 2003: Dual Leg Perforated Square Metal Tubing with Anchor Sign – Update 3

In all, the proposed three new temporary traffic signs have better ability of turning trembling resistance than sign 2000. These traffic signs can be recommended for further tests and evaluations with wider applications in work zones with high winds.

CHAPTER 3: FINITE ELEMENT ANALYSIS FOR TEMPORARY TRAFFIC SIGNS

In this section, the **finite element analysis** (FEA) for temporary traffic signs is conducted. Through the results, the rank of resistance ability of traffic signs could be obtained. At the end, a plan of traffic sign distribution in Texas is provided.

3.1. Finite Element Analysis Tool

Autodesk Fusion 360 (shown in Figure 60) was chosen to conduct the finite element analysis for all kinds of temporary traffic signs. This tool can be used to build up the traffic sign models and simulate high wind. The simulation results like safety factor of the traffic sign, stress distribution of traffic signs, displacement of the traffic signs, and so on could be obtained.

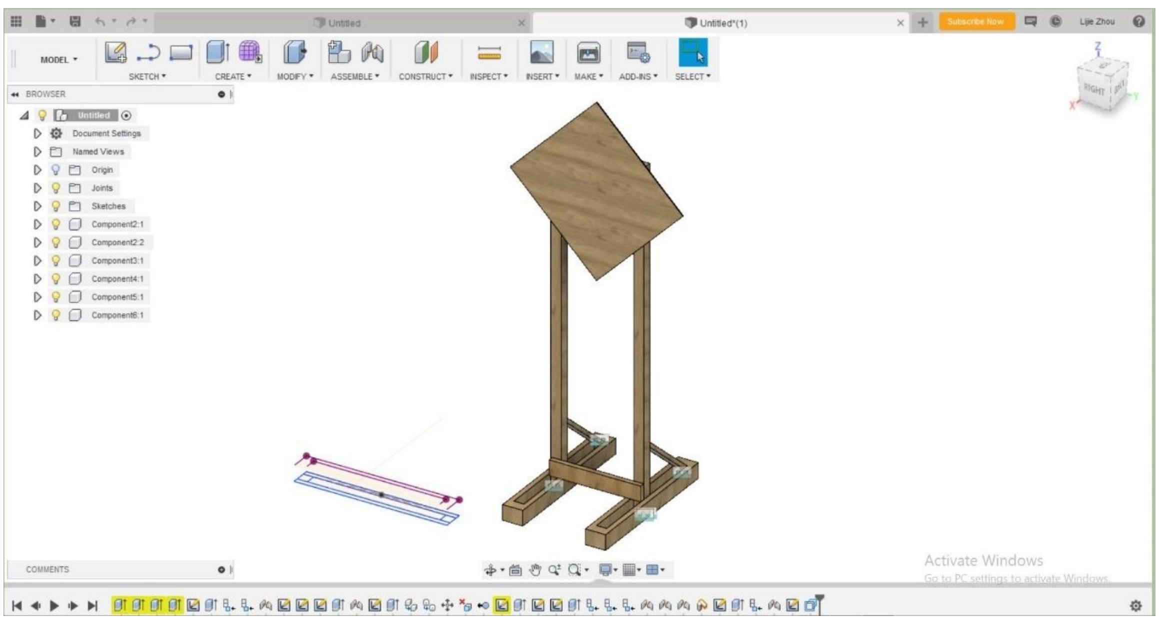


Figure 60. Autodesk Fusion 360 Software for Finite Element Analysis

3.2. Finite Element Analysis Method

A total of 8 kinds of temporary traffic sign models were built in Autodesk Fusion 360, which includes **two** types of wood temporary traffic sign models (sign 1000 and sign 1001), **four** types of existing square metal tubing traffic sign models (sign 1004, sign 1005, sign 1006 and sign 2000), and **three** types of new alternative design traffic sign models (sign 2001, sign 2002 and sign 2003).

Based on TxDOT *Complaint Work Zone Traffic Control Device List and Barricade and Construction General Notes and Requirements*, the size and material of each temporary traffic sign could be gotten. All these traffic sign models were built in the Autodesk Fusion 360 according to the different size they have. After that, simulations were conducted. Four levels of high wind speed which are 40 mph, 70mph, 80 mph and 90 mph would be vertically functioned on the surface of traffic signs.

With a design wind speed, the associated wind load is computed by Equation (2).

$$G = \frac{1}{2} * \mathrm{rho} * v^2 * A * C \qquad (2)$$

where, G is the force of the wind load in pounds, rho is the air density, v is the wind velocity, A is the surface area of the billboard and C is a dimensionless drag coefficient (assumed to be 1.0). (This equation got from the science paper named How to Calculate Wind Load on a Large Flat Surface, updated March 13, 2018 by Brian Baer. The website of this paper is https://sciencing.com/calculate-projected-area-wind-loads-7788161.html.)

The wind Force can be computed by Equation (3).

$$F = G * 0.45 * g\ (N) \qquad (3)$$

where, F is Wind Force in N, 0.45 is the conversion value of pound to kilogram, g is referred as the acceleration of gravity, its value is 9.8 N/kg.

Based on equations (2) and (4), for the 16 feet square areas of traffic sign, the wind force functioned on the traffic sign surface could be obtained as shown in Table 6. The temporary traffic signs that the area is 16 feet square include Sign 1000, Sign 1001, Sign 1004, Sign 1005, Sign 2000, Sign 2001, Sign 2002, and Sign 2003.

Table 6. Wind Load of 16 Feet Square Areas of Temporary Traffic Signs

Traffic Sign Area (ft^2)	Wind Speed (mph)	Wind Load (lb)	Wind Force (N)
16	90	4,860	21,618
	80	3,840	17,081
	70	2,940	13,078
	40	960	4,270

For the 9 square feet areas of traffic sign, the wind force functioned on the traffic sign surface could be obtained shown in Table 7. The temporary traffic signs that the area is 9 feet square include sign 1006 only.

Table 7. Wind Load of 9 Feet Square Areas of Temporary Traffic Signs

Traffic Sign Area (ft^2)	Wind Speed (mph)	Wind Load (lb)	Wind Force (N)
9	90	2,734	12,160
	80	2,160	9,608
	70	1,654	7,356
	40	540	2,402

Once the simulation was finished, some results and analysis of traffic signs would be given by the Autodesk Fusion 360 Software like minimum safety factor, maximum stress and maximum displacement, etc. The minimum safety factor is a very important factor to weight the safety of the traffic signs. The bigger the minimum safety factor was, the safer the traffic sign would be.

3.3. Finite Element Analysis Results

In this section, the main simulation results of all kinds of temporary traffic signs under the different wind force are displayed as following, which includes minimum safety factor, maximum pressure (MPa), maximum displacement (mm), and deviation angle α (°).

Sign 1000: The finite element analysis simulation of Sign 1000 was shown in Figure 61. This is a displacement analysis, and the maximum displacement of the Sign 1000 is 6.075mm. The many little squares shown on the traffic sign surface are split by the finite element analysis. The colorful stipe shown in the lower right corner represents the different degree of displacement.

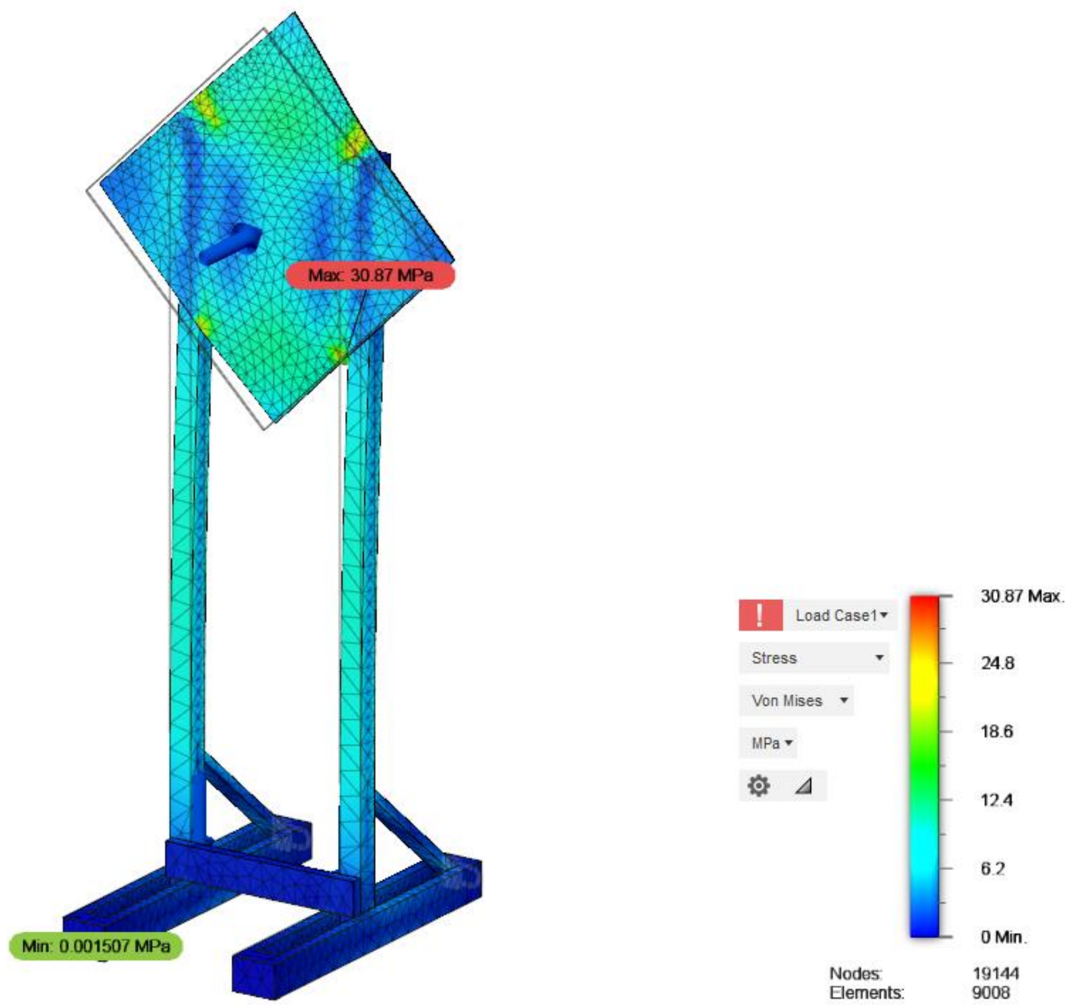


Figure 61. Sign 1000 Finite Element Analysis Simulation

The results of Sign 1000 finite element analysis simulation are shown in Table 8.

Table 8. Sign 1000 Finite Element Analysis Simulation Results

Traffic Sign Type	Wind Speed (mph)	Wind Force (N)	Min Safety Factor	Max Pressure (MPa)	Max Displacement (mm)	α (°)
Sign 1000	90	21,618	0.151	51.01	812.2	17.998
	80	17,081	0.191	40.31	642.0	14.402
	70	13,078	0.250	30.87	491.9	11.131
	40	4,270	0.760	10.10	10.1	0.231

<u>Sign 1001</u>: The finite element analysis simulation of Sign 1001 is shown in Figure 62.

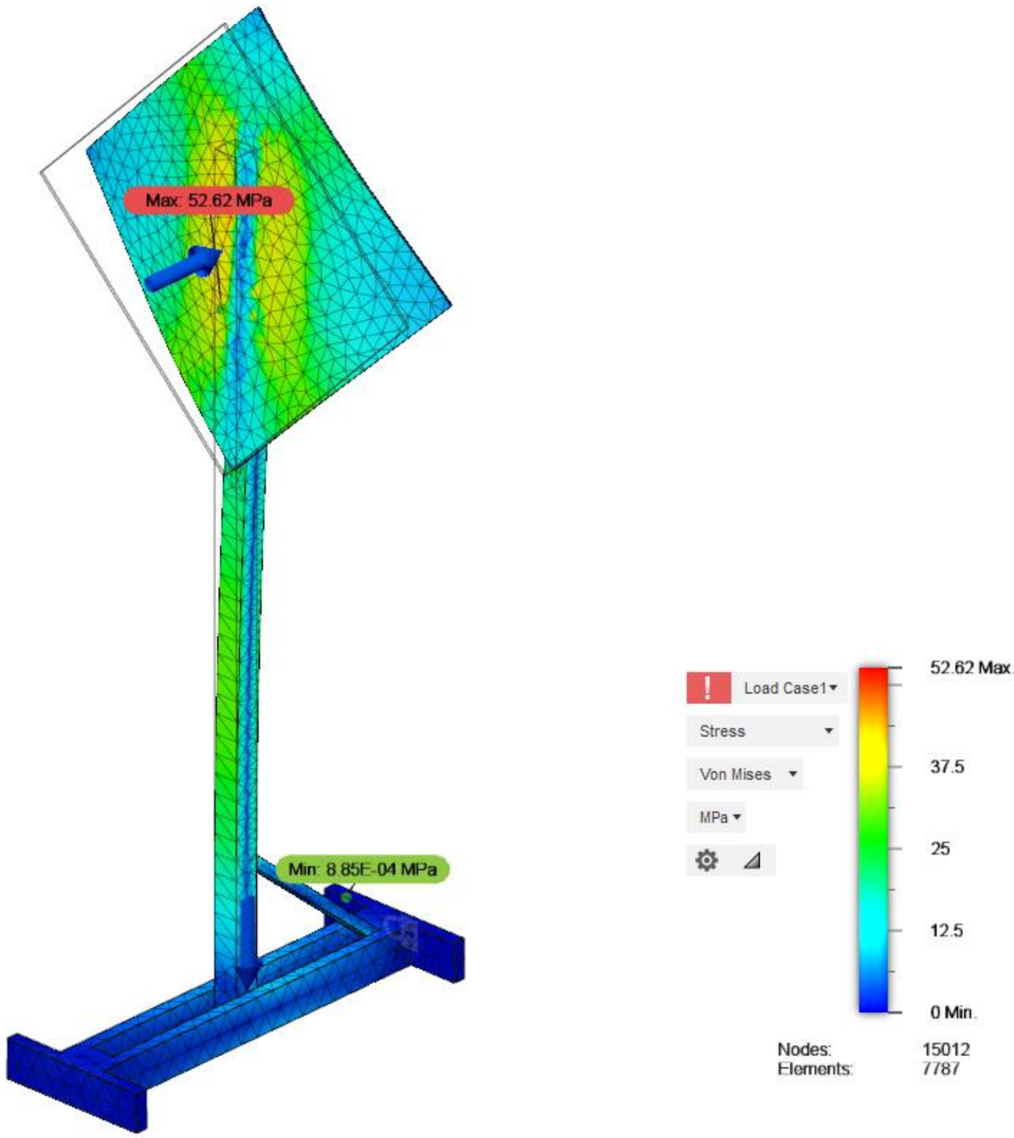


Figure 62. Sign 1001 Finite Element Analysis Simulation

The results of Sign 1001 finite element analysis simulation are shown in Table 9.

Table 9. Sign 1001 Finite Element Analysis Simulation Results

Traffic Sign Type	Wind Speed (mph)	Wind Force (N)	Min Safety Factor	Max Pressure (MPa)	Max Displacement (mm)	α (°)
Sign 1001	90	21,618	0.147	52.62	1312.0	27.690
	80	17,081	0.186	41.58	1037.0	22.529
	70	13,078	0.240	31.84	794.2	17.624
	40	4,270	0.740	10.40	260.0	5.937

<u>Sign 1004:</u> The finite element analysis simulation of Sign 1004 is shown in Figure 63.

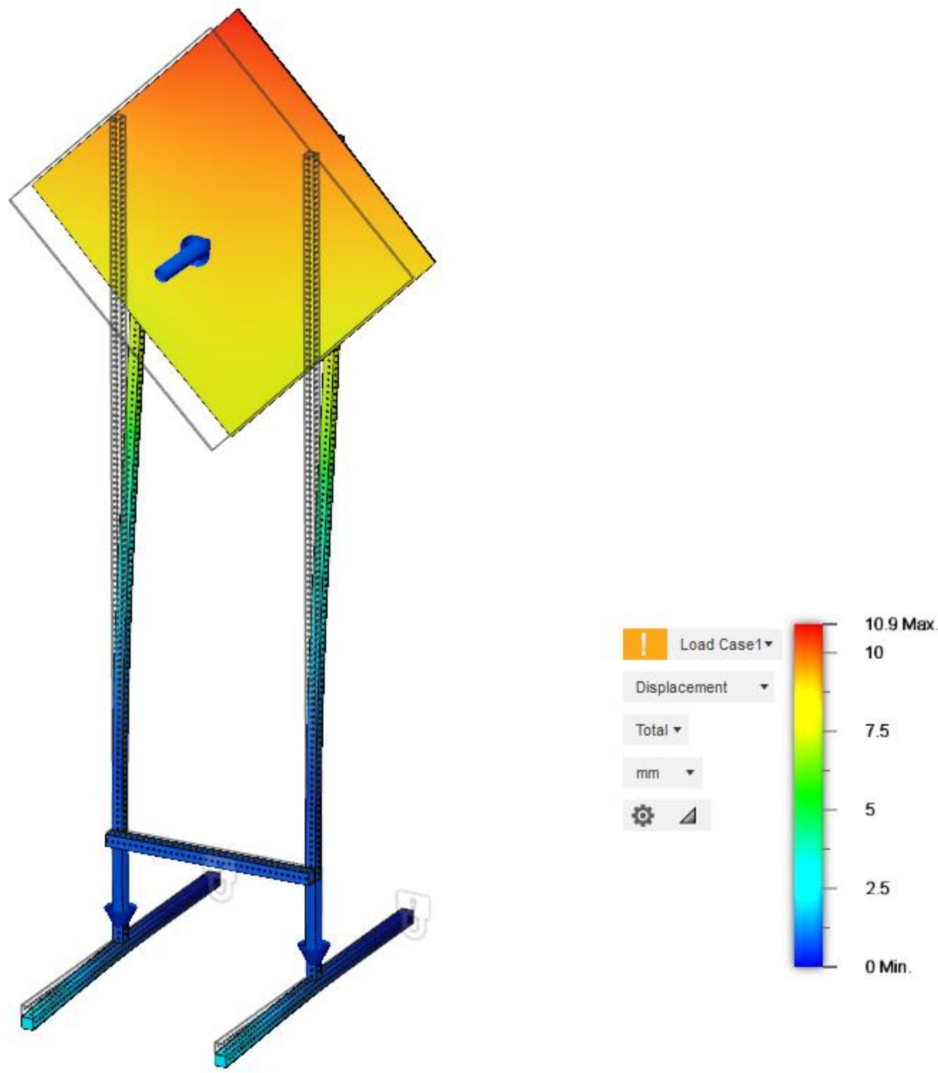


Figure 63. Sign 1004 Finite Element Analysis Simulation

The results of Sign 1004 finite element analysis simulation are shown in Table 10.

Table 10. Sign 1004 Finite Element Analysis Simulation Results

Traffic Sign Type	Wind Speed (mph)	Wind Force (N)	Min Safety Factor	Max Pressure (MPa)	Max Displacement (mm)	α (°)
Sign 1004	90	21,618	2.371	87.31	11.9	0.252
	80	17,081	3.060	67.60	9.0	0.191
	70	13,078	4.122	50.22	6.4	0.137
	40	4,270	5.095	40.62	1.4	0.029

Sign 1005: The finite element analysis simulation of Sign 1004 is shown in Figure 64.

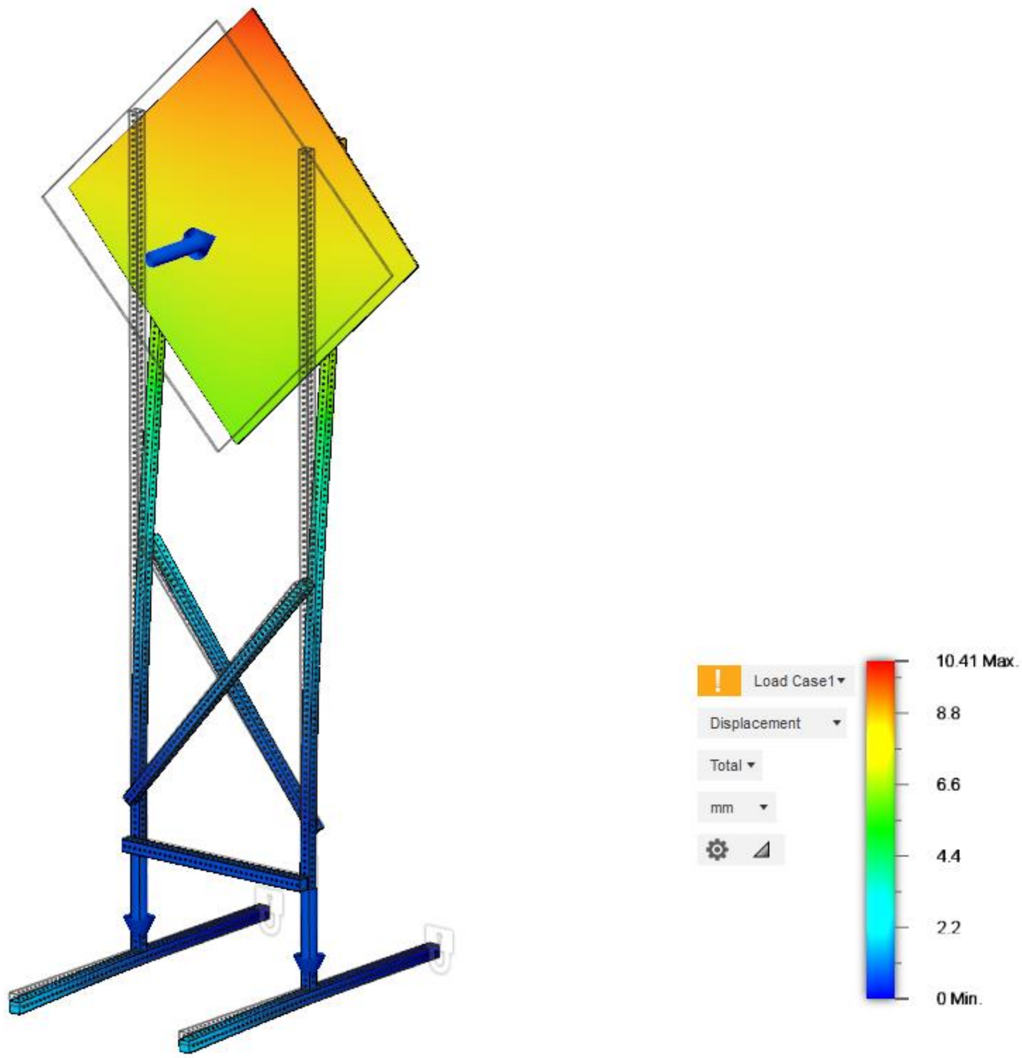


Figure 64. Sign 1005 Finite Element Analysis Simulation

The results of Sign 1005 finite element analysis simulation are shown in Table 11.

Table 11. Sign 1005 Finite Element Analysis Simulation Results

Traffic Sign Type	Wind Speed (mph)	Wind Force (N)	Min Safety Factor	Max Pressure (MPa)	Max Displacement (mm)	α (°)
Sign 1005	90	21,618	1.626	127.30	18.6	0.396
	80	17,081	2.020	102.40	14.3	0.303
	70	13,078	2.575	80.39	10.4	0.221
	40	4,270	5.050	40.96	1.9	0.041

Sign 1006: The finite element analysis simulation of Sign 1006 is shown in Figure 65.

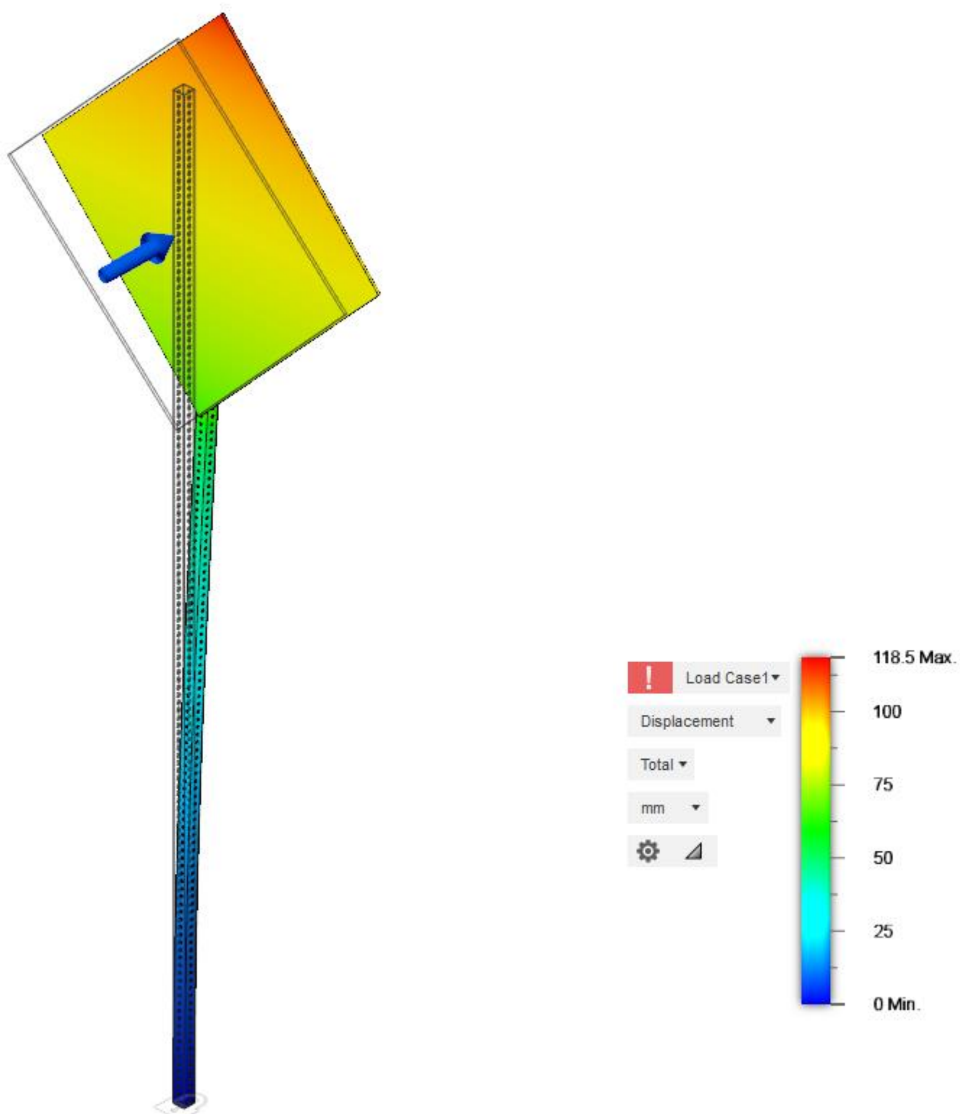


Figure 65. Sign 1006 Finite Element Analysis Simulation

The results of Sign 1006 finite element analysis simulation are shown in Table 12.

Table 12. Sign 1006 Finite Element Analysis Simulation Results

Traffic Sign Type	Wind Speed (mph)	Wind Force (N)	Min Safety Factor	Max Pressure (MPa)	Max Displacement (mm)	α (°)
Sign 1006	90	12,160	0.018	11721.00	5175.0	62.447
	80	9,608	0.022	9261.00	4089.0	56.563
	70	7,356	0.029	7090.00	3130.0	49.218
	40	2,402	0.089	2315.00	1022.0	20.733

Sign 2000: The finite element analysis simulation of Sign 2000 is shown in Figure 66.

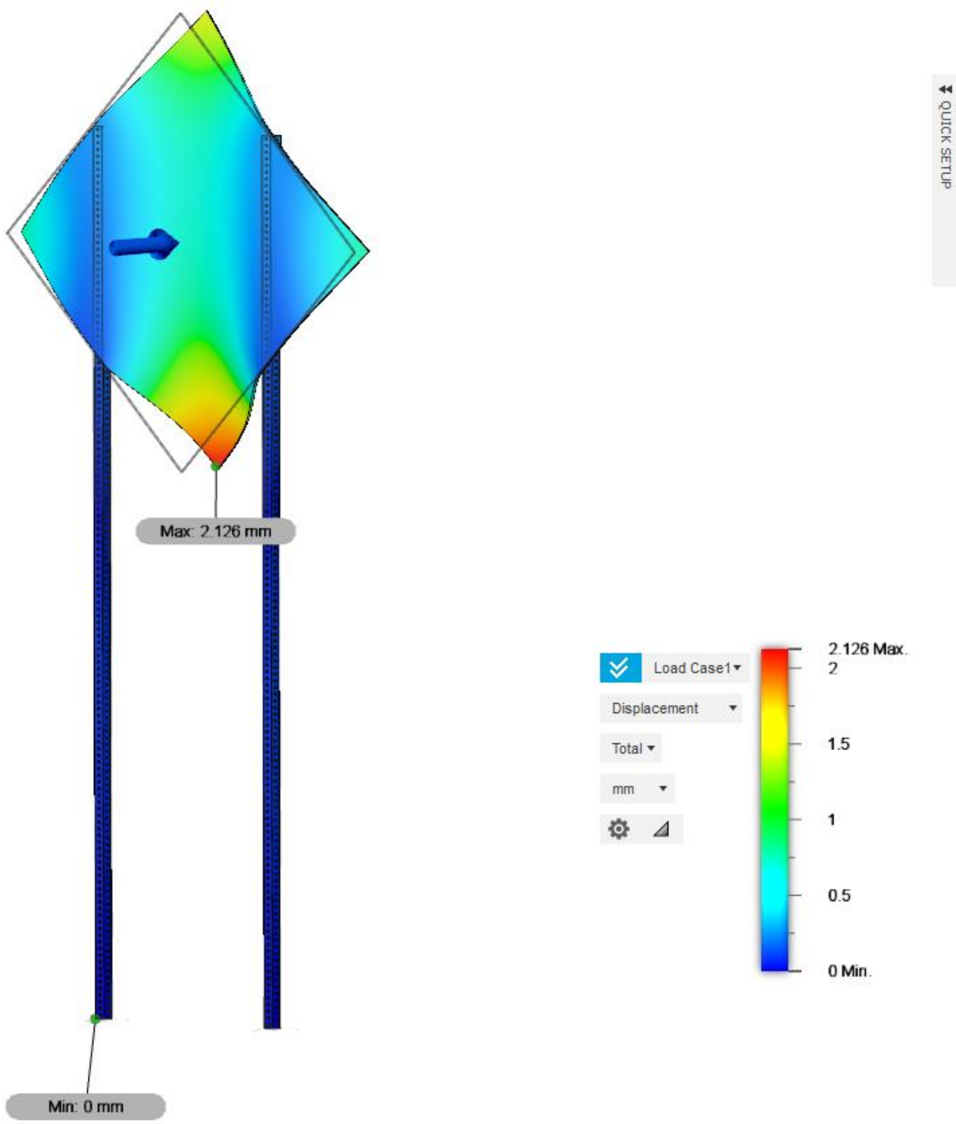


Figure 66. Sign 2000 Finite Element Analysis Simulation

The results of Sign 2000 finite element analysis simulation are shown in Table 13.

Table 13. Sign 2000 Finite Element Analysis Simulation Results

Traffic Sign Type	Wind Speed (mph)	Wind Force (N)	Min Safety Factor	Max Pressure (MPa)	Max Displacement (mm)	α (°)
Sign 2000	90	21,618	1.670	123.80	9.4	0.318
	80	17,081	2.116	97.81	7.5	0.251
	70	13,078	2.764	74.89	5.7	0.193
	40	4,270	8.470	24.45	1.9	0.063

Sign 2001: The finite element analysis simulation of Sign 2001 is shown in Figure 67.

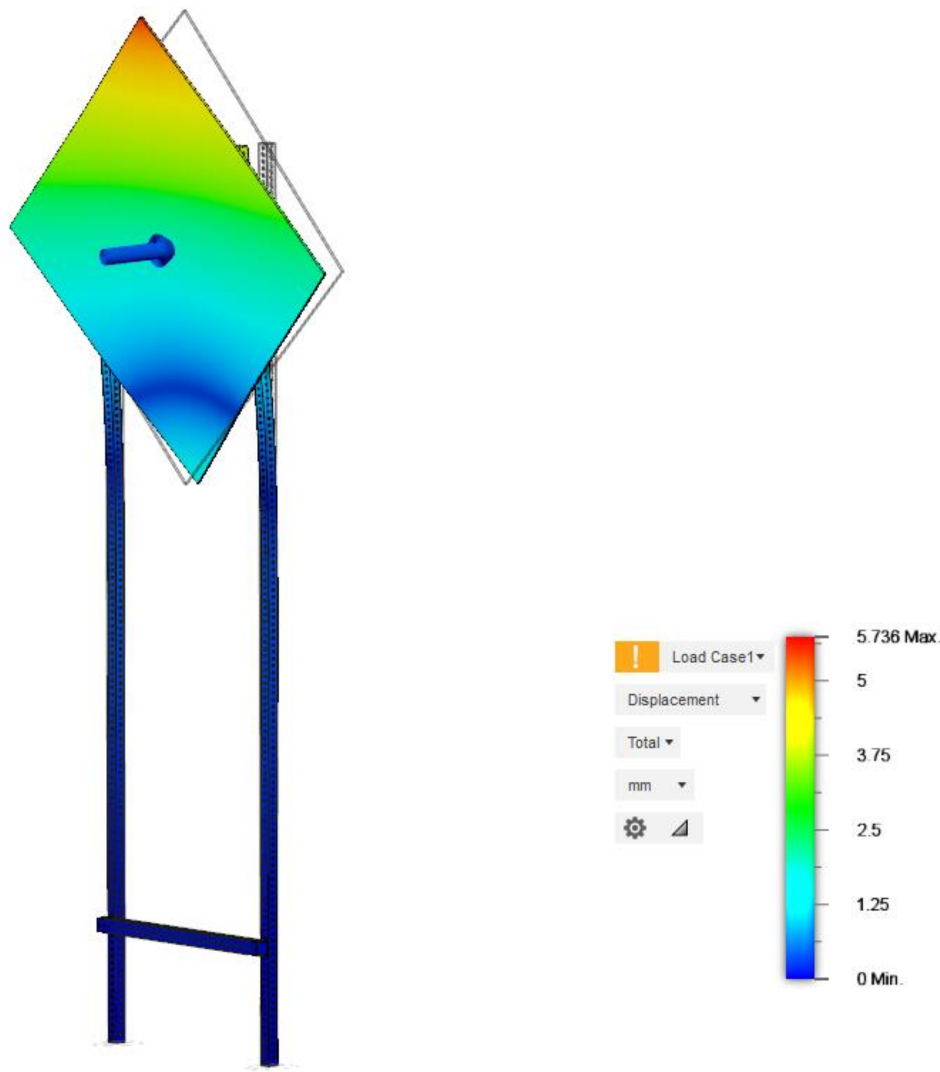


Figure 67. Sign 2001 Finite Element Analysis Simulation

The results of Sign 2001 finite element analysis simulation are shown in Table 14.

Table 14. Sign 2001 Finite Element Analysis Simulation Results

Traffic Sign Type	Wind Speed (mph)	Wind Force (N)	Min Safety Factor	Max Pressure (MPa)	Max Displacement (mm)	α (°)
Sign 2001	90	21,618	1.760	117.90	9.5	0.320
	80	17,081	2.220	93.18	7.5	0.253
	70	13,078	2.900	71.34	5.7	0.193
	40	4,270	8.890	23.29	1.9	0.063

<u>Sign 2002</u>: The finite element analysis simulation of sign 2002 was shown in Figure 68.

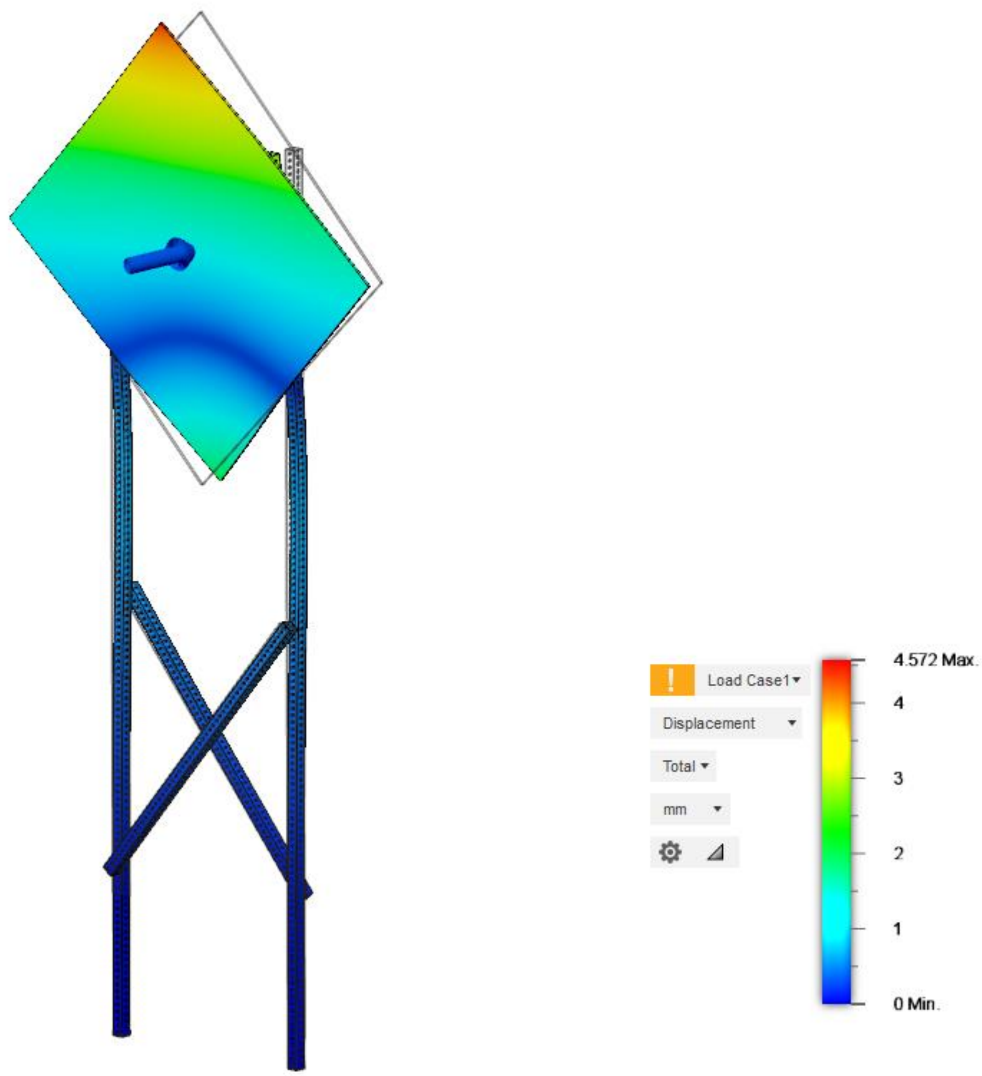


Figure 68. Sign 2002 Finite Element Analysis Simulation

The results of sign 2002 finite element analysis simulation are shown in Table 15.

Table 15. Sign 2002 Finite Element Analysis Simulation Results

Traffic Sign Type	Wind Speed (mph)	Wind Force (N)	Min Safety Factor	Max Pressure (MPa)	Max Displacement (mm)	α (°)
Sign 2002	90	21,618	1.611	128.50	7.6	0.255
	80	17,081	2.040	101.50	6.0	0.201
	70	13,078	2.660	77.70	4.6	0.154
	40	4,270	8.160	25.37	1.5	0.050

<u>Sign 2003</u>: The finite element analysis simulation of Sign 2003 is shown in Figure 69.

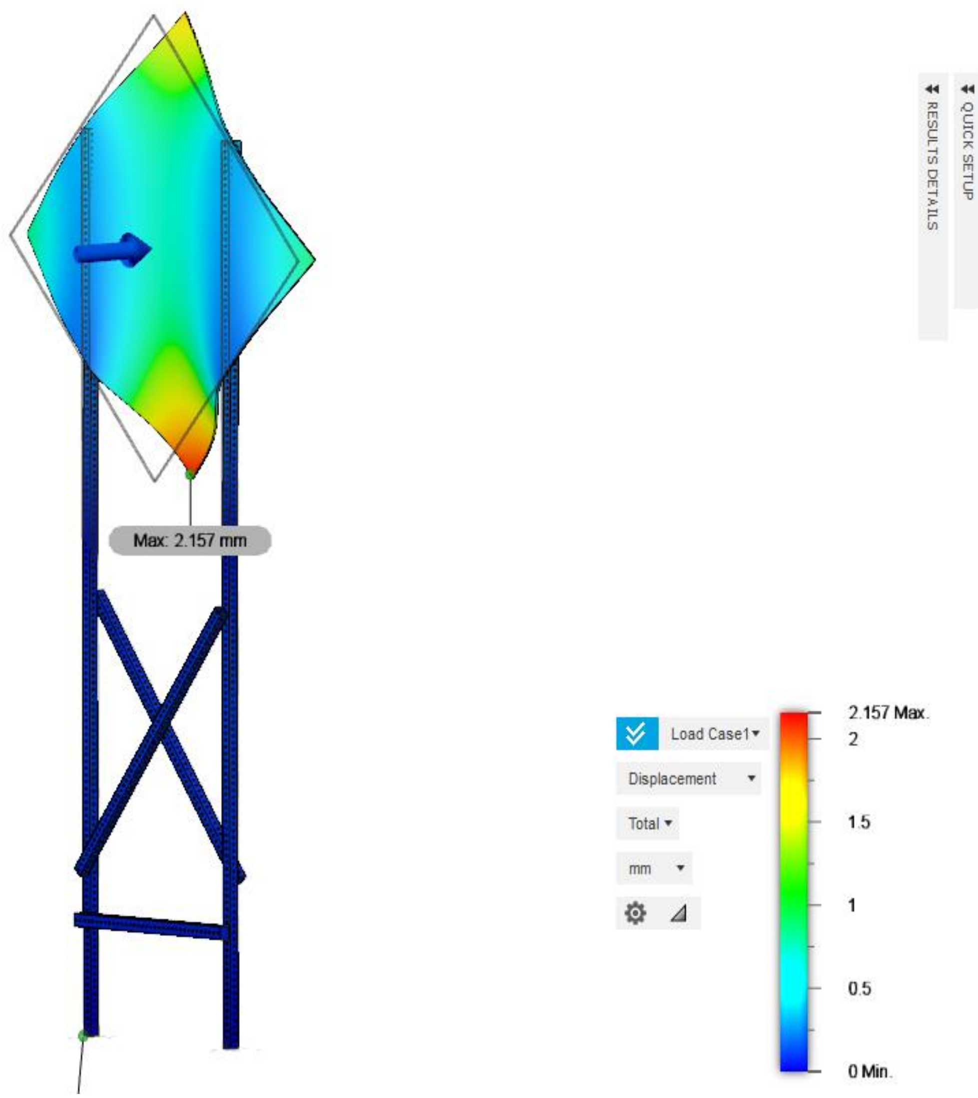


Figure 69. Sign 2003 Finite Element Analysis Simulation

The results of Sign 2003 finite element analysis simulation are shown in Table 16.

Table 16. Sign 2003 Finite Element Analysis Simulation Results

Traffic Sign Type	Wind Speed (mph)	Wind Force (N)	Min Safety Factor	Max Pressure (MPa)	Max Displacement (mm)	α (°)
Sign 2003	90	21,618	1.670	124.20	6.4	0.215
	80	17,081	2.110	98.14	5.0	0.170
	70	13,078	2.750	75.14	3.9	0.130
	40	4,270	8.440	24.53	1.3	0.043

3.4. Discussion and Recommendation Based on the Finite Element Analysis Results

Minimum safety factor is a critical factor to judge the safety of the temporary traffic signs in the different levels high speed wind. In general, when the minimum safety factor is smaller or equal to 3, the structures might be broken or permanently bend due to the high-speed wind. And the remaining factors can be used as a reference. The smaller the maximum pressure (MPa) or maximum displacement (mm) or deviation angle is, the safer the traffic signs would be. Therefore, based on the safety factors of different levels wind force, temporary traffic signs rank in the different levels high speed wind can be given.

3.4.1 Discussion of Signs under Wind Speed 90 mph Based on FEA Factors

Table 17 shows the finite element analysis results of all different kinds of traffic signs with 90 mph wind speed.

Table 17. Finite Element Analysis Results of Traffic Signs with 90 mph Wind Speed

Traffic Sign Type	Sign 1000	Sign 1001	Sign 1004	Sign 1005	Sign 1006	Sign 2000	Sign 2001	Sign 2002	Sign 2003
Min Safety Factor	0.151	0.147	2.371	1.626	0.018	1.670	1.760	1.611	1.670
Max Pressure (MPa)	51.01	52.62	87.31	127.30	11721.00	123.80	117.90	128.50	124.20
Max Displacement (mm)	812.20	1312.0	11.9	18.6	5175.0	9.4	9.5	7.6	6.4
α (°)	17.998	27.690	0.252	0.396	62.447	0.318	0.320	0.255	0.215

Figure 70 shows the minimum safety factor results of all different kinds of traffic signs with 90 mph wind speed, and there is no value of minimum safety factor bigger than 3. Because the wind is too strong in that situation and no traffic signs can hold out. Therefore, no temporary traffic sign can resist the 90mph high wind. However, based on the values of minimum safety factor of all kinds of traffic signs, a rank of wind resistance ability can be given:

Sign 1004 > Sign 2001 > Sign 2000 = Sign 2003 > Sign 1005 > Sign 2002 > Sign 1000 > Sign 1001 > Sign 1006.

Figure 70. Minimum Safety Factor of Traffic Signs with 90 mph Wind Speed

Figure 71 shows the maximum pressure of traffic signs with 90 mph wind speed. From the Figure 71, the maximum pressure of Sign 1006 is very big, while the maximum pressure of the rest of traffic signs are small. Under the circumstance that the safety factor meets the requirement, based on the maximum pressure, the traffic signs with small maximum pressure are better than the traffic signs with big maximum pressure.

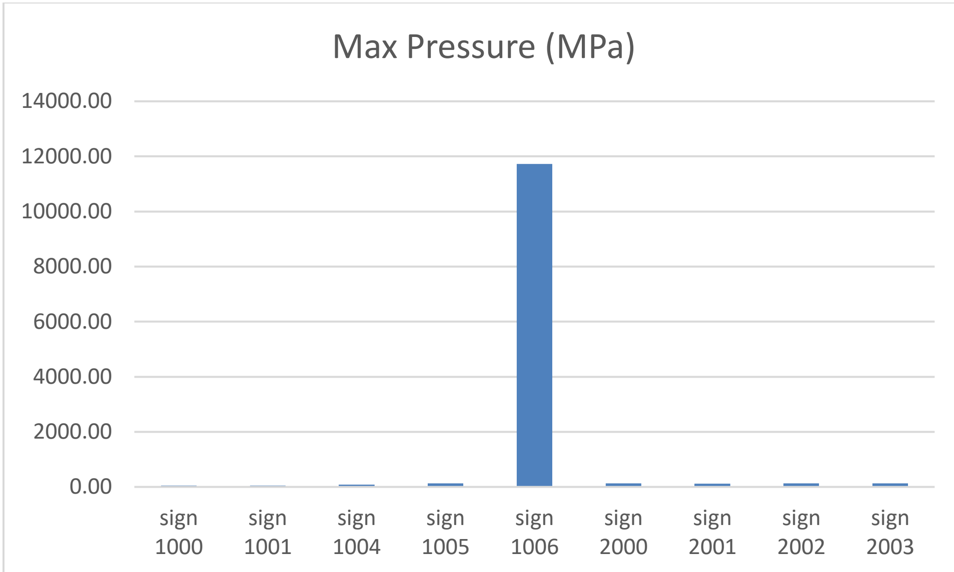


Figure 71. Maximum Pressure of Traffic Signs with 90 mph Wind Speed

Figure 72 shows the maximum Displacement of traffic signs with 90 mph wind speed. From the Figure 72, the maximum displacement of Sign 1006, Sign 1000, and Sign 1001 are much bigger, while the maximum displacement of the rest of traffic signs are small. Under the circumstance that the safety factor meets the requirement, based on the maximum pressure, the traffic signs with smaller maximum displacement are better than the traffic signs with bigger maximum displacement.

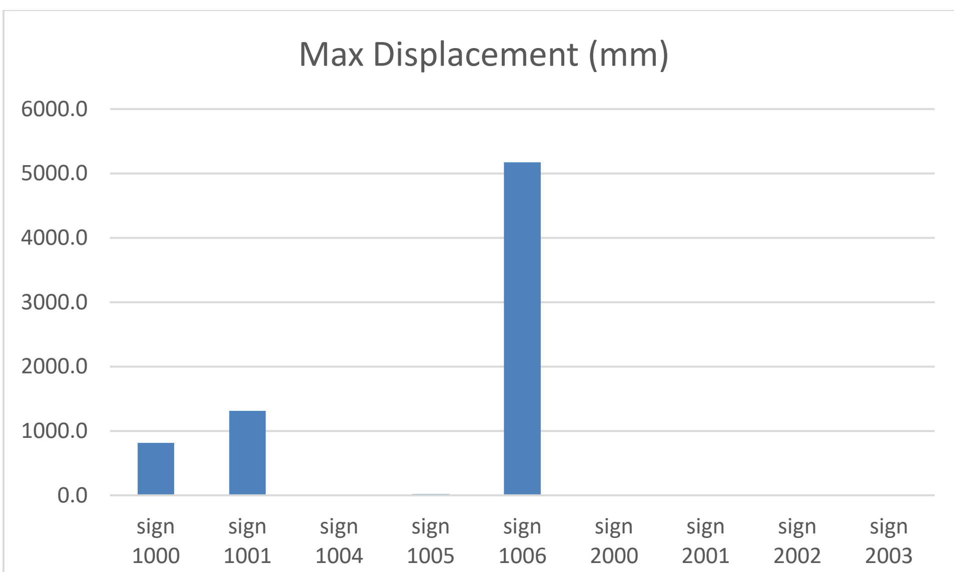


Figure 72. Maximum Displacement of Traffic Signs with 90 mph Wind Speed

Figure 73 shows the deviation angle α (°) of traffic signs with 90 mph wind speed. From Figure 73, the deviation angle of Sign 1001, Sign 1000, and Sign 1006 are much bigger, while the deviation angle of the rest of traffic signs are much smaller. Under the circumstance that the safety factor meets the requirement, based on anger α, the traffic signs with smaller deviation are better than the traffic signs with bigger deviation angle.

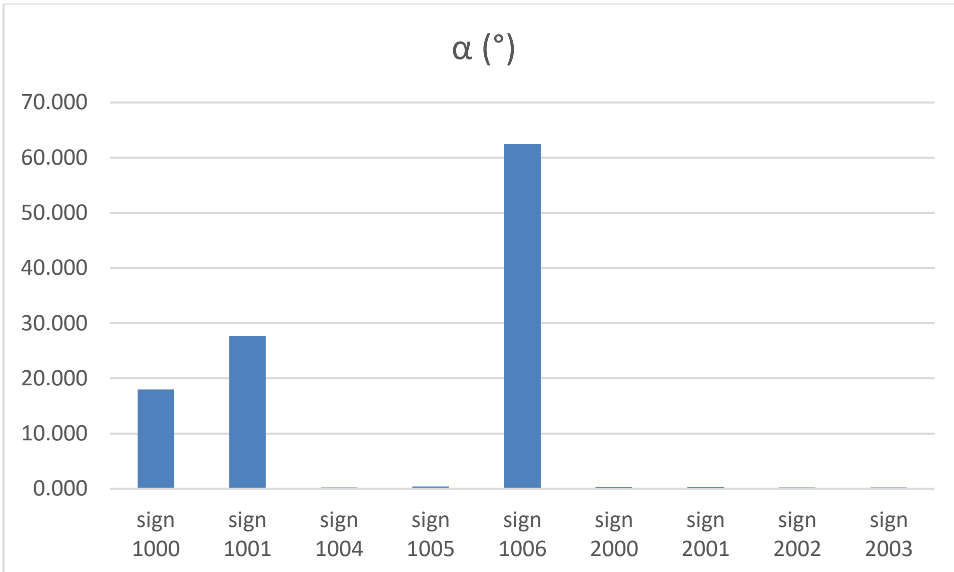


Figure 73. Deviation Angle α (°) of Traffic Signs with 90 mph Wind Speed

3.4.2 Discussion of Signs under Wind Speed 80 mph Based on FEA Factors

Table 18 shows the finite element analysis results of all different kinds of traffic signs with 80 mph wind speed.

Table 18. Finite Element Analysis Results of Traffic Signs with 80 mph Wind Speed

Traffic Sign Type	sign 1000	sign 1001	sign 1004	sign 1005	sign 1006	sign 2000	sign 2001	sign 2002	sign 2003
Min Safety Factor	0.191	0.186	3.060	2.020	0.022	2.116	2.220	2.040	2.110
Max Pressure (MPa)	40.310	41.580	67.600	102.40	9261.00	97.81	93.18	101.50	98.14
Max Displaceme nt (mm)	642.0	1037.0	9.0	14.270	4089.0	7.5	7.5	6.0	5.0
α (°)	14.402	22.529	0.191	0.303	56.563	0.251	0.253	0.201	0.170

Figure 74 shows the minimum safety factor results of all different kinds of traffic signs with 80 mph wind speed. From Figure 74, there is only one traffic sign's minimum safety factor is bigger than 3. A rank based on the minimum safety factor can be provided as:

> Sign 1004 > Sign 2001 > Sign 2000 > Sign 2003 > Sign 1005 > Sign 2002 > Sign 1000 > Sign 1001 > Sign 1006.

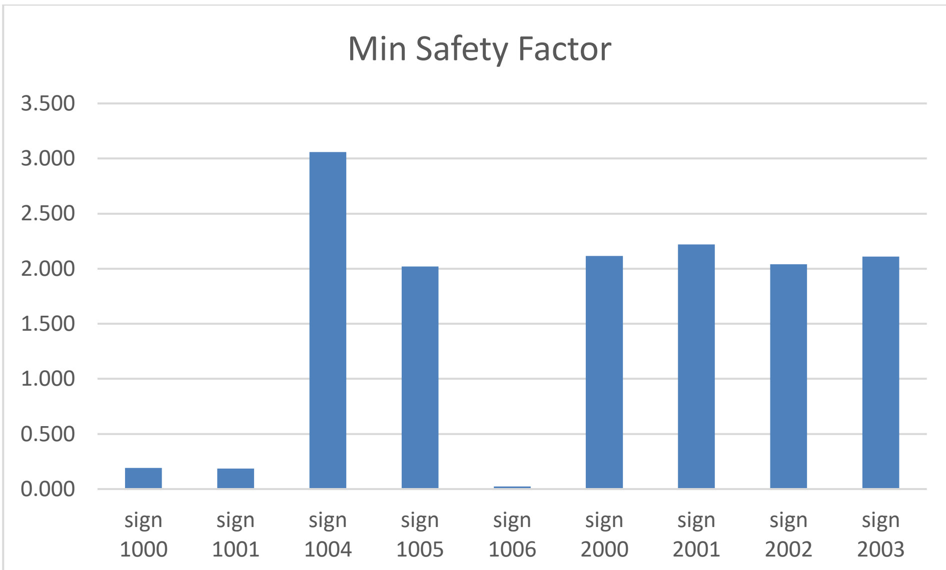


Figure 74. Minimum Safety Factor of Traffic Signs with 80 mph Wind Speed

Figure 75 shows the maximum pressure of traffic signs with 80 mph wind speed. From the Figure 75, the maximum pressure of sign 1006 is very big, while the maximum pressure of the rest of traffic signs are small. Under the circumstance that the safety factor meets the requirement, based on the maximum pressure, the traffic signs with small maximum pressure are better than the traffic signs with big maximum pressure.

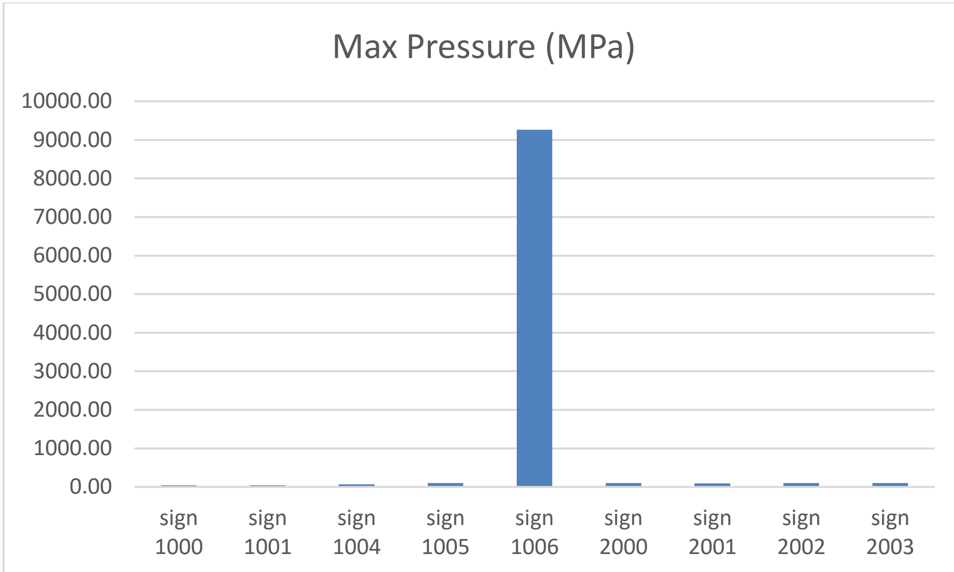


Figure 75. Maximum Pressure of Traffic Signs with 80 mph Wind Speed

Figure 76 shows the maximum Displacement of traffic signs with 80 mph wind speed. From the Figure 76, the maximum displacement of sign 1006, sign 1000, and sign 1001 are much bigger, while the maximum displacement of the rest of traffic signs are small. Under the circumstance that the safety factor meets the requirement, based on the maximum pressure, the traffic signs with small maximum displacement are better than the traffic signs with big maximum displacement.

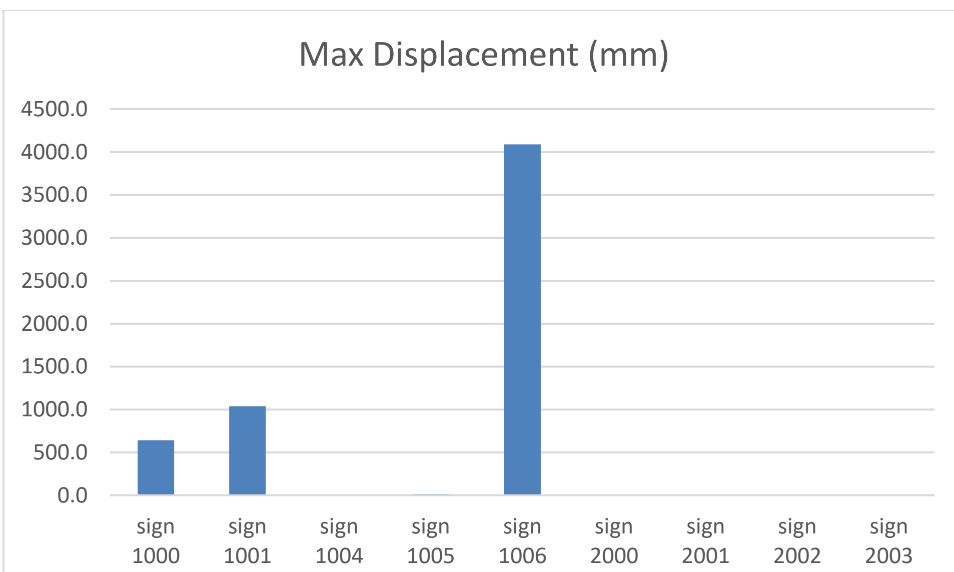


Figure 76. Maximum Displacement of Traffic Signs with 80 mph Wind Speed

Figure 77 shows the deviation angle α (°) of traffic signs with 80 mph wind speed. From the Figure 77, the deviation angle of sign 1001, sign 1000, and sign 1006 are much bigger, while the deviation of the remaining traffic signs is much smaller. Under the circumstance that the safety factor meets the requirement, based on the angle, the traffic signs with small deviation are better than the traffic signs with big deviation angle.

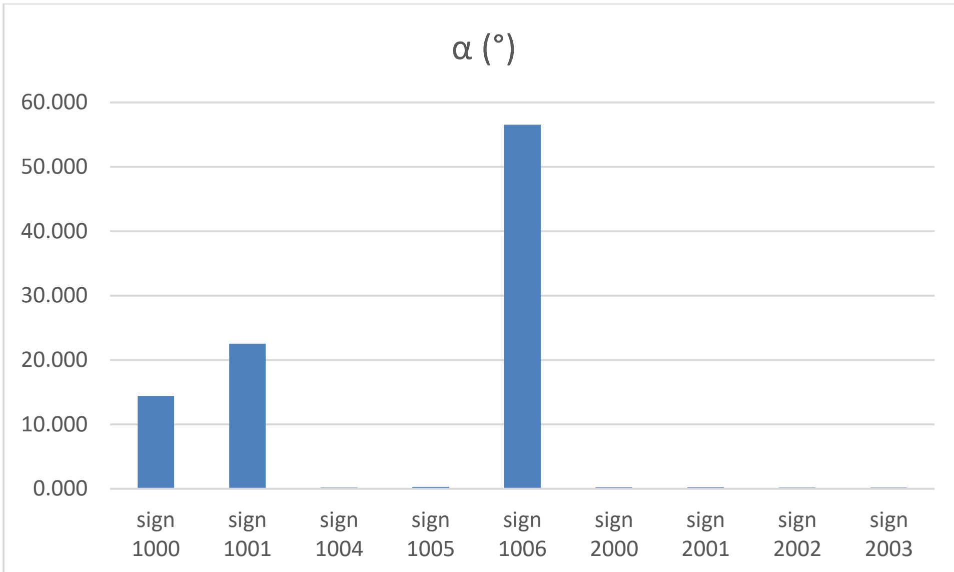


Figure 77. Deviation Angle α (°) of Traffic Signs with 80 mph Wind Speed

3.4.3 Discussion of Signs under Wind Speed 70 mph Based on FEA Factors

Table 19 shows the finite element analysis results of all different kinds of traffic signs with 70 mph wind speed.

Table 19. Finite Element Analysis Results of Traffic Signs with 70 mph Wind Speed

Traffic Sign Type	Sign 1000	Sign 1001	Sign 1004	Sign 1005	Sign 1006	Sign 2000	Sign 2001	Sign 2002	Sign 2003
Min Safety Factor	0.250	0.240	4.122	2.575	0.029	2.764	2.900	2.660	2.750
Max Pressure (MPa)	30.87	31.84	50.22	80.39	7090.00	74.89	71.34	77.70	75.14
Max Displacement (mm)	491.9	794.2	6.4	10.4	3130.0	5.7	5.7	4.6	3.9
α (°)	11.131	17.624	0.137	0.221	49.218	0.193	0.193	0.154	0.130

Figure 78 shows the minimum safety factor results of all different kinds of traffic signs with 80 mph wind speed. From Figure 78, traffic signs safety rank can be given:

Sign 1004 = Sign 2000 = Sign 2003 = Sign 1005 > Sign 1000 > Sign 1001 > Sign 2001 > Sign 2002 > Sign 1006.

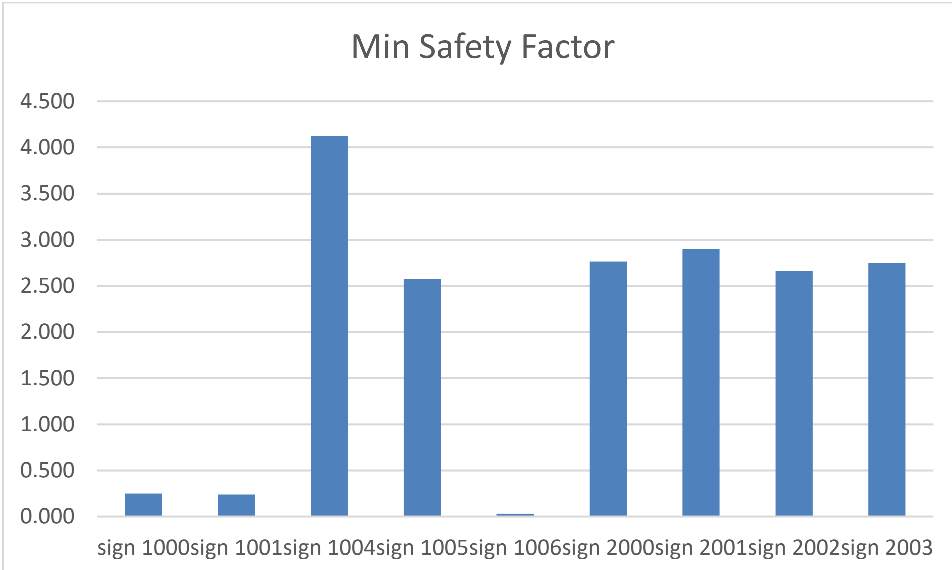


Figure 78. Minimum Safety Factor of Traffic Signs with 70 mph Wind Speed

Figure 79 shows the maximum pressure of traffic signs with 70 mph wind speed. From Figure shown 79, the maximum pressure of Sign 1006 is very big, while the maximum pressure of the rest of traffic signs are small. Under the circumstance that the safety factor meets the requirement, based on the maximum pressure, the traffic signs with small maximum pressure are better than the traffic signs with big maximum pressure.

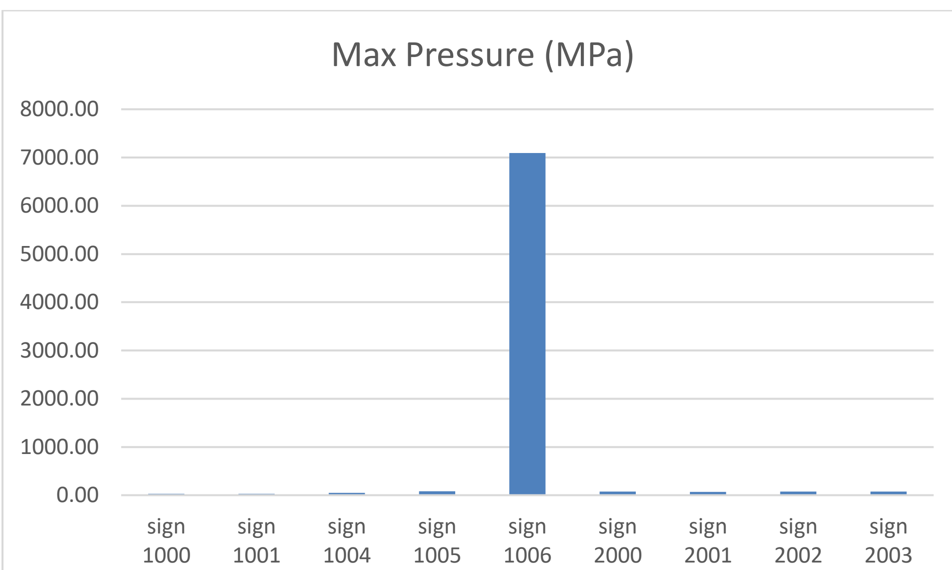


Figure 79. Maximum Pressure of Traffic Signs with 70 mph Wind Speed

Figure 80 shows the maximum Displacement of traffic signs with 70 mph wind speed. From the Figure 80, the maximum displacement of Sign 1006, Sign 1000, and Sign 1001 are much bigger, while the maximum displacement of the rest of traffic signs are small. Under the circumstance that the safety factor meets the requirement, based on the maximum pressure, the traffic signs with smaller maximum displacement are better than the traffic signs with bigger maximum displacement.

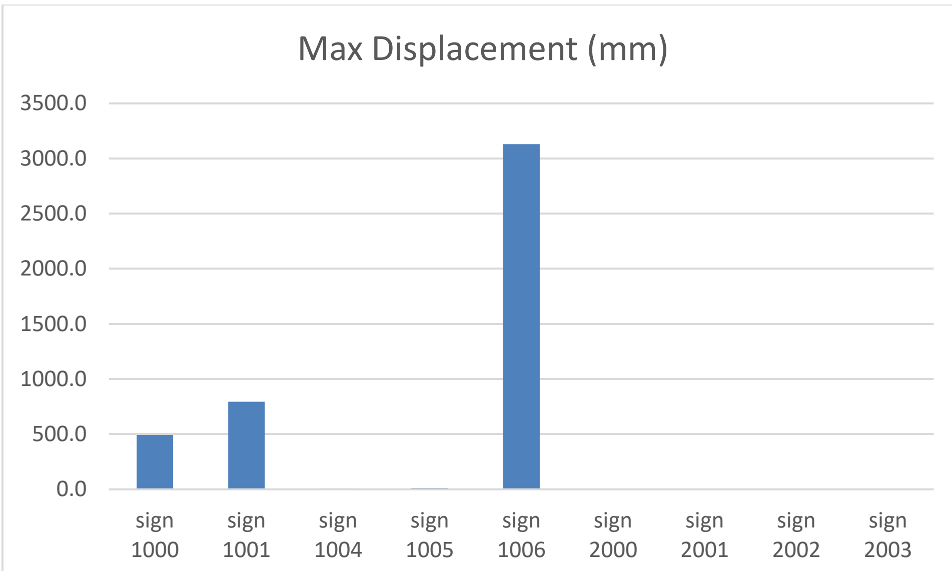


Figure 80. Maximum Displacement of Traffic Signs with 70 mph Wind Speed

Figure 81 shows the deviation angle α (°) of traffic signs with 70 mph wind speed. From Figure 81, the deviation angle of Sign 1001, Sign 100, Sign 1004, and Sign 1005 are much bigger, while the deviation of Sign 1006, Sign 2000, Sign 2001, Sign 2002, and Sign 2003 are much smaller. Under the circumstance that the safety factor meets the requirement, based on the tan α, the traffic signs with small deviation are better than the traffic signs with big deviation angle.

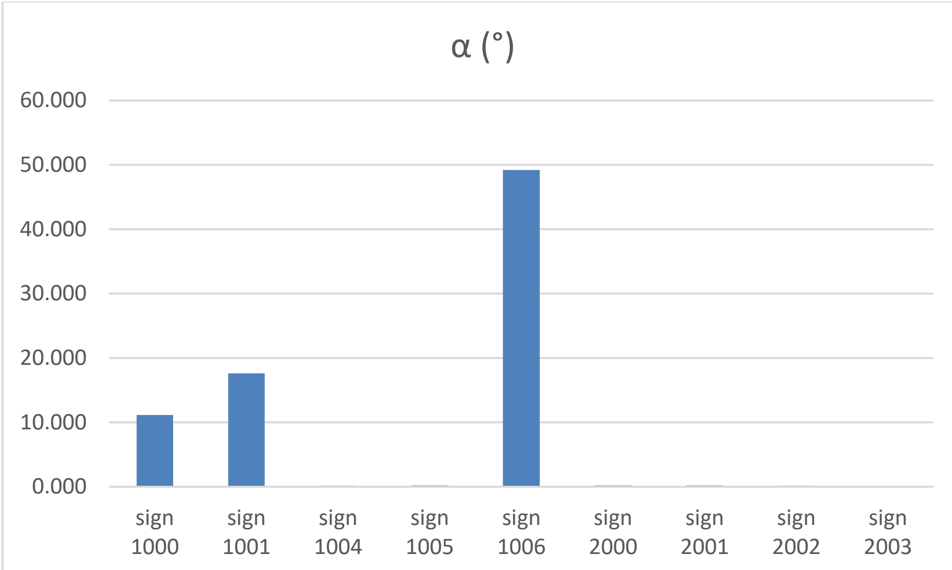


Figure 81. Deviation Angle α (°) of Traffic Signs with 70 mph Wind Speed

3.4.4 Discussion of Signs under Wind Speed 40 mph Based on FEA Factors

Table 20 shows the finite element analysis results of all different kinds of traffic signs with 40 mph wind speed.

Table 20. Finite Element Analysis Results of Traffic Signs with 40 mph Wind Speed

Traffic Sign Type	Sign 1000	Sign 1001	Sign 1004	Sign 1005	Sign 1006	Sign 2000	Sign 2001	Sign 2002	Sign 2003
Min Safety Factor	0.760	0.740	5.095	5.050	0.089	8.470	8.890	8.160	8.440
Max Pressure (MPa)	10.10	10.40	40.62	40.96	2315.00	24.45	23.29	25.37	24.53
Max Displacement (mm)	10.1	260.0	1.4	1.9	1022.0	1.9	1.9	1.5	1.3
α (°)	0.231	5.937	0.029	0.041	20.733	0.063	0.063	0.050	0.043

Figure 82 shows the minimum safety factor results of all different kinds of traffic signs with 80 mph wind speed. Based on Figure 82, traffic signs safety ranks are:

> Sign 1004 = Sign 2000 = Sign 2003 = Sign 1005 = Sign 1000 = Sign 1001 > Sign 2001 > Sign 2002 > Sign 1006.

Even though the structures might break due to the high-speed wind, several traffic signs were recommended for the areas with 40 mph wind speed in Texas, which includes Sign 1004, Sign 2000, Sign 2003, Sign 1005, Sign 1000, Sign 1001, Sign 2001, and Sign 2002.

Figure 82. Minimum Safety Factor of Traffic Signs with 40 mph Wind Speed

Figure 83 shows the maximum pressure of traffic signs with 40 mph wind speed. From the Figure shown 83, the maximum pressure of sign 1006 is very big, while the maximum pressure of the rest of traffic signs are small. Under the circumstance that the safety factor meets the requirement, based on the maximum pressure, the traffic signs with smaller maximum pressure are better than the traffic signs with big maximum pressure.

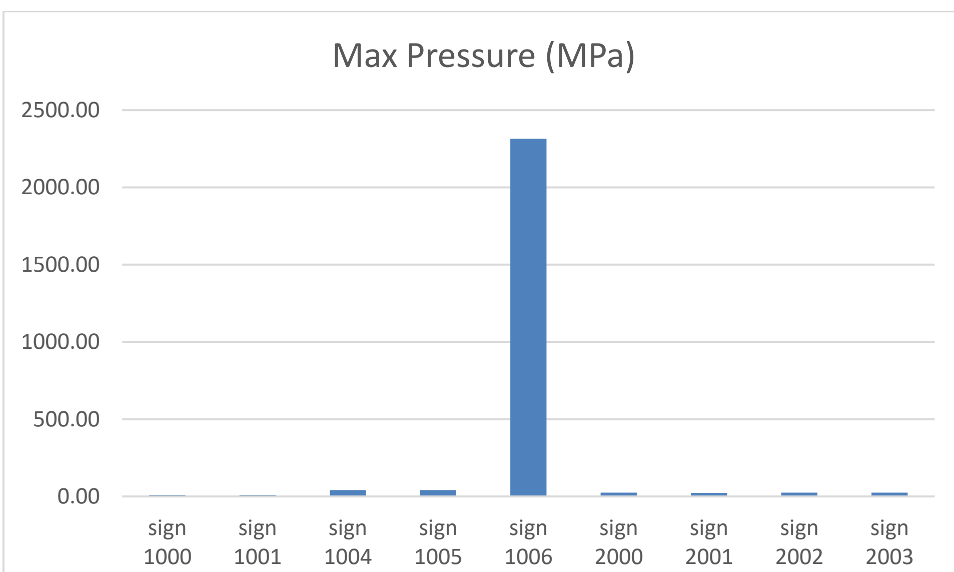


Figure 83. Maximum Pressure of Traffic Signs with 40 mph Wind Speed

Figure 84 show the maximum displacement of different signs, where the maximum displacements for Sign 1006, Sign 1000, and Sign 1001 are much bigger, while the maximum displacement of the rest of traffic signs are small. Under the circumstance that the safety factor meets the requirement, based on the maximum pressure, the traffic signs with smaller maximum displacement are better than the traffic signs with bigger maximum displacement.

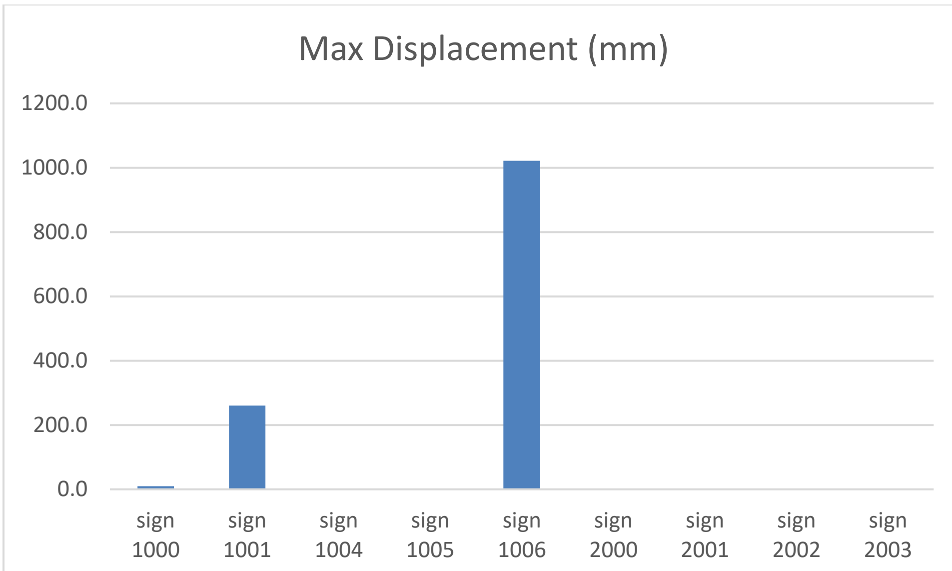


Figure 84. Maximum Displacement of Traffic Signs with 40 mph Wind Speed

Figure 85 shows the deviation angle α (°) of traffic signs with 40 mph wind speed. From the Figure 85, the deviation angle of Sign 1001, Sign 1000, Sign 1004, and Sign 1005 are much bigger, while the deviation of Sign 1006, Sign 2000, Sign 2001, Sign 2002, and Sign 2003 are much smaller. Under the circumstances when the safety factor meets the requirement, based on anger α, traffic signs with smaller deviation are better than signs with bigger deviation angle.

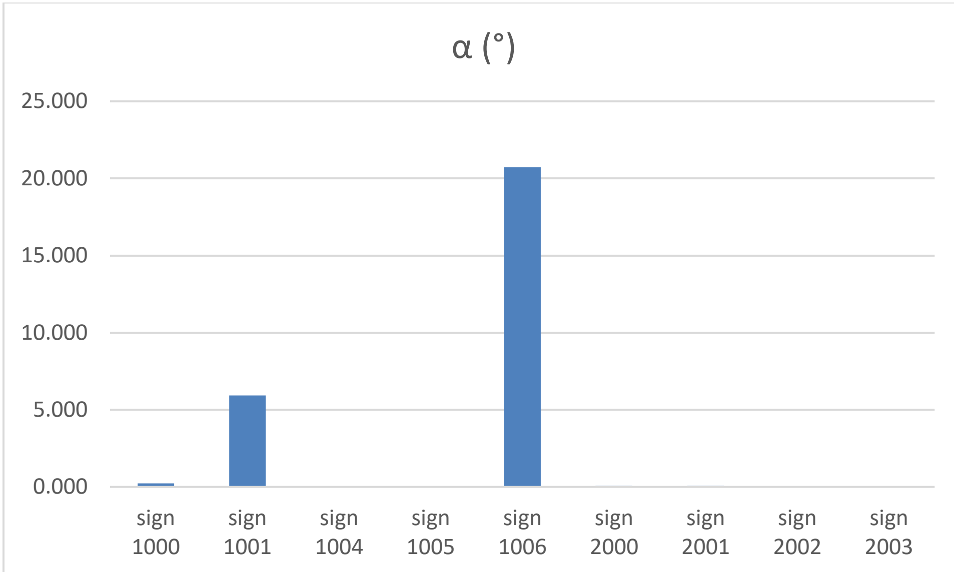


Figure 85. Deviation Angle α (°) of Traffic Signs with 40 mph Wind Speed

3.5. The Normalized Performance Rating of Traffic Signs Based on FEA Simulation Results

In section 3.4, there are four evaluation factors (minimum safety factor, maximum stress, maximum displacement, and deviation angle). In order to provide a uniform evaluation of all signs with various FEA factors, a normalized rating procedure is conducted to integrate all FEA factors into one index. This will better help to identify the best/better signs under different wind speeds.

3.5.1 Normalized Rating Method of Traffic Signs

The method that is used to rate the performance of traffic signs is Normalized Rating Method, which was based on the simulation results. The formula is illustrated in Equation (4):

$$Y = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (4)$$

where,

Y: Normalized performance rating (minimum safety factor, maximum stress, maximum displacement, and deviation angle) of each traffic sign

X: Measured evaluation factor of each traffic signs

X_{min}: The minimum value of evaluation factor among all traffic signs

X_{max}: The maximum value of evaluation factor among all traffic signs

3.5.2 Normalized Rating Standard of Traffic Signs

In FEA, there are five main evaluation factors to be normalized, including: minimum safety factor, maximum stress, maximum displacement, deviation angle, and the Integrated Performance Index (IPI, sum of the former four). Besides, these five rating standard factors have their own standards, which are:

(1) Minimum Safety Factor (The bigger, the better. By using a converted Y', where Y'=1.0-Y, then, the situation would be transferred to "The smaller, the better").

(2) Maximum Stress (The smaller, the better).

(3) Maximum Displacement (The smaller, the better).

(4) Deviation Angle (The smaller, the better).

(5) Integrated Performance Index (Sum of the above four. The smaller, the better).

3.5.3 Normalized Performance Rating of Traffic Signs Based on the Normalized Method

According to Equation (4), the normalized performance indexes of all temporary traffic signs can be easily calculated. The following sections discuss the performance rating of signs with wind speeds of 90 mph, 80 mph, 70 mph, and 40 mph.

3.5.3.1 Normalized Performance Rating of Traffic Signs with Wind Speed 90 mph

Table 21 shows the performance rating of traffic signs with 90 mph wind speed. In Table 21, based on the factor "Min Safety Factor", the value of Sign 1004 is the lowest (rated as 0.004768), while the value of Sign 1006 is the highest (rated as 4.0). According to factor "Max Pressure", Sign 1000 receives the lowest value (rated as 0.0) and Sign 1006 receives the highest one (rated as 1.0). For factor "Max Displacement", Sign 2003 is the lowest value (0.0) and Sign 1006 is the highest (1.0). For factor "Deviation Angle", Sign 1006 obtained the highest value (1.0) and Sign 2003 got the lowest grade (0.0).

Per the Integrated Performance Index, Sign 1004 receives the lowest value (0.004768) and Sign 1006 gets the highest one (4.0), which means Sign 1004 has the best wind resistance performance, and Sign 1006 has the worst wind resistance performance.

Table 21. Performance Rating of Traffic Signs with 90 mph Wind Speed Based on the Normalized Method

Traffic Sign Type	Sign 1000	Sign 1001	Sign 1004	Sign 1005	Sign 1006	Sign 2000	Sign 2001	Sign 2002	Sign 2003
Min Safety Factor	0.943476	0.945176	**0.0**	0.316617	**1.0**	0.297918	0.259669	0.322992	0.297918
Max Pressure (MPa)	**0.0**	0.000138	0.003111	0.006537	**1.0**	0.006237	0.005732	0.00664	0.006272
Max Displacement (mm)	0.155905	0.252604	0.001063	0.00237	**1.0**	0.000591	0.000599	0.000226	**0.0**
α (°)	0.285753	0.441493	0.000595	0.002908	**1.0**	0.001655	0.001687	0.000643	**0.0**
Integrated Performance Index	1.385135	1.639411	**0.004768**	0.328433	**4.0**	0.306401	0.267686	0.330501	0.304189

Figure 86 shows the trend of IPI of all signs. The smaller the IPI is, the better the wind resistance ability of traffic signs is. Therefore, a ranking sequence of sign's wind resistance ability can be listed as:

Sign 1004 > Sign 2001 > Sign 2003 > Sign 2000 > Sign 2002 > Sign 1005 > Sign 1000 > Sign 1001 > Sign 1006.

Based on such ranking sequence, the recommended traffic signs from FEA in areas with 90 mph wind speed shall include: Sign 1004, Sign 2001, Sign 2003, Sign 2000, Sign 2002, and Sign 1005. Among them, Sign 2001, 2003, 2000, and 2002 are imbedding signs, while Signs 1004 and 1005 are skid signs.

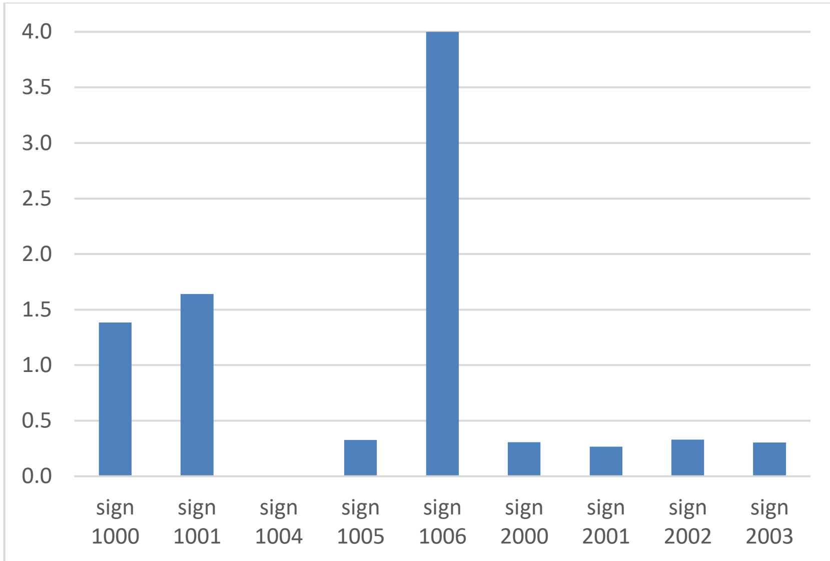


Figure 86. Integrated Performance Index of Traffic Signs with 90 mph Wind Speed Based on the Normalized Method

3.5.3.2 Normalized Performance Rating of Traffic Signs with Wind Speed 80 mph

Table 22 shows the performance rating of traffic signs with 80 mph wind speed. From Table 22, based on the factor "Minimum Safety", Sign 1004 is the lowest (0.0) and Sign 1006 is the highest (1.0). Based on factor "Max Pressure", Sign 1000 is the lowest (0.0), and Sign 1006 is the highest (1.0). For factor "Max Displacement", Sign 2003 is the lowest (0.0) and Sign 1006 is the highest (1.0). For factor "Deviation Angle", Sign 1006 is the highest (1.0) and Sign 2003 is the lowest (0.0).

Based on the IPI, Sign 1004 gets the lowest value (0.004297) and Sign 1006 receives the highest one (4.0), which means that Sign 1004 has the best wind resistance performance, while Sign 1006 has the worst wind resistance performance.

Table 22. Performance Rating of Traffic Signs with 80 mph Wind Speed Based on the Normalized Method

Traffic Sign Type	Sign 1000	Sign 1001	Sign 1004	Sign 1005	Sign 1006	Sign 2000	Sign 2001	Sign 2002	Sign 2003
Min Safety Factor	0.944371	0.946017	**0.0**	0.34233	**1.0**	0.310731	0.276498	0.335747	0.312706
Max Pressure (MPa)	**0.0**	0.000138	0.00296	0.006734	**1.0**	0.006236	0.005734	0.006636	0.006272
Max Displacement (mm)	0.155965	0.252685	0.000965	0.002258	**1.0**	0.000591	0.000599	0.000226	**0.0**
α (°)	0.252372	0.396485	0.000372	0.002358	**1.0**	0.001436	0.001472	0.00055	**0.0**
Integrated Performance Index	1.352708	1.595325	**0.004297**	0.353681	**4.0**	0.318994	0.284302	0.34316	0.318977

Figure 87 shows the IRI of all tested traffic signs. The bigger the IRI is, the better the wind resistance performance of traffic signs is. The sequence of traffic signs' wind resistance performance can be listed as:

> Sign 1004 > Sign 2001 > Sign 2003 > Sign 2000 > Sign 2002 > Sign 1005 > Sign 1000 > Sign 1001 > Sign 1006.

Based on this sequence, the recommended traffic signs from FEA for areas with 80 mph wind speed include: Sign 1004, Sign 2001, Sign 2003, Sign 2000, Sign 2002, and Sign 1005. Among them, Sign 2001, 2003, 2000, and 2002 are imbedding signs, while Signs 1004 and 1005 are skid signs.

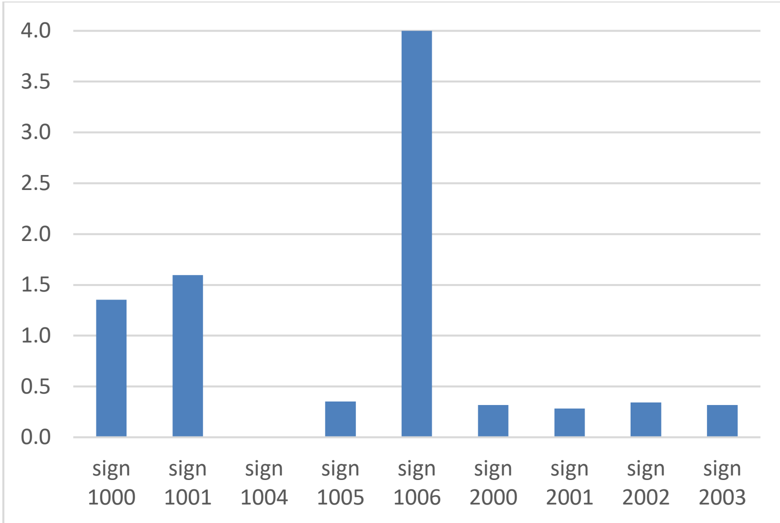


Figure 87. Integrated Performance Index of Traffic Signs with 80 mph Wind Speed Based on the Normalized Method

3.5.3.3 Normalized Performance Rating of Traffic Signs with Wind Speed 70 mph

Table 23 shows the performance rating of traffic signs with 70 mph wind speed. From Table 23, based on factor "Min Safety", Sign 1004 is the lowest (0.0) and Sign 1006 is the highest (1.0). According to the factor "Max Pressure", Sign 1000 gets the lowest value (0.0) and Sign 1006 has the highest value (1.0). For factor "Max Displacement", Sign 2003 is the lowest (0.0) and Sign 1006 is the highest (1.0). For factor "Deviation Angle", Sign 1006 obtained the highest value (1.0) and Sign 2003 gets the lowest one (0.0).

Based on the IPI combining all four factors, Sign 1004 gets the lowest value (0.003706) and Sign 1006 gets the highest one (4.0), which means that Sign 1004 has the best wind resistance performance, and Sign 1006 has the worst wind resistance performance.

Table 23. Performance Rating of Traffic Signs with 70 mph Wind Speed Based on the Normalized Method

Traffic Sign Type	Sign 1000	Sign 1001	Sign 1004	Sign 1005	Sign 1006	Sign 2000	Sign 2001	Sign 2002	Sign 2003
Min Safety Factor	0.946005	0.948449	**0.0**	0.377962	**1.0**	0.331786	0.298559	0.357195	0.335206
Max Pressure (MPa)	**0.0**	0.000137	0.002741	0.007015	**1.0**	0.006236	0.005733	0.006634	0.006271
Max Displacement (mm)	0.156114	0.252815	0.000822	0.002094	**1.0**	0.000591	0.000599	0.000226	**0.0**
α (°)	0.224108	0.35638	0.000143	0.001854	**1.0**	0.001283	0.001283	0.000489	**0.0**
Integrated Performance Index	1.326228	1.557782	**0.003706**	0.388925	**4.0**	0.339896	0.306173	0.364544	0.341478

Figure 88 shows the IPI of all relevant traffic signs, which indicates a sequence of wind resistance performance of traffic signs as:

> Sign 1004 > Sign 2001 > Sign 2003 > Sign 2000 > Sign 2002 > Sign 1005 > Sign 1000 > Sign 1001 > Sign 1006.

Based on this sequence, the recommended traffic signs from FEA for areas with 70 mph wind speed include: Sign 1004, Sign 2001, Sign 2003, Sign 2000, Sign 2002, and Sign 1005. Among them, Sign 2001, 2003, 2000, and 2002 are imbedding signs, while Signs 1004 and 1005 are skid signs.

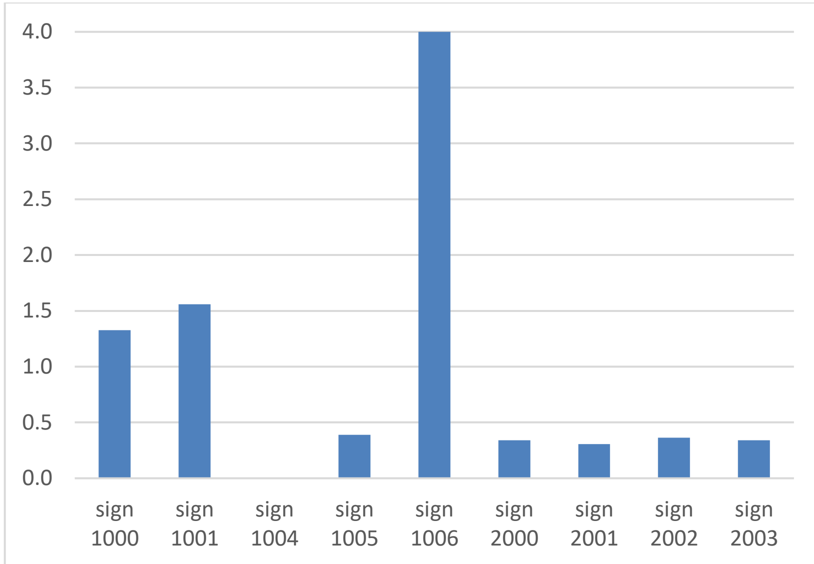


Figure 88. Integrated Performance Index of Traffic Signs with 70 mph Wind Speed Based on the Normalized Method

3.5.3.4 Normalized Performance Rating of Traffic Signs with Wind Speed 40 mph

Table 24 shows the performance rating of traffic signs with 40 mph wind speed. From Table 24, for factor "Min Safety", Sign 1004 is the lowest (0.0) and Sign 1006 is the highest (1.0). For factor "Max Pressure", Sign 1000 gets the lowest (0.0) and Sign 1006 gets the highest (1.0). For factor "Max Displacement", Sign 2003 receives the lowest (0.0) and Sign 1006 gets the highest value (1.0). For factor "Deviation Angle", Sign 1006 obtains the highest value (1.0) and the Sign 1004 gets the lowest one (0.0).

Based on IPI combining all four factors, Sign 2001 gets the lowest value (0.007963) and Sign 1006 gets the highest one (4.0), which means that Sign 2001 has the best wind resistance performance, and Sign 1006 has the worst wind resistance performance.

Table 24. Performance Rating of Traffic Signs with 40 mph Wind Speed Based on the Normalized Method

Traffic Sign Type	Sign 1000	Sign 1001	Sign 1004	Sign 1005	Sign 1006	Sign 2000	Sign 2001	Sign 2002	Sign 2003
Min Safety Factor	0.923759	0.926031	0.431201	0.436314	**1.0**	0.047722	**0.0**	0.082945	0.051131
Max Pressure (MPa)	**0.0**	0.00013	0.013241	0.013389	**1.0**	0.006226	0.005723	0.006625	0.006261
Max Displacement (mm)	0.008658	0.253481	9.8E-05	0.000648	**1.0**	0.000591	0.000599	0.000226	**0.0**
α (°)	0.009757	0.285355	**0.0**	0.00058	**1.0**	0.001642	0.001642	0.001014	0.000676
Integrated Performance Index	0.942174	1.464998	0.44454	0.45093	**4.0**	0.056181	**0.007963**	0.090811	0.058067

Figure 89 shows the IPI of all traffic signs, which illustrates a sequence of wind resistance performance of traffic signs as:

> Sign 2001 > Sign 2000 > Sign 2003 > Sign 2002 > Sign 1004 > Sign 1005 > Sign 1000 > Sign 1001 >> Sign 1006.

Based on this rank, several traffic signs were recommended for the areas with 90 mph wind speed, which includes Sign 1004, Sign 2001, Sign 2003, Sign 2000, Sign 2002, Sign 1005, Sign 1000, and Sign 1001. Among them, Sign 2001, 2003, 2000, and 2002 are imbedding signs, while Signs 1004, 1005, 1000, and 1001 are skid signs. Signs 1000 and 1001 are wooden ones.

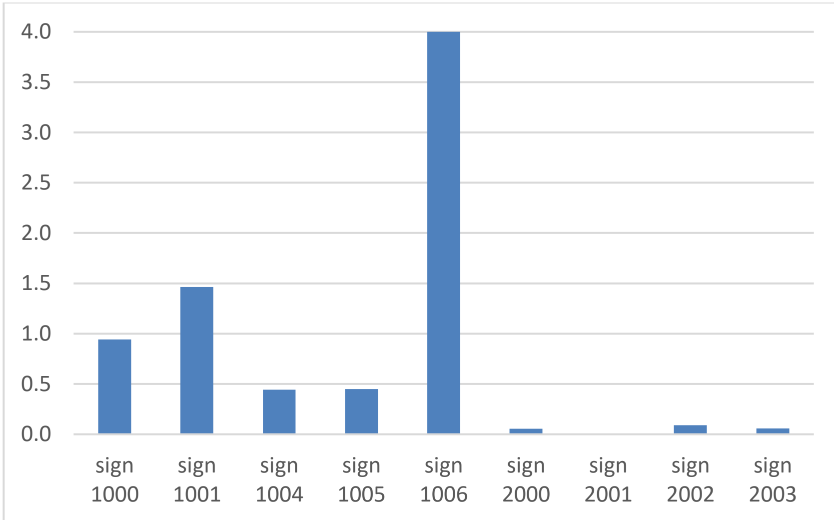


Figure 89. Integrated Performance Index of Traffic Signs with 40 mph Wind Speed Based on the Normalized Method

3.5.4 Traffic Sign Wind Resistance Performance Comparison under Different Wind Speed

With the normalized performance analyses, traffic signs with different wind speed can be compared. Figure 90 shows the relationship between traffic sign performance and wind speed. The smaller the IPI is, the better the traffic sign wind resistance performance is. Figure 90 shows the traffic signs performance of three traffic signs: Sign 1001, Sign 1000, and Sign 1006. Figure 91 shows the traffic signs performance of six traffic signs: Sign 1004, Sign 2001, Sign 2000, Sign 2003, Sign 2002, and Sign 1005. Figure 90 and Figure 91 are connected to each other based on the Y-axis (IPI). The ranges of decrease and increase of IPI of traffic signs in Figure 90 and Figure 91, respectively, are both very small. This implied that, the changes of IPI are small when wind speed is higher than 40 mph. The overall sequence of wind resistance performance under all types of high wind speeds (>= 40 mph) is:

> Sign 1004 > Sign 2001 > Sign 2000 > Sign 2003 > Sign 2002 > Sign 1005 **>>** Sign 1000 > Sign 1001 **>>** Sign 1006.

Figures 90 and 91 also indicate that, in general, embedding traffic signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003) with anchors commonly have stronger wind resistance performance. Another phenomenon is that, among skid traffic signs, the metal signs (Sign 1004 and Sign 1005) have better performance of resisting high speed wind than the wooden ones (Sign 1000 and Sign 1001).

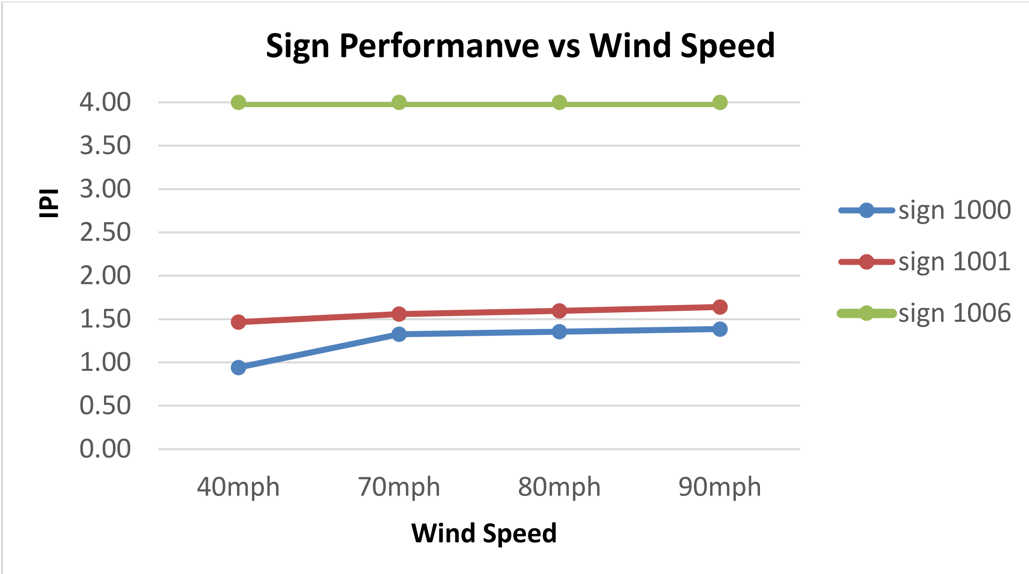


Figure 90. Traffic Sign Wind Resistance Performance Comparison under Different Wind Speed

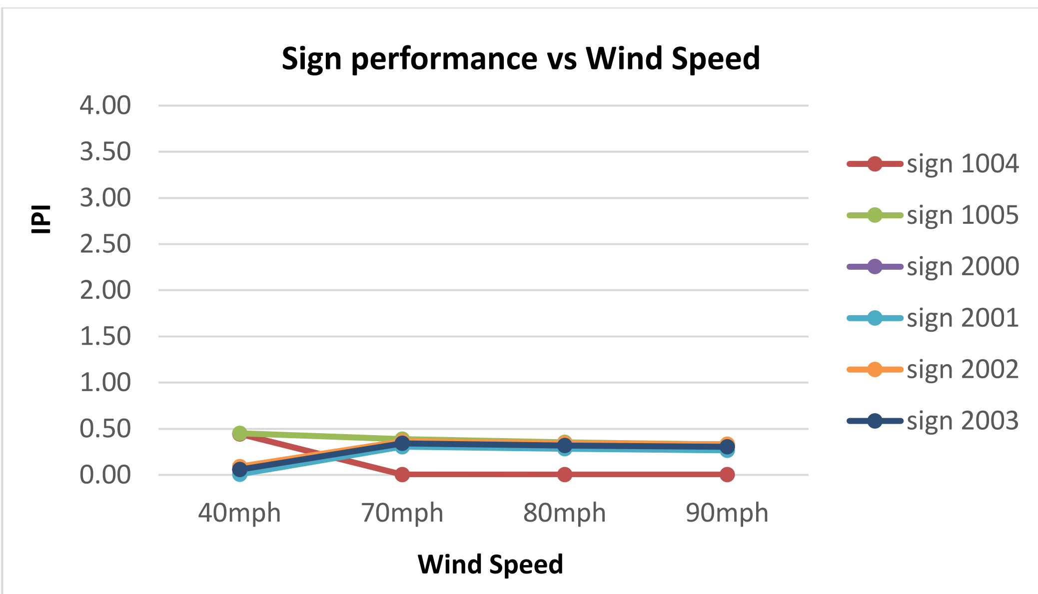


Figure 91. Traffic Sign Wind Resistance Performance Comparison under Different Wind Speed

3.6. Modification of Temporary Traffic Sign

From the simulation results in 3.4, there are many temporary traffic signs that would be fallen done under high wind. Several possible modifications of those traffic signs are considered with the following three scenarios:

(1) Extending the base by 10 inches;

(2) Adding another 4 sandbags on the base;

(3) Extending the base by 10 inches, and add another 4 sandbags on the base.

Four traffic sign design were modified through FEA simulation, which are Sign 1000, Sign 1001, Sign 1004, and Sign 1005. The comparisons of these results are discussed in following sections.

3.6.1 Performance Change when Modifying Sign 1000

Table 25 compares performance changes of traffic Sign 1000 under 90 mph wind speed. In Table 25, the changes of four factors (minimum safety factor, maximum pressure, maximum displacement, and deviation angle α (°)) are clearly displayed.

Based on the change of "Minimum Safety Factor", adding another four sandbags on the base will increase the safety of Sign 1000. The reason why the Minimum Safety Factor is still small is that, the wind that is blown on Sign 1000 is too strong for the sign to hold for a long time. The traffic sign may be fallen down or broken under the high wind. Adding more sandbag could, to a certain extent, improve the performance of wind resistance. The Minimum Safety Factor of the other two modification scenarios show a trend of reduction, which means these two scenarios reduce the wind resistance performance of traffic signs.

However, the Deviation Angle α (°) and Maximum Displacement increase for all three scenarios, which means these modification scenarios would not increase the performance of wind resistance.

In summary, adding more sandbags would increase the safety but not the Maximum Displacement nor Deviation Angle of Sign 1000. Extending the base by 10 inches would not help the improvement of any performance index.

Table 25. The Comparison of Modification for Traffic Sign 1000 under 90 mph Wind Speed

Modification of Traffic Sign 1000	Minimum Safety Factor	Maximum Pressure (MPa)	Maximum Displaceme nt (mm)	α (°)
Original	0.151	51.01	812.2	17.998
Extend the base by 10 inches	0.14 ↓	56.41 ↑	998.9 ↑	21.78 ↑
Add another 4 sandbags on the base	0.16 ↑	48.24 ↓	899.4 ↑	19.787 ↑
Extend the base by 10 inches and add another 4 sandbags on the base	0.137 ↓	56.42 ↑	999.9 ↑	21.799 ↑

3.6.2 Performance Change when Modifying Sign 1001

Table 26 compares performance changes of Sign 1001 under 90 mph wind speed. In Table 26, the changes of four factors (minimum safety factor, maximum pressure, maximum displacement, and deviation angle α (°)) are clearly displayed.

Adding another four sandbags on the base increases the Minimum Safety Factor, which to some certain extent, improves the performance of wind resistance. The Minimum Safety Factor of the other two scenarios are decreased. This means, these two scenarios reduce the wind resistance performance of Sign 1001.

However, the scenarios of extending the base by 10 inches and in the meantime adding another four sandbags on the base reduce the Deviation Angle α (°), which means these two scenarios improve wind resistance performance.

Thus, all three scenarios (adding more sandbags, extending the base by 10 inches, and both extending the base by 10 inches and adding more sandbags on the base) can basically improve the wind resistance performance of Sign 1001.

Table 26. The Comparison of Modification for Traffic Sign 1001 under 90 mph Wind Speed

Modification of Traffic Sign 1001	Minimum Safety Factor	Maximum Pressure (MPa)	Maximum Displacement (mm)	α (°)
Original	0.147	52.62	1312.0	27.690
Extend the base by 10 inches	0.13 ↓	57.37	1107 ↓	23.884 ↓
Add another 4 sandbags on the base	0.15 ↑	52.63 ↑	1319 ↑	27.816 ↑
Extend the base by 10 inches and add another 4 sandbags on the base	0.135 ↓	57.37 ↑	1108 ↓	23.903 ↓

3.6.3 Performance Change when Modifying Sign 1004

Table 27 compares performance changes of Sign 1004 under different modification scenarios with 90 mph wind speed. In Table 27, the changes of four factors (minimum safety factor, maximum pressure, maximum displacement, and deviation angle α (°)) are clearly displayed.

Both the scenario “add another 4 sandbags on the base”, and the scenario “extend the base by 10 inches” increase the Minimum Safety Factor.

The first two scenarios reduce the Maximum Pressure, while all three modification scenarios reduce the Maximum Displacement and Deviation angle α (°). This implies that, these modification scenarios will basically improve the wind resistance performance of Sign 1004.

So, all three scenarios (adding more sandbags, extending the base by 10 inches, and both extending the base by 10 inches and adding more sandbags on the base) can improve the wind resistance performance of Sign 1004.

Table 27. The Comparison of Modification for Traffic Sign 1004 with 90 mph Wind Speed

Modification of Traffic Sign 100	Minimum Safety Factor	Maximum Pressure (MPa)	Maximum Displaceme nt (mm)	α (°)
Original	2.371	87.31	11.9	0.252
Extend the base by 10 inches	2.49 ↑	83.14 ↓	10.6 ↓	0.225 ↓
Add another 4 sandbags on the base	2.4 ↑	83.93 ↓	10.9 ↓	0.231 ↓
Extend the base by 10 inches and add another 4 sandbags on the base	2.22 ↓	93.4 ↑	10.7 ↓	0.227 ↓

3.6.4 Performance Change when Modifying Sign 1005

Table 28 compares the modification scenarios of Sign 1005 under 90 mph wind speed. In Table 28, the changes of four factors (minimum safety factor, maximum pressure, maximum displacement, and deviation angle α (°)) are clearly illustrated.

In Table 28, the values of Minimum Safety Factor for all three modifications are reduced, which means that, these modifications would decrease the safety performance of Sign 1005. However, the Maximum Displacement and Angle α (°) are reduced for all three modification scenarios.

So, as for the sign 1005, all three scenarios (adding more sandbags, extending the base by 10 inches, and both extending the base by 10 inches and adding more sandbags on the base) could improve the wind resistance performance of Sign 1005.

Table 28. The Comparison of Modification for Traffic Sign 1005 with 90 mph Wind Speed

Modification of Traffic Sign 1005	Minimum Safety Factor	Maximum Pressure (MPa)	Maximum Displacement (mm)	α (°)
Original	1.626	127.30	18.6	0.396
Extend the base by 10 inches	1.266 ↓	163.6 ↑	12.4 ↓	0.264 ↓
Add another 4 sandbags on the base	1.57 ↓	131.7 ↑	17.5 ↓	0.372 ↓
Extend the base by 10 inches and & another 4 sandbags on the base	1.246 ↓	166.1 ↑	12.5 ↓	0.265 ↓

3.7 Comments on Finite Element Analysis Results

Sections 3.1-3.5 conducted FEA for temporary signs at work zones, while Section 3.6 implies that, modification of traffic signs would in some cases improve the wind resistance performance, but not very significant.

As having been summarized in section 3.5.4, the FEA suggests an overall sequence of wind resistance performance under all types of high wind speeds (>= 40 mph):

> Sign 1004 > Sign 2001 > Sign 2000 > Sign 2003 > Sign 2002 > Sign 1005 >> Sign 1000 > Sign 1001 >> Sign 1006.

In the above sign series, there is a significant reduction in performance beginning with Sign 1000. So, the better performed signs under high wind could be listed as:

> Sign 1004 > Sign 2001 > Sign 2000 > Sign 2003 > Sign 2002 > Sign 1005

Within this series, there are two groups of signs: Embedding Signs (Sign 2001, Sign 2000, Sign 2003, and Sign 2002), and Skid Signs (Sign 1004 and Sign 1005). The four Embedding Signs can be recalled from Figure 56, Figure 57, Figure 58, and Figure 59 in Section 2.4; while the two Skid Signs are in Figure 36 and Figure 37 in Section 2.3.2.1.

The EFA analyses, especially its Minimum Safety Factor, mainly consider if a sign would be broken under a certain level of high wind. It did not consider the situation if a sign would directly affect the traffic, especially during evening when no any worker is at the site to watch. This could happen to the skid signs which are not directly embedded to the ground.

Considering about this, the Embedding Signs (Sign 2001, Sign 2000, Sign 2003, and Sign 2002) shall be **demanded** to use under extremely higher wind areas. The also well performed Skid Signs (Sign 1004 and Sign 1005) can be used in relatively higher wind occasions. These are also consistent with the site observations in Chapter 2.

CHAPTER 4: COST EVALUATION AND IMPLICATION

4.1. Evaluation Rating

There are three parts of the evaluation rating, which includes the evaluation analysis from (1) the survey, (2) the evaluation analysis of the functional considerations through field observations, and (3) the evaluation analysis based on the finite element analysis. The evaluation rating process contains a number of criteria such as wind (1) resistance, (2) durability, (3) site adaptability, (4) installation costs, (5) maintenance costs, (6) environmental effects, and (7) handling costs.

4.1.1 Evaluation Rating from Survey

The survey used for evaluation rating purpose was designed on October 2018, revised on November 2018, distributed on December 2019, and followed up on January 2019. The survey involves 11 types of signs.

1. Sign 1000: Wooded skids with 2 wooden legs sign
2. Sign 1001: Wooden long/intermediate-term single leg (H-leg) sign
3. Sign 1002: Com’s long/intermediate-term single leg (H-leg) sign
4. Sign 1003: H-base single upright with leg PSST skid sign
5. Sign 1004: Independent dual upright with leg PSST skid sign
6. Sign 1005: Dual leg PSST skid support sign
7. Sign 1006: Perforated square metal tubing with anchor sign
8. Sign 1007: Wood & HPPL short-term/short-duration H-leg sign
9. Sign 1008: X-base with single upright sign
10. Sign 1009: JB Witt PVC sign
11. Sign 1010: Hwy Com’s short-term H-leg sign

The survey consists of performance rating and setup rating. The performance rating includes wind resistance and durability of the signs. The setup rating includes site adaptability, installation costs, maintenance costs and handling costs of the signs. There are four levels of the rating: good, above average, average, below average, and poor. The overall rating is based on the majority of the voting. For example, among the survey participants, 3 ones vote for above average of a sign’s durability, 2 ones vote for average, 1 person vote for below average, then the overall rating of this sign's durability is above average. The evaluation rating results are shown in Table 29.

Table 29. Evaluation Rating Results Through Survey

Sign Type/ Criterion	Wind resistance	Durability	Site adaptability	Installation costs	Maintenance costs	Handling costs
1000						
1001						
1002						
1003						
1004						
1005						
1006						
1007						
1008						
1009						
1010						

Evaluation Legend	Good	Above Average	Average	Below Average	Poor

Based on Table 29, Sign 1006 (the *Perforated Square Metal Tubing with Anchor Sign*) obtained the highest rating. The rating for this sign on all criteria are "good". In the meantime, Sign 1004 (the *Independent Dual Upright with Leg PSST Skid Sign*) received the good rating on wind resistance and durability, and above average rating on adaptability, installation costs, maintenance costs, and handling costs. Sign 1005 (the *Dual Leg PSST Skid Support Sign*) received the above average rating on all criteria. Some signs have imbalanced performances on different criteria such as Sign 1008 (the *X-base with Single Upright Sign*). It has good site adaptability, lower installation costs, lower maintenance costs, and lower handling costs due to its lightweight structure and foldable base. But it received only an average performance on wind resistance and durability, also due to its lightweight structure. It was because of their overall better ratings, Sign 1004, Sign 1005, and Sign 1006 among those 11 signs, were selected for field observations and finite element analysis.

4.1.2 Evaluation Rating from the Functional Considerations through the Field Observation

The evaluation ratings of functional considerations through the field observation involve metal skid signs (e.g., Sign 1004, Sign 1005, Sign 1003), wooden skid signs (Sign 1000 and Sign 1001), embedding metal signs (e.g. Sign 2000), etc.

1. Sign 1004: Independent dual upright with leg PSST skid sign
2. Sign 1005: Dual leg PSST skid support Sign
3. Sign 1006: Perforated Square Metal Tubing with Anchor Sign
4. Sign 1008: X-base with Single Upright Sign
5. Sign 1000: Wooden Skids with 2 Wooden Legs Sign
6. Sign 1001: Wooden long/intermediate – term Single Leg (H-leg) Sign
7. Sign 1003: H-based Single Upright with Leg PPST Skid Sign
8. Sign 2000: Dual Leg Perforated Square Metal Tubing with Anchor Sign

During filed observations, the research team recorded and observed the performance of *the above eight traffic signs* with a large amount of video and photo records*. The performance measures used to evaluate traffic signs* in field observation and lab analyses include*:*

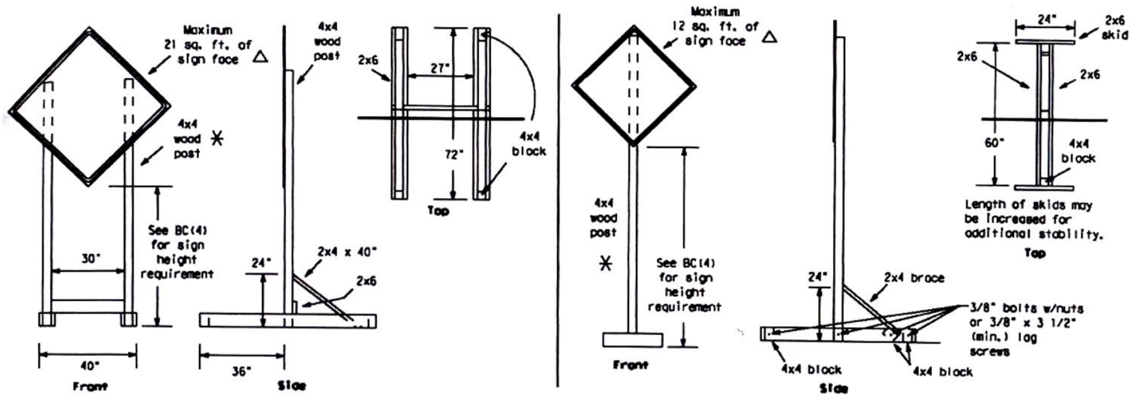
1. Trembling forth and back
2. Turning trembling
3. The direction of the traffic sign
4. The break of traffic sign support
5. The flexibility of the traffic signs
6. The damage of the traffic signs
7. The impact for the ground

The performance measure *trembling forth and back* means the traffic sign moved forth and back in the wind. *Turning trembling* indicates that the traffic sign had a rotation trend, which could make traffic sign to be fallen after a long run. The measure *direction of the traffic sign* means that, the connections between the traffic sign and its supports could be loosened, and thus, the traffic sign itself would change its face direction under high winds. The measure *break of traffic sign support* means that, traffic sign body supports were broken or cracked. The measure *flexibility of the traffic signs* indicates parts loosen like nuts. The measure *damage of the traffic signs* means the break or crack of traffic signs. The measure *impact for the ground* mainly indicates the size of the hole(s) surrounding sign posts at the ground level caused by the constant trembling of traffic signs. As the size of the hole grows, traffic signs at the end will be fallen down. Table 30 is a sample evaluation form summarizing the observations from video and photo records from field tests.

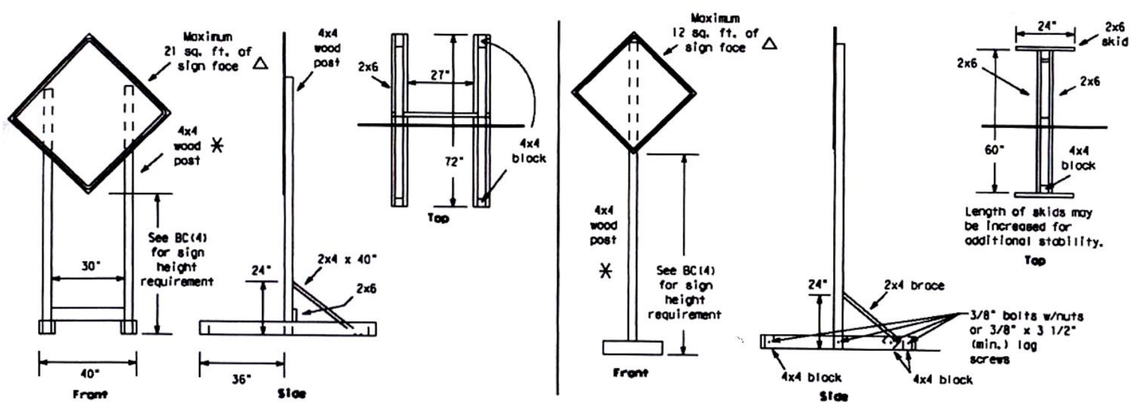
Table 30. Evaluation Rating Form Based on Field Observation

		Trembling Forth and back	Turning Trembling	The direction of Traffic Sign	The Break of Traffic Sign Support	The Flexibility of Traffic Sign	The Damage of Traffic Sign	The impact for the ground
Main Four Kinds of Temporary Traffic Sign	Sign 1004							
	Sign 1005							
	Sign 1006							
	Sign 1008							
Wood Temporary Traffic Sign	Sign 1000							
	Sign 1001							
Other Temporary Traffic Sign	Sign 1003							
	Sign 2000							

Based on the field observation, Sign 1003 (*H-based Single Upright with Let PPST Skid Sign with Ballast*) is widely used with a relatively performance. There are other types of signs that are also widely used with relatively good performance, including the ones with skid mounted wood sign supports: Sign 1000 (*Wooden Skids with 2 Wooden Legs Sign*) and Sign 1001 (*Wooden long/intermediate – term Single Leg* (*H-leg*) Sign). The structure and component of the *Skid Mounted Wood Sign Supports* are shown in Figure 92(a) and 92(b). There is an additional type of sign that is not included in the survey, which is coded as Sign 2000 (*Dual Leg Perforated Square Metal Tubing with Anchor Sign*). Both Sign 2000 and Sign 1003 from field observations are shown in Figure 93(a) and 93(b).



(a) Sign 1000: Wooden Skid with 2 Wooden Legs Sign



(b) Sign 1001: Wooden long /intermedia-term Single Leg (H-Leg) Sign

Figure 92. Skid Mounted Wood Sign Supports

(a) Sign 2000: Dual Leg Perforated Square Metal Tubing with Anchor Sign

(b) Sign 1003: H-base Single Upright with Leg PSST Skid Sign

Figure 93. Sign 2000 and Sign 1003

The evaluation rating criteria with multiple factors include wind resistance, durability, site adaptability, installation costs, maintenance costs, handling costs, and environmental effects. These are not evaluated in the survey. The evaluation rating is based on three grading levels: good, average, and fair. The evaluation results are obtained based on field observations and the interview with an on-site TxDOT engineer. Table 31 illustrates the sample form of evaluation based on field observations.

Table 31. Evaluation Rating Considering Multiple Factors Based on Field Observations

Sign Type/ Criterion	wind resistance	durability	site adaptability	installation costs	maintenance costs	handling costs	environmental effects
1004	Good	Good	Good	Good	Average	Average	Average
1005	Good	Good	Good	Average	Good	Average	Average
1006	Average	Good	Good	Good	Good	Good	Average
1008	Average	Average	Good	Good	Fair	Good	Average
1000	Good	Fair	Good	Good	Good	Good	Good
1001	Good	Fair	Good	Good	Good	Good	Good
1003	Average	Good	Good	Good	Average	Average	Average
2000	Good	Good	Average	Average	Good	Good	Average

Evaluation Legend	Good	Average	Fair

The rating color in Table 31 is based on the information obtained from field observations, where no sign design receives a perfect overall rating on all evaluation criteria. Among all sign types, Sign 1004, Sign 1005, and Sign 2000 obtained the best rating on criteria like wind resistance and durability. In the meantime, Sign 1000 and Sign 1001 receives a good rating on environmental effects because of its heavy wooden structure. Overall, Sign 1006, Sign 1008, Sign 1000, Sign 1001, and Sign 1003 have their own advantages on one or more criteria, but with some disadvantages on wind resistance or durability. Sing 1004, while having several good performances, receives average scores in maintenance costs, handling costs, and environmental effects.

4.1.3 Evaluation Rating from Finite Element Analysis

The evaluation rating of the functional considerations through the finite element analysis involves following signs:

1. Sign 1004: Independent Dual Upright with Leg PSST Skid Sign
2. Sign 1005: Dual Leg PSST Skid Support Sign
3. Sign 1006: Perforated Square Metal Tubing with Anchor
4. Sign 1000: Wooden Skids with 2 Wooden Legs Sign
5. Sign 1001: Wooden long/intermediate – term Single Leg (H-leg) Sign

6. Sign 2000: Dual Leg Perforated Square Metal Tubing with Anchor Sign
7. Sign 2001: Dual Leg Perforated Square Metal Tubing with Anchor Sign– Update 1
8. Sign 2002: Dual Leg Perforated Square Metal Tubing with Anchor Sign– Update 2
9. Sign 2003: Dual Leg Perforated Square Metal Tubing with Anchor Sign– Update 3

Chapter 3 indicates the FEA suggested sign sequence on wind resistance performance under all types of high wind speeds (>= 40 mph) as:

Sign 1004 > Sign 2001 > Sign 2000 > Sign 2003 > Sign 2002 > Sign 1005 >>
Sign 1000 > Sign 1001 >> Sign 1006.

Also, Section 3.7 suggests that, the Embedding Signs (Sign 2001, Sign 2000, Sign 2003, and Sign 2002) shall be **demanded** to use under extremely higher wind areas. The also well performed Skid Signs (Sign 1004 and Sign 1005) can be used in relatively higher wind areas.

4.2 Cost Evaluation

Each recommended sign has its own costs and benefits, which are analyzed here. The signs include:

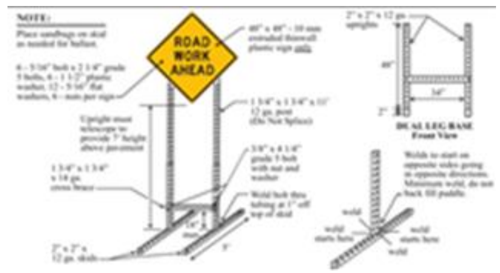
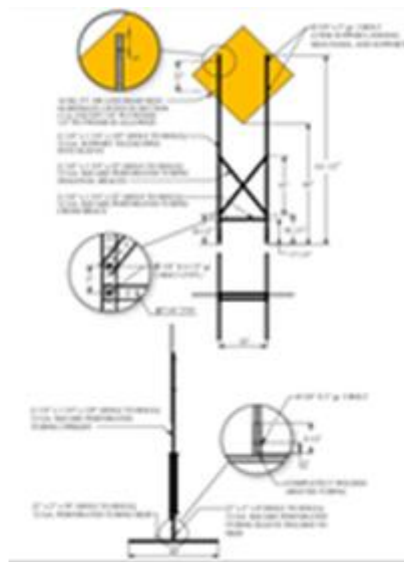
1. Sign 1004: Independent dual upright with leg PSST skid sign
2. Sign 1005: Dual leg PSST skid support Sign
3. Sign 1006: Perforated Square Metal Tubing with Anchor Sign
4. Sign 1008: X-base with Single Upright Sign
5. Sign 1000: Wooden Skids with 2 Wooden Legs Sign
6. Sign 1001: Wooden long/intermediate – term Single Leg (H-leg) Sign
7. Sign 1003: H-based Single Upright with Leg PPST Skid Sign
8. Sign 2000: Dual Leg Perforated Square Metal Tubing with Anchor Sign
9. Sign 2001: Dual Leg Perforated Square Metal Tubing with Anchor Sign– Update 1
10. Sign 2002: Dual Leg Perforated Square Metal Tubing with Anchor Sign– Update 2
11. Sign 2003: Dual Leg Perforated Square Metal Tubing with Anchor Sign– Update 3

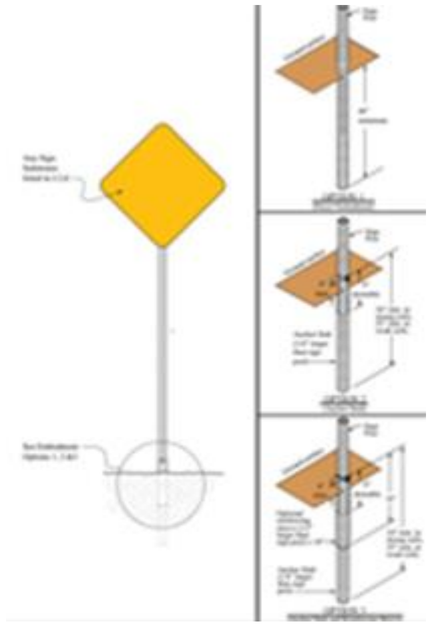
4.2.1 Costs of Recommended Sign Designs

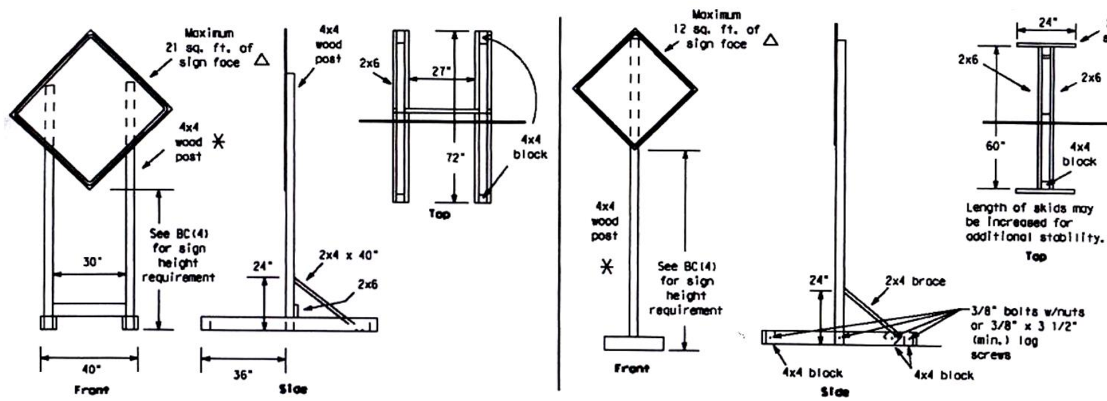
The costs of each sign design include:

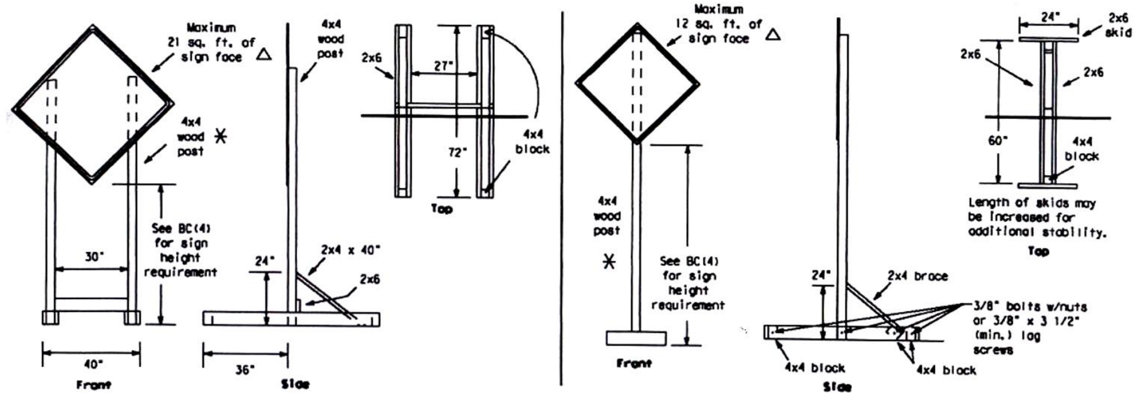
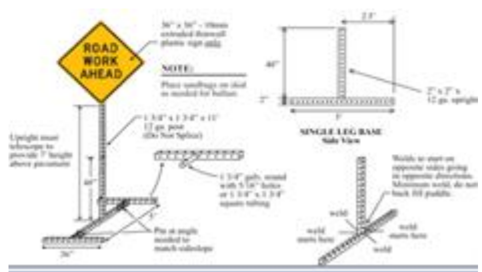
- Material costs: Main materials to support signs are square steel tube and wooden post. The price for a 7 feet square steel tube normally ranges from $17 to $40. The price for an 8 feet wood post normally ranges from $10 to $30, depending on the wooded type. Thus, under normal conditions, the metal materials are more expensive than the wooden ones. The cost of a Barricades Unlimited Sign Support (sign 1008) normally ranges from $120 to $164. Since the life cycle for metal support would be longer than a wooden one, the economic cost-benefit analysis of sign supports shall consider their life spans and replacement costs.
- Installation and handling costs: Installation and handling costs depend on the complexity and size of signs. Sign 1004, Sign 1005, Sign 1006, Sign 1003, Sign 2000, Sign 2001, Sign 2002, and Sign 2003 could be assembled on-site, thus require more installation costs and less handling costs. Sign 1000 and Sign 1001 need to be assembled pre-time, thus require less installation and handling costs. Sign 1008 is easy to install and as it can be folded, thus less handling costs. The installation costs also associate with the complexity of signs, especially for those that need to be assembled on-site, which is also related to the number of parts to assemble. The comparison of complexity to assemble each sign is shown in Table 32.

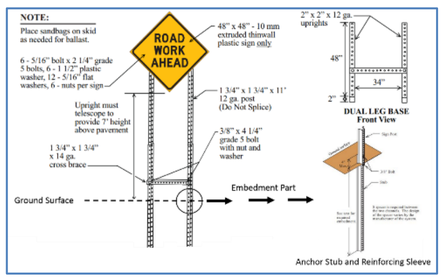
Table 32. Complexity to Assemble Signs On-site

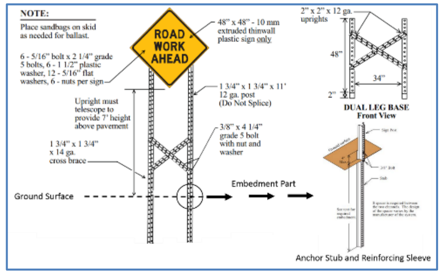
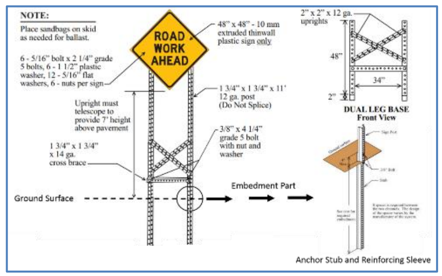
Sign Type	Structure	Number of Main Parts	Require on-site assembly?
1004		6	Yes
1005		6	Yes

Sign Type	Structure	Number of Main Parts	Require on-site assembly?
1006		3	Yes

<table>
<tr><th>Sign Type</th><th>Structure</th><th>Number of Main Parts</th><th>Require on-site assembly?</th></tr>
<tr><td>1008</td><td></td><td>2</td><td>No</td></tr>
<tr><td>1000</td><td>
</td><td>6</td><td>No</td></tr>
</table>

Sign Type	Structure	Number of Main Parts	Require on-site assembly?
1001		6	No
1003		5	Yes

Sign Type	Structure	Number of Main Parts	Require on-site assembly?
2000		3	Yes
2001		4	Yes

Sign Type	Structure	Number of Main Parts	Require on-site assembly?
2002		5	Yes
2003		6	Yes

The maintenance costs include:

1) Sign cleaning, which is inessential for a temporary traffic sign;
2) Vegetation control, which is inessential for a temporary traffic sign;
3) Theft and vandalism. Steel signs that are inserted into ground such as Sign 1004, Sign 1005, Sign 1006, Sign 2000, Sign 2001, Sign 2002, and Sign 2003 are more immune to theft and vandalism than wooded signs like Sign 1000 and Sign 1001, as well as other ground placing signs such as Sign 1008 and Sign 1003;
4) Repair and replacement. Metal signs such as sign 1003, 1004, 1005, 1006, 2000, 2001, 2002 and 2003 are more immune to decay by weather and bugs such as termite, so they generally need less repair. In the meantime, they could be assembled on-site, thus, replacement of parts or the whole sign process is also easier.

Table 33 compares the costs of all studied signs.

Table 33. Costs Comparison Between Recommended Sign Designs

Sign Type	Material	Installation	Handling	Maintenance
1004	High	High	Average	Low
1005	High	High	Average	Low
1006	Low	Low	Average	Low
1008	Low	Low	Low	High
1000	Average	Low	High	High
1001	Average	Low	High	High
1003	Average	Average	Average	Average
2000	Low	Low	Average	Low
2001	Average	Average	Average	Low
2002	Average	Average	Average	Low
2003	High	High	Average	Low

From Table 33, Sign 1004, Sign 1005, and Sign 2003 require more material and installation costs. Once installed, their consequent maintenance costs will be lower. Sign 1006 has the overall lowest cost. For Sign 1008, Sign 1000, and Sign 1001, the material and installation costs are relatively low, but they tend to require more maintenance after usage. Sign 1003, Sign 2000, Sign 2001, and Sign 2002 are moderate choices in terms of costs among all studied signs.

4.2.2 Benefits of Recommended Sign Designs

Sign that are analyzed in section 4.2.1 are also associated with the benefits, which can be classified as: (1) budget benefits, and (2) structural benefits. The detailed benefits of each sign are listed in Table 34.

Table 34. Benefits of the Recommended Signs

Sign Type	Benefits
1004	• High wind resistance • High durability • Site adaptability • Wind resistance can be enhanced by adding ballast
1005	• High wind resistance • Firm structure • High durability
1006	• High durability • Easy to install
1008	• Low price • Easy to handle and install • Site adaptability • Stability can be enhanced by adding ballast
1000	• Low price • Site adaptability • Wind resistance can be enhanced by adding ballast • Environmental efficient
1001	• Low price • Site adaptability • Wind resistance can be enhanced by adding ballast • Environmental efficient
1003	• High durability • Site adaptability • Wind resistance can be enhanced by adding ballast
2000	• High wind resistance • High durability • Easy to install
2001	• High wind resistance • High durability
2002	• High wind resistance • High durability
2003	• High wind resistance • High durability

As are shown in Table 34, the costs of sign are directly associated with their benefits. For example, a high durability and firm structure will be linked to higher material and installation costs. A high wind resistance sign design may limit their site adaptability. The selection of proper sign design shall also be considered based on their functional needs and environmental configurations.

CHAPTER 5: WARRANTS OF RECOMMENDED TECHNOLOGIES AND MATERIALS

In Chapter 5, a user-friendly standard sheet for temporary traffic signs in Texas work zones is first provided, followed by the map of recommended temporary signs under different wind speed in State of Texas. Finally, the recommended temporary signs in each TxDOT district and county together with the months to apply these recommendations are tabulated as a referent to TxDOT Engineers.

5.1 User-friendly Standard Sheet of Temporary Signs in Texas

As different work zone locations have various geographical and construction environments, it is not realistic to specify a sign that is suitable for all work zones under all environmental situations. Proper warrants of recommended technologies and materials should consider the diversity of work zone conditions. In this chapter, the work zone conditions are considered into the following aspects.

1. Environmental Conditions
   i) Hard ground surface or soft ground surface
   ii) Sloped ground or non-sloped ground
   iii) Moderate wind speed or high wind speed
2. Construction Project Conditions
   i) Budget of the materials and installation of the traffic signs
   ii) Maintenance manpower level
   iii) Ballast availability

A user-friendly standard sheet will be provided below. By utilizing the standard sheet, proper sign design recommendations will be proposed to the policy maker. The user-friendly standard sheet is illustrated in Table 35.

Table 35. User-friendly Standard Sheet

Sign Type	Advantages	Disadvantages	Recommendation
1004	• High wing resistance • High durability • Easy to handle • Easy to maintain Requires minimum replacement • Good site adaptability	• The material costs are higher • Requires heavy ballast	This sign is good for sites that are with **hard ground** such as paved road and shoulder, under **intense wind speeds** with **limited maintenance manpower**. The initial budget for the sign is relatively higher. However, the subsequent cost after installation shall be low. As it is not inserted into ground, **ballasts** such as sandbags are required. This sign is better performed on **non-slope ground**.
1005	• High durability • Easy to handle • Easy to maintain Requires minimum replacement • Good site adaptability	• The material costs are higher • Requires heavy ballast	This sign is good for the sites that have **soft ground** such as grassland or unpaved road, under **intense wind speeds** with **limited maintenance manpower**. The initial cost is relatively higher. However, the subsequent cost after installation is low. As it is not inserted onto ground, **ballasts** such as sandbags are required. This sign is better performed on **non-slope ground**.

Sign Type	**Advantages**	**Disadvantages**	**Recommendation**
1006	• High durability • Easy to handle • Easy to maintain • Requires minimum replacement • The material costs are limited	• Low wind resistant • Only having one leg thus easier to overturn • Need to be embedded into ground with lower site adaptability	This sign is good for the sites that have **soft ground** such as grassland or unpaved road, under **low wind speeds** and with **limited maintenance manpower**. The initial cost is relatively higher. However, the subsequent cost after installation is lower. As this sign is embedded into ground, **no ballasts** are required. This sign can be used on **sloped ground**.
1008	• Easy to handle • Easy to install • Material costs are low • High site adaptability	• Low wind resistance • Low durability • Easy to be damaged	This sign is good for the sites with **any ground types**, under **low wind speeds** and with **more maintenance manpower**. The initial material costs are low. Thus, multiple signs can be deployed. It is easy to be damaged by wind and vandalism, which thus requires more attention. This sign is with lightweight and **heavy ballasts** such as sandbags and tires are required. This sign can be used on **sloped ground**.

Sign Type	**Advantages**	**Disadvantages**	**Recommendation**
1000	• Moderate wind resistance • Do not need on-site installation • High site adaptability • Environmentally friendly	• Low durability • Easy to be damaged • Harder to handle • Requires heavy ballast	This sign is good for the sites with **any ground types**, under **moderate wind speeds** and with more **maintenance manpower**. The initial material costs are low. Multiple signs can be deployed. However, maintenance cost will be higher. It is easy to be damaged by weather such as humidity and sunshine, which thus requires more attention. This sign is with lightweight, and **heavy ballasts** such as sandbags are required. This sign can be used on **non-sloped ground**.

Sign Type	Advantages	Disadvantages	Recommendation
1001	• Moderate wind resistance • Do not need on-site installation • High site adaptability • Environmentally friendly	• Low durability • Easy to be damaged • Harder to handle • Requires heavy ballast	This sign is good for the sites with **any ground types**, under **moderate wind speeds** and with **more maintenance manpower**. The initial material costs are low. Multiple signs can be deployed. Maintenance cost will be higher. It is easy to be damaged by weather such as humidity and sunshine, which thus requires more attention. This sign is with lightweight, and thus **heavy ballasts** such as sandbags are required. This sign can be used on **non-sloped ground**.
1003	• High durability • Easy to handle • Easy to maintain Requires minimum replacement • Good site adaptability	• The material costs are higher • Higher potential to overturn • Requires heavy ballast	This sign is good for the sites that have **hard ground** such as paved road and shoulder, under **low wind speeds** and with **limited maintenance manpower**. The initial budget for one sign is relatively higher. However, the subsequent cost after installation is lower. As it is not embedded into ground, **ballasts** such as sandbags are required. This sign is better performed on **non-slope ground**.

Sign Type	**Advantages**	**Disadvantages**	**Recommendation**
2000	• High wing resistance • High durability • Easy to handle • Easy to maintain Requires minimum replacement	• The material costs are higher • Requires to be inserted into ground, thus lower site adaptability	This sign is good for the sites that have **soft ground** such as grassland or unpaved road, under **intense wind speeds** and with **limited maintenance manpower**. The initial cost for one sign is average, and the subsequent cost after installation is low. As this sign is embedded into ground, **no ballasts** are required. This sign can be used on **sloped ground**.
2001	• High wing resistance • High durability • Easy to handle • Easy to maintain Requires minimum replacement	• Requires to be inserted into ground, thus lower site adaptability	This sign is good for the sites that have **soft ground** such as grassland or unpaved road, under **high wind speeds** and with **limited maintenance manpower**. The installation cost for this sign is average, and the maintenance cost is low. As this sign is embedded into the ground, **no ballasts** are required. This sign can be used on **sloped ground**.

Sign Type	Advantages	Disadvantages	Recommendation
2002	• High wing resistance • High durability • Easy to handle • Easy to maintain Requires minimum replacement	• Requires to be inserted into ground, thus lower site adaptability	This sign is good for the sites that have **soft ground** such as grassland or unpaved road, under **high wind speeds** and with **limited maintenance manpower**. The installation cost for this sign is average, and the maintenance cost is low. As this sign is embedded into ground, **no ballasts** are required. This sign can be used on **sloped ground**.
2003	• High wing resistance • High durability • Easy to handle • Easy to maintain Requires minimum replacement	• High installation costs • Requires to be inserted into ground, thus lower site adaptability	This sign is good for the sites that have **soft ground** such as grassland or unpaved road, under **intense wind speeds** and with **limited maintenance manpower**. The initial cost for one sign is relatively higher. However, the subsequent cost after installation is lower. As this sign is embedded into ground, **no ballasts** are required. This sign can be used on **sloped ground**.

Table 35 provides a detailed user-friendly standard sheet that contains advantages and disadvantages of each sign. Proper sign design could be selected based on work zone condition, manpower level, and budget availability. The utilization of ballasts can significantly improve the performance of wind resistance and stability of Sign 1004, Sign 1008, Sign 1000, Sign 1001, and Sign 1003. Common ballast materials on traffic signs are sandbags and used vehicle tires. The choice of ballasts depends on the size of sign supports. Based on field observation, steel sign supports usually use sand bag ballast, wood and portable sign support can use both sand bags and used tires as ballast.

5.2 Map of Recommended Signs under Different Wind Speed in State of Texas

Based on the analysis, the identified temporary traffic signs at work zones under different wind speeds are summarized in Table 36. For areas where the wind speed is higher than 70 mph, Sign 1004, Sign 2001, Sign 2003, Sign 2000, Sign 2002, and Sign 1005 are good options. In areas with 40 mph wind speed, additional two traffic signs (Sign 1000 and Sign 1001) can be used. Under each wind speed level, there are two categories of signs: the embedding sign and the skid sign.

Table 36. Recommended Temporary Traffic Signs under Different Wind Speed

Wind Speed (mph)	Field Observation and FEA Recommended Temporary Signs for Texas Work Zones	
	Type of Signs	Code of Signs
90	Embedding	Sign 2001, Sign 2003, Sign 2000, Sign 2002
	Skid	Sign 1004 and Sign 1005
80	Embedding	Sign 2001, Sign 2003, Sign 2000, Sign 2002
	Skid	Sign 1004 and Sign 1005
70	Embedding	Sign 2001, Sign 2003, Sign 2000, Sign 2002
	Skid	Sign 1004 and Sign 1005
40	Embedding	Sign 2001, Sign 2003, Sign 2000, Sign 2002
	Skid	Sign 1004, Sign 1005, Sign 1000, and Sign 1001

All these results were based on the field observation and finite element analysis, which were discussed in ideal cases with limitations. In real cases, many other influencing factors like vehicle to sign crash, high vehicle wind force, ground slop, and so on, may also possibly turn down traffic signs. The field observation and simulation results shall be considered together with wind turner tests, which is however beyond the scope of this research project.

Figure 94 illustrates the traffic sign distribution map in Texas, which is based on Figure 3 for 25 years' Mean Recurrence Interval of Fastest Mile Wind Velocity at 33 feet height in

Texas. In Figure 94, zone 1 represents the areas where wind speed is 90 mph, where embedding traffic signs are mandatorily recommended. Zone 2 represents the areas where wind speed is 80 mph, where embedding traffic signs are recommended. Zone 3 represents the areas where the wind speed is 70 mph, where both embedding and skid signs are recommended.

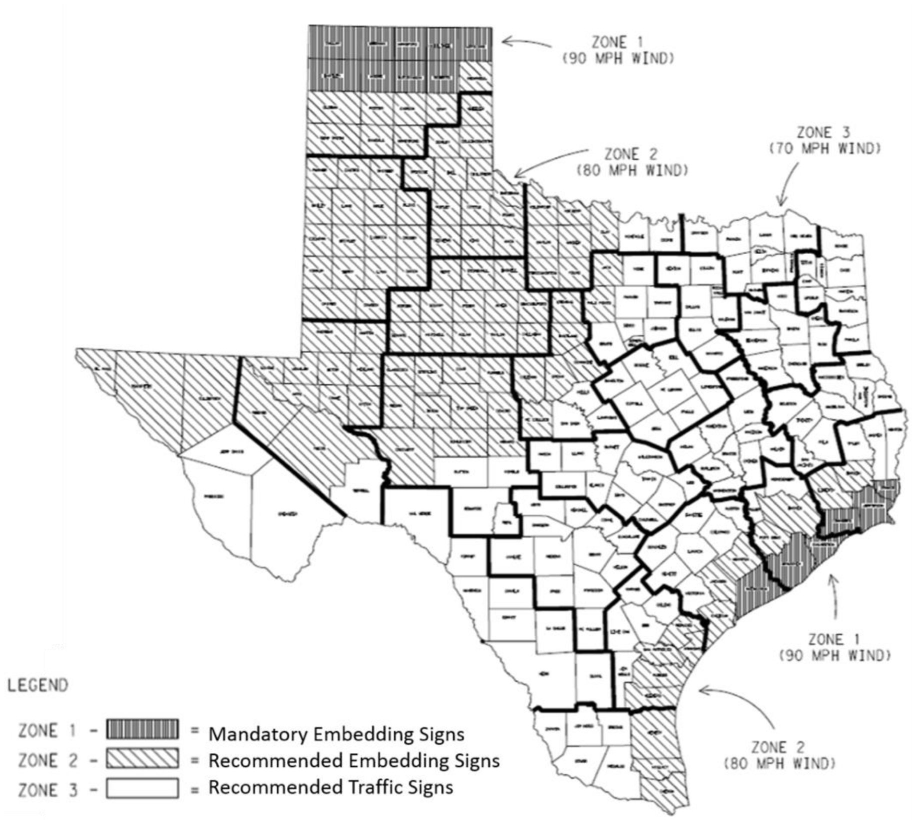
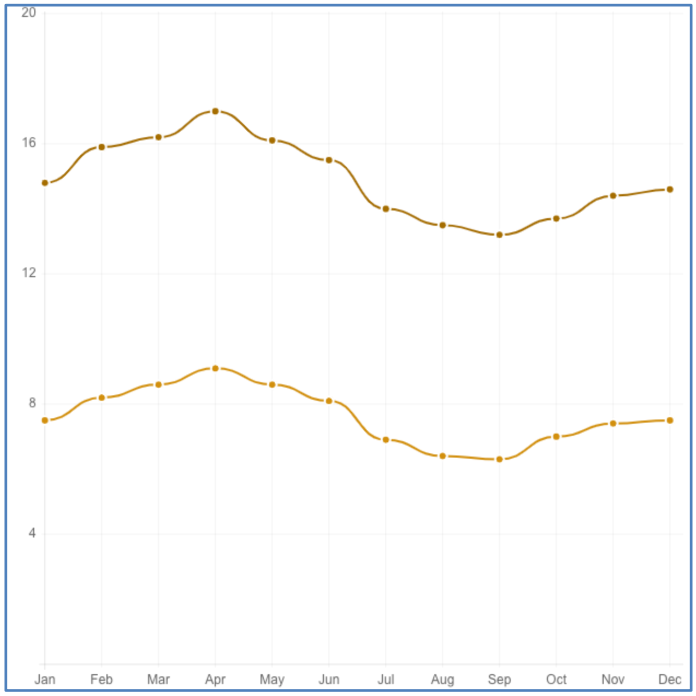


Figure 94. Recommended Temporary Traffic Sign Zones in Texas

5.3 Recommended Temporary Signs for Each TxDOT District and County with Months to Apply

In order to identify the months that a certain temporary sign shall be applied to a certain TxDOT district and county, the wind distribution information in Texas is analyzed. Texas is normally experiencing moderate wind with the highest wind happening in April, followed by May and March (https://championtraveler.com/dates/best-time-to-visit-texas-us/). Figure 95 illustrates the monthly average (lower curve) and maximum (upper curve) wind speeds in Texas with wind speed unit in Knot. In April, the average Texas wind speed is around 9.1 knots (10.5 mph), while the maximum sustained winds (the highest speed for the day lasting more than a few moments) are in late April with sustained speeds up to 17.6 knots (20.25 mph).



Source: https://championtraveler.com/dates/best-time-to-visit-texas-us/

Figure 95. Texas Monthly Average Wind Speed (Max and Average) in knots.

Table 37 lists the monthly wind distribution of 10 windy cities in Texas, where the months marked in blue highlight the months with relatively higher wind speed.

Table 37. Monthly Wind Distribution of Ten Cities in Texas *(Speed unit: mph)*

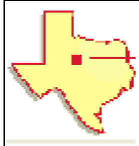
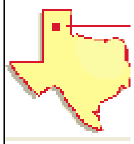
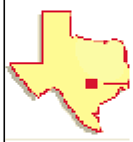
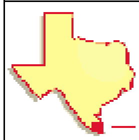
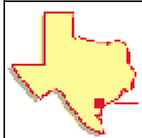
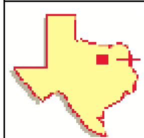
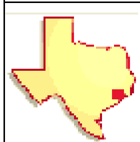
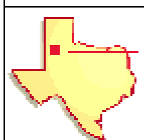
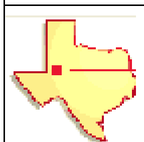
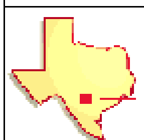
City		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	**Abilene**	12.7	13.8	15	15	15	15	11.5	10.4	11.5	12.7	12.7	12.7
	**Amarillo**	13.8	13.8	16.1	16.1	16.1	15	13.8	12.7	13.8	13.8	13.8	13.8
	**Austin**	9.2	10.4	11.5	11.5	11.5	10.4	9.2	8.1	8.1	8.1	9.2	9.2
	**Pharr**	12.7	17.3	17.3	17.3	15	13.8	12.7	11.5	10.4	10.4	13.8	12.7
	**Corpus Christi**	15	16.1	17.3	15	13.8	12.7	12.7	12.7	11.5	10.4	13.8	15
	**Dallas**	10.8	11.2	12.1	12.1	11.3	10.3	10	8.6	8.7	9.7	10.7	10.4
	**Houston**	9.2	9.2	11.5	11.5	10.4	10.4	8.1	9.2	6.9	9.2	8.1	9.2
	**Lubbock**	11.5	12.7	13.8	15	15	13.8	12.7	11.5	11.5	11.5	11.5	12.7
	**Odessa**	9.2	10.4	12.7	12.7	13.8	12.7	11.5	10.4	10.4	11.5	10.4	10.4
	**San Antonio**	10.4	11.5	11.5	11.5	11.5	11.5	10.4	10.4	9.2	10.4	10.4	10.4

Table 38 illustrates the wind coefficient related to each city's yearly average. The highlighted ones are where wind speed is higher than yearly average. These distributions are used to identify the months each district and county shall mandatorily use embedding signs.

Table 38. Monthly Wind Distribution in Ten Texas Cities in Relation to Respective Yearly Average

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	0.96	1.05	1.14	1.14	1.14	1.14	0.87	0.79	0.87	0.96	0.96	0.96
Amarillo	0.96	0.96	1.12	1.12	1.12	1.04	0.96	0.88	0.96	0.96	0.96	0.96
Austin	0.95	1.07	1.19	1.19	1.19	1.07	0.95	0.84	0.84	0.84	0.95	0.95
Pharr	0.92	1.26	1.26	1.26	1.09	1.00	0.92	0.84	0.76	0.76	1.00	0.92
Corpus Christi	1.08	1.16	1.25	1.08	1.00	0.92	0.92	0.92	0.83	0.75	1.00	1.08
Dallas	1.03	1.07	1.15	1.15	1.08	0.98	0.95	0.82	0.83	0.92	1.02	0.99
Houston	0.98	0.98	1.22	1.22	1.11	1.11	0.86	0.98	0.73	0.98	0.86	0.98
Lubbock	0.90	0.99	1.08	1.17	1.17	1.08	0.99	0.90	0.90	0.90	0.90	0.99
Odessa	0.81	0.92	1.12	1.12	1.22	1.12	1.01	0.92	0.92	1.01	0.92	0.92
San Antonio	0.97	1.07	1.07	1.07	1.07	1.07	0.97	0.97	0.86	0.97	0.97	0.97

These ten cities are distributed in different areas of Texas, covering all wind speed zones in Figure 3 and Figure 94. Thus, the monthly wind speed distributions in these ten cities can be converted for the distributions of wind speed in all wind and sign zones in Figure 94. If there is no county that has a city included in Table 38, the wind distribution of a city in same wind zone with similar geolocation will be applied. This is sufficiently enough to identify the months that each type of recommended temporary signs to apply in all TxDOT districts and counties. Such information is listed in details in Table 39.

Table 39. Traffic Sign Recommendation for the Counties in Texas with Specific Months to Apply

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
		Skid Signs are not Recommended	Limit the Use of Skid Signs	
ABL	Callahan	N/A	Mar, Apr, May, Jun	Jan, Feb, Jul, Aug, Sep, Oct, Nov, Dec
	Fisher			
	Haskell			
	Howard			
	Jones			
	Kent			
	Mitchell			
	Nolan			
	Scurry			
	Shackelford			
	Stonewall			
	Borden			
	Taylor			
AMA	Dallam	Mar, Apr, May, Jun	N/A	Jan, Feb, Jul, Aug, Sep, Oct, Nov, Dec
	Hansford			
	Hartley			
	Hutchinson			
	Lipscomb			
	Moore			
	Ochiltree			
	Roberts			
	Sherman			

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003) Skid Signs are not Recommended	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003) Limit the Use of Skid Signs	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
	Armstrong	N/A	Mar, Apr, May, Jun	Jan, Feb, Jul, Aug, Sep, Oct, Nov, Dec
	Carson			
	Deaf Smith			
	Gray			
	Hemphill			
	Oldham			
	Potter			
	Randall			
ATL	Bowie	N/A	Jan, Feb, Mar, Apr, May, Nov	Jun, Jul, Aug, Sep, Oct, Dec
	Camp			
	Cass			
	Harrison			
	Marion			
	Morris			
	Panola			
	Titus			
	Upshur			
AUS	Bastrop	N/A	Feb, Mar, Apr, May, Jun	Jan, Jul, Aug, Sep, Oct, Nov, Dec
	Blanco			
	Burnet			
	Caldwell			
	Gillespie			
	Hays			

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003) Skid Signs are not Recommended	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003) Limit the Use of Skid Signs	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
	Lee			
	Llano			
	Mason			
	Travis			
	Williamson			
BMT	Chambers	Jan, Feb, Mar, Apr, Dec	N/A	May, Jun, Jul, Aug, Sep, Oct, Nov
	Jefferson			
	Orange			
	Hardin	N/A	Mar, Apr, May, Jun	Jan, Feb, Aug, Sep, Oct, Dec Jul, Nov
	Liberty			
	Jasper	N/A	N/A	Jan to Dec
	Newton			
	Tyler			
BWD	Brown	N/A	Mar, Apr, May, Jun	Jan, Feb, Jul, Aug, Sep, Oct, Nov, Dec
	Coleman			
	Comanche			
	Eastland			
	McCulloch			
	Stephens			
	Lampasas	N/A	N/A	Jan to Dec
	Mills			
	San Saba			
BRY	Brazos	N/A	N/A	Jan to Dec

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
		Skid Signs are not Recommended	**Limit the Use of Skid Signs**	
	Burleson			
	Freestone			
	Grimes			
	Leon			
	Madison			
	Milam			
	Robertson			
	Walker			
	Washington			
CHS	Briscoe	N/A	Mar, Apr, May, Jun	Jan, Feb, Jul, Aug, Sep, Oct, Nov, Dec
	Childress			
	Collingsworth			
	Cottle			
	Dickens			
	Donley			
	Foard			
	Hall			
	Hardeman			
	King			
	Knox			
	Motley			
	Wheeler			
CRP	Aransas	N/A	Jan, Feb, Mar, Apr, Dec	May, Jun, Jul, Aug, Sep, Oct, Nov

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003) Skid Signs are not Recommended	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003) Limit the Use of Skid Signs	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
	Kleberg			
	Nueces			
	Refugio			
	San Patricio			
	Bee	N/A	N/A	Jan to Dec
	Goliad			
	Jim Wells			
	Karnes			
	Live Oak			
DAL	Collin	N/A	N/A	Jan to Dec
	Dallas			
	Denton			
	Ellis			
	Kaufman			
	Navarro			
	Rockwall			
ELP	Brewster	N/A	N/A	Jan to Dec
	Jeff Davis			
	Presidio			
	Culberson	N/A	Jan, Feb, Mar, Apr, May	Jun, Jul, Aug, Sep, Oct, Nov Dec
	El Paso			
	Hudspeth			
FTW	Erath	N/A	N/A	Jan to Dec

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
		Skid Signs are not Recommended	Limit the Use of Skid Signs	
	Hood			
	Johnson			
	Parker			
	Somervell			
	Tarrant			
	Wise			
	Jack	N/A	Mar, Apr, May, Jun	Jan, Feb, Jul, Aug, Sep, Oct, Nov, Dec
	Palo Pinto			
HOU	Fort Bend	N/A	Mar, Apr, May, Jun	Jan, Feb, Jul, Aug, Sep, Oct, Nov, Dec
	Harris			
	Brazoria	Feb, Mar, Apr, May	N/A	Jan, Jun, Jul, Aug, Sep, Oct, Nov, Dec,
	Galveston			
	Montgomery	N/A	N/A	Jan to Dec
	Waller			
LRD	Dimmit	N/A	N/A	Jan to Dec
	Duval			
	Kinney			
	La Salle			
	Maverick			
	Val Verde			
	Webb			
	Zavala			
LBB	Bailey	N/A	Mar, Apr, May, Jun	Jan, Feb, Jul, Aug, Sep, Oct, Nov, Dec

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
		Skid Signs are not Recommended	Limit the Use of Skid Signs	
	Castro			
	Cochran			
	Crosby			
	Dawson			
	Floyd			
	Garnes			
	Garza			
	Hale			
	Hockley			
	Lamb			
	Lubbock			
	Lynn			
	Parmer			
	Swisher			
	Terry			
	Yoakum			
LFK	Angelina	N/A	N/A	Jan to Dec
	Houston			
	Nacogdoches			
	Polk			
	Sabine			
	San Augustine			
	San Jacinto			

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
		Skid Signs are not Recommended	Limit the Use of Skid Signs	
	Shelby			
	Trinity			
ODA	Crane	N/A	Mar, Apr, May, Jun	Jan, Feb, Jul, Aug, Sep, Oct, Nov, Dec
	Ector			
	Loving			
	Martin			
	Midland			
	Pecos			
	Reeves			
	Upton			
	Ward			
	Andrews			
	Winkler			
	Terrell	N/A	N/A	Jan to Dec
PAR	Delta	N/A	N/A	Jan to Dec
	Fannin			
	Franklin			
	Grayson			
	Hopkins			
	Hunt			
	Lamar			
	Rains			
	Red River			

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
		Skid Signs are not Recommended	**Limit the Use of Skid Signs**	
PHR	Kenedy Cameron Willacy	N/A	Feb, Mar, Apr, May, Jun	Jan, Jul, Aug Sep, Oct, Nov Dec
	Hidalgo Jim Hogg Brooks Starr Zapata	N/A	N/A	Jan to Dec
SJT	Coke Concho Crockett Glasscock Irion Menard Reagan Runnels Schleicher Sterling Tom Green	N/A	Jan, Feb, Mar, Apr, May	Jun, Jul, Aug, Sep, Oct, Nov, Dec
	Edwards Kimble Real Sutton	N/A	N/A	Jan to Dec

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
		Skid Signs are not Recommended	**Limit the Use of Skid Signs**	
SAT	Atascosa	N/A	N/A	Jan to Dec
	Bandera			
	Bexar			
	Comal			
	Frio			
	Guadalupe			
	Kendall			
	Kerr			
	McMullen			
	Medina			
	Uvalde			
	Wilson			
TYL	Anderson	N/A	N/A	Jan to Dec
	Cherokee			
	Gregg			
	Henderson			
	Rusk			
	Smith			
	Van Zandt			
	Wood			
WAC	Bell	N/A	N/A	Jan to Dec
	Bosque			
	Coryell			

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003) Skid Signs are not Recommended	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003) Limit the Use of Skid Signs	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
	Falls			
	Hamilton			
	Hill			
	Limestone			
	McLennan			
WFS	Archer	N/A	Mar, Apr, May, Jun	Jan, Feb, Jul, Aug, Sep, Oct, Nov, Dec
	Baylor			
	Clay			
	Throckmorton			
	Wichita			
	Wilbarger			
	Young			
	Cooke	N/A	N/A	Jan to Dec
	Montague			
YKM	Austin	N/A	N/A	Jan to Dec
	Colorado			
	DeWitt			
	Fayette			
	Gonzales			
	Lavaca			
	Victoria			
	Calhoun	N/A	Jan, Feb, Mar, Apr, Dec	May, Jun, Jul, Aug, Sep, Oct, Nov
	Jackson			

TxDOT District	Affected County	Strongly Recommend Embedding Signs (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs are Recommend (Sign 2000, Sign 2001, Sign 2002, Sign 2003)	Embedding Signs and Skid Signs, including the Wooden Signs, are all Recommended
		Skid Signs are not Recommended	Limit the Use of Skid Signs	
	Wharton			
	Matagorda	Jan, Feb, Mar, Apr, Dec	N/A	May, Jun, Jul, Aug, Sep, Oct, Nov

In Table 38, TxDOT districts and their counties in Zone 1 are provided with the months that embedding signs (e.g., Sign 2000, Sign 2001, Sign 2002, and Sign 2003) are strongly recommended while skid signs shall not be used. For districts and counties in Zone 2, the months are also provided for recommended use of embedding signs while limiting the use of skid signs (e.g. Sign 1004 and Sign 1005). There is no limitation of sign use in other districts/counties and months for the rest of Zone 1 and Zone 2, and for Zone 3 in all months of the year. In these cases, all temporary signs can normally be used., which involves embedding signs, skid signs including those wooden ones like Sign 1000 and Sign 1001, are all applicable. The symbol “N/A” in Table 38 means that, the relevant specific recommendation is not applicable in those situations.

It should be noted that, Table 38 is a reference to traffic engineers in each TxDOT district. Since there are significant uncertainties in wind occurrences each year, the selection of sign types shall be strongly related to the forecasted wind speed in work zone areas. For example, Table 38 does not restrict the use of any type of signs in Harris County of Houston district in September. If a Hurricane with strong wind speed is forecasted in this area in September, the traffic engineers shall refer to Section 3.7 that, the Embedding Signs (Sign 2001, Sign 2000, Sign 2003, and Sign 2002) shall be **demanded** in extremely higher wind occasions.

CHAPTER 6. VALUE OF RESEARCH

6.1 Value of Research Table

This project is of great value of research. Table 39 lists the impacts of this project on different social and economic aspects to TxDOT and the entire State of Texas. The numerical values of this research are provided in sections following Table 40.

Table 40. Estimation of Value of Research

Benefit Area	Quality	Economy	Both	TxDOT	State	Both	Definition in context to the Problem Statement
Level of Knowledge			X	X			Research provides a better indication of which high wind options are effective.
Customer Satisfaction	X					X	Provides customers clear communication and reliable work zone signage will improve customer satisfaction.
System Reliability	X					X	Maintaining work zone signage helps prevent confusion and having fewer temporary signs blow over, particularly in high wind areas, will improve system reliability.
Increased Service Life			X	X			Less damage to temporary signs fall over will increase their service life
Improved Productivity and Work Efficiency			X			X	Contractors lose valuable production time and costs maintaining and replacing work zone signs. Those efforts and resources could be used more efficiently on construction. TxDOT inspectors spend time inspecting and verifying corrections to TCP, some of that time could be better spent on construction activities.
Expedited Project Delivery			X			X	Contractors lose valuable production time and costs maintaining and replacing work zone signs. Those efforts and resources could be used more efficiently on construction.

Benefit Area	Quality	Economy	Both	TxDOT	State	Both	Definition in context to the Problem Statement
Traffic and Congestion Reduction	X				X		Proper signage could help reduce motorist uncertainty and traffic congestion.
Reduced Construction, Operations, and Maintenance Cost		X			X		The current statewide average low bid for item 502 barricades, signs and traffic handling is over $6800 per month. A reliable system of ballasting traffic control devices will reduce this line item as contractors can focus on construction activities instead of maintaining/replacing traffic control signs/drums/etc.
Safety	X					X	Maintaining proper signage improves the traveling public and workers' safety in the work zones.

6.2 Inputs

- Approximate number of temporary signs in work zones of Texas in 2019 = 4,923
- 2019 Average AADT of work zones = 149
- Congestion cost = $10/vehicle/hour
- User cost = $22.12/hour
- Average construction cost per temporary sign = $250
- Average cost of temporary sign failure = $200
- 2019 Number of fatalities in work zones of Texas = 161
- 2019 Number of serious injury crashes in work zone of Texas = 684
- Average cost of one fatality = $1,234,489
- Average cost of one serious injury crash = $18,674

6.3 System Reliability

$$Cost = Cost\ of\ temporary\ sign\ failure * Number\ of\ temporary\ sign\square *$$
$$Possibility\ of\ temporary\ signs\ failure = \$200 * 4{,}923 * 10\% = \$98{,}462$$

6.4 Increased Service Life

Establishment of methods and criteria for service life prediction would lead to extended service lives of temporary signs.

$$Cost = Cost\ of\ temporary\ sign\ failure * Number\ of\ temporary\ signs *$$
$$Percentage\ of\ improvement = \$250 * 4{,}923 * 67\% = \$659{,}692$$

6.5 Improved Productivity and Work Efficiency

Temporary signs findings would improve TxDOT knowledge of which maintenance measures and corrosion protection measures have the greatest impact on extending the service lives of temporary signs, thus allowing TxDOT and consultants to be more efficient by specifying measures that have a higher impact; reduced work on temporary signs maintenance or replacement would also allow more time for other production work; funding could be allocated more efficiently across the various temporary signs funding programs.

$$Cost = Percentage\ of\ improvement * Number\ of\ temporary\ signs *$$
$$Construction\ cost\ per\ temporary\ sign = 67\% * 4{,}923 * \$250 = \$824{,}615$$

6.6 Reduced Administrative Cost

The reduced administrative cost is $15,000.

6.7 Traffic and Congestion Reduction

Texas drivers lose near 52 hours and $1,200 annually due to congestion in five of the largest metropolitan areas in the state. If the remaining life of a temporary sign is known, maintenance works and repairs can be optimized and made when really necessary. Therefore, the requirements for traffic control will be reduced, and when traffic control is reduced, traffic and congestion is reduced as well.

$Cost = AADT * Number\ of\ temporary\ signs * Possibility\ of\ temporary\ signs\ failure * Percentage\ of\ improvement * Congestion\ cost * 0.5 hour = 149 * 4{,}923 * 10\% * 67\% * \$10 * 0.5 = \$245{,}101$

6.8 Reduced User Cost

With an optimum plan of maintenance and repairs, the temporary signs will have less traffic and congestion. User cost usually are vehicle operating costs, travel time costs, and crash costs. These costs are the result of timing, duration, scope, and number of maintenance and repair work zones of each project. Work zones typically restrict the normal capacity of temporary signs and increase congestion; thus, user costs are caused by stops, speed changes, detours, delays and accidents.

$Cost = \$22.12/hour * AADT * Number\ of\ temporary\ signs * 0.5 hour * Percentage\ of\ imprvement * Possibility\ of\ temporary\ signs\ failure = \$22.12 * 149 * 0.5 * 67\% * 10\% = \$542.164$

6.9 Reduced Construction, Operations, and Maintenance Cost

Improved maintenance and accurate knowledge of the remaining life of a temporary sign will reduce construction costs. With better maintenance practices, the service life of a temporary sign could be extended, therefore the need for repairs and replacements will decrease. Each year, TxDOT spent around $50 million to do maintenance to temporary signs and around $300 million to replace, widen, repair or rehabilitate them. These expenditures are expected to be reduced by $14,302,230 with the implementation of the results from this research.

$Costs = (Cost\ of\ temporary\ sign\ failure * Number\ of\ temporary\ signs + Number\ of\ temporary\ signs * Construction\ cost\ per\ temporary\ sign) * Possibility\ of\ temporary\ signs\ failure * Percentage\ of\ improvement = (\$250 * 4923 + \$200 * 4923) * 67\% * 10\% = \$148{,}431$

6.10 Materials and Pavements

Accurate calculation of remaining life of temporary signs will allow to implement optimized maintenance and repair procedures. Accordingly, less maintenance and repair works will have to be scheduled, decreasing the expenditures on these works. Moreover, this research will find alternative materials that would provide advantages to service life of temporary signs in Texas.

$$Costs = Number\ of\ temporary\ signs * Possibility\ of\ temporary\ signs\ failure * Percentage\ of\ improvement * construction\ cost\ per\ temporary\ sign = 4{,}923 * 10\% * 67\% * \$250 = \$82{,}462$$

6.11 Safety

The major outcome of temporary signs improvement is the increased safety of work zones. Knowledge of the remaining life of a temporary sign means a more reliable system, with appropriate application of maintenance works and repairs. The less maintenance works performed, the safer the road is for workers doing the maintenance and for the users of the temporary signs. The implementation of improved technologies for new temporary signs will also increase their reliability and therefore their safety.

$$Cost = Number\ of\ fatality * Cost\ of\ fatality + Number\ of\ crash * Cost\ of\ crash = 161 * \$1{,}234{,}489 + 648 * \$18674 = \$211{,}525{,}745$$

Appendix A. Survey Form

Following is the Microsoft Word version of the survey; this text was placed online on SurveyMonkey.com.

Dear Respondent,
You are invited to take this survey, which is designed to collect information on the needs, concerns, and expectations of TxDOT engineers regarding the temporary signs at work zones in high wind areas in Texas. The purpose is to understand the existing technologies and materials that TxDOT engineers are using; as well as the performances, and practical and specific safety issues encountered in relevant TxDOT districts. This questionnaire is administered strictly by TxDOT and performed by Texas Southern University (TSU) through the research project 0-6993.
You are selected as we believe that, you are in a TxDOT district with high winds. Please kindly respond based on your experience in the ballasting and use of the following temporary signs in work zones all over your district. Refer to the link below for TxDOT **Compliant Work Zone Traffic Control Device List** (2017) to get detailed description of the temporary signs being evaluated (ftp://ftp.txdot.gov/pub/txdot-info/trf/pdf/cwztcd.pdf).
Please use the scale below for your ratings. (When this survey form is being uploaded on website in SurveyMonkey.com, TSU team will use pull out windows for the following 5 scales.)
1: Poor 2: Below Average 3: Average 4: Above Average 5: Outstanding

In the following survey questions, "Performances" means how firmly they stand against strong wind; "Safety issues" means how hazardous it could be to road users and residents if the temporary signs are blown away by the wind.
Should there be any technical questions, please contact Dr. Fengxiang Qiao at fengxiang.qiao@tsu.edu in TSU.
Thank you in advance for your participation!
Fengxiang Qiao, Ph.D.
Supervisor of TxDOT project 0-6993, and
Professor in Texas Southern University
fengxiang.qiao@tsu.edu

Part I: Basic Information

1. What TxDOT district are you currently located?

____

2. Do you experience high wind regularly in the above-named district?

____

3. Based on your own experiences and/or knowledge, which of the following wind speed would you consider a high wind that could induce the turnover of a temporary traffic sign in work zones?
   i. 19 – 24 mph
   ii. 25 – 31 mph
   iii. 32 – 38 mph
   iv. 39 – 46 mph
   v. 47 – 55 mph
   vi. Other value. Please specify ___________________
4. What period(s) in a calendar year do you experience high wind?

____

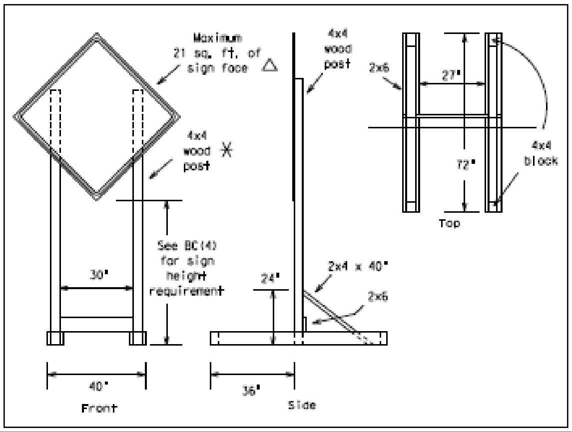
5. Does the high wind affect the ballasted temporary signs on work zones in this district?

____

6. Does the reasons why TxDOT requires only the use of their own approved temporary signs and rejects those produced by vendors in work zones include any of the following:
   i. For quality assurance
   ii. To avoid liability
   iii. To control the market
   iv. To cut down cost of project implementation
   v. Other (Specify) ____

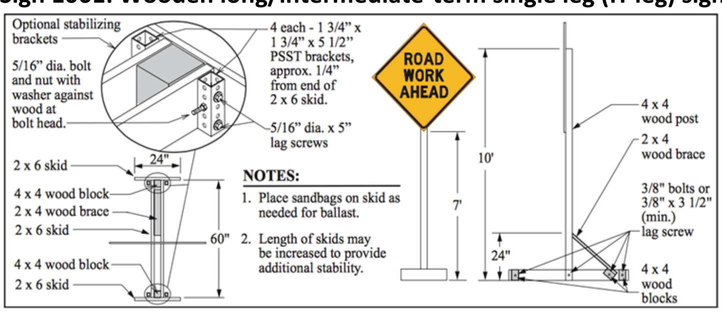
Part II: Please Kindly Evaluate the Temporary Signs in the Following Questions.

Sign 1000: Wooded skids with 2 wooden legs



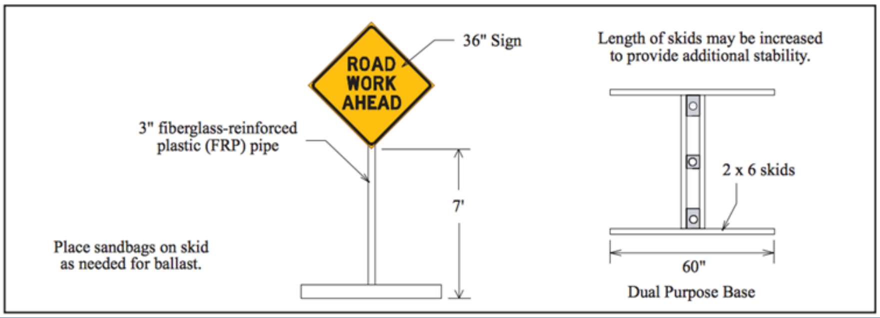
Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Sign 1001: Wooden long/intermediate-term single leg (H-leg) sign



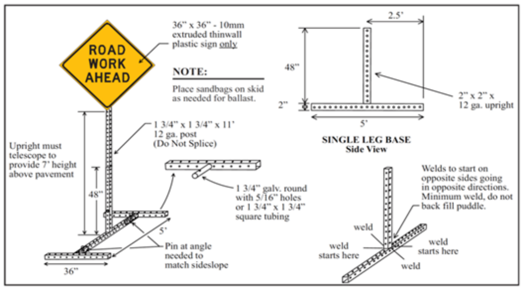
Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Sign 1002: Com's long/intermediate-term single leg (H-leg) sign



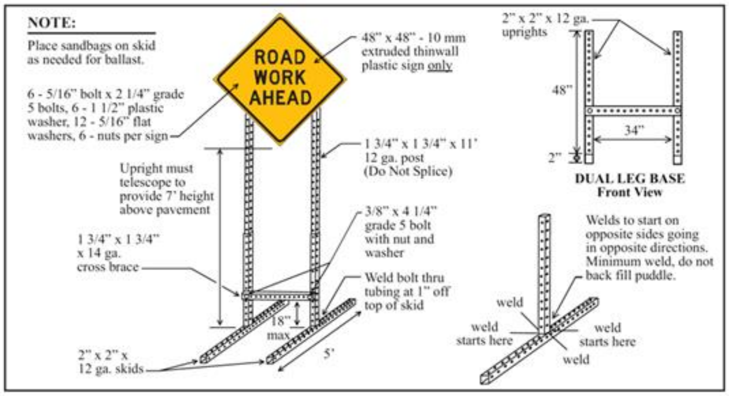
Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Sign 1003: H-base single upright with leg PSST skid sign



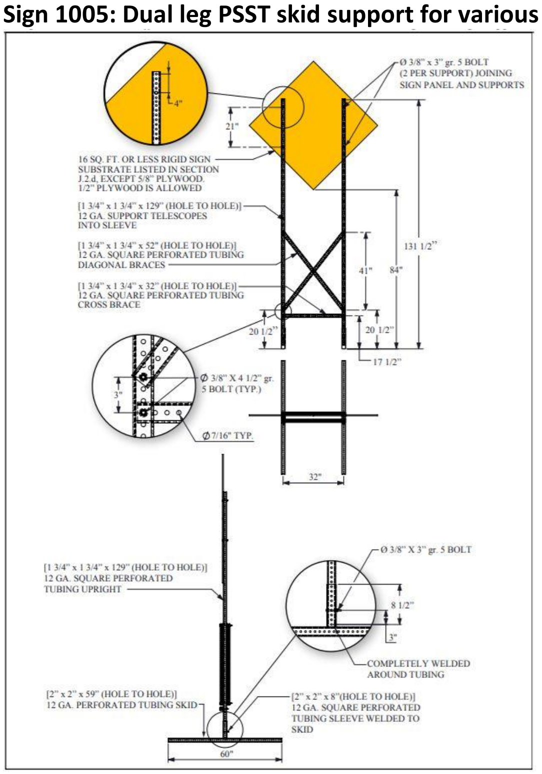
Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Sign 1004: Independent dual upright with leg PSST skid sign



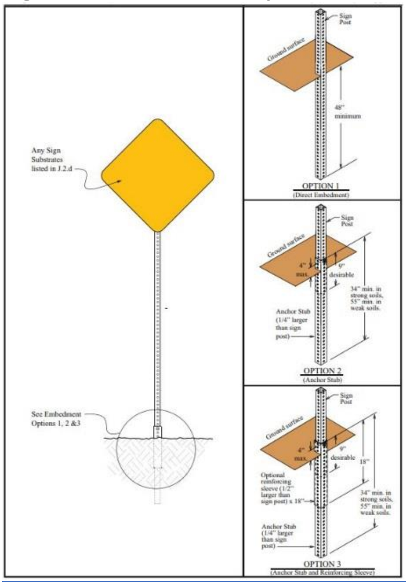
Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Sign 1005: Dual leg PSST skid support for various substrates (7 foot mounting height)



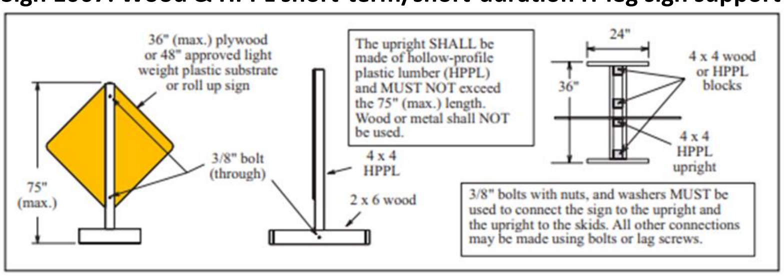
Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Sign 1006: Perforated square metal tubing with anchor



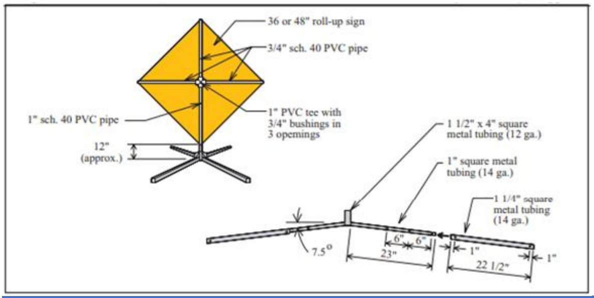
Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Sign 1007: Wood & HPPL short-term/short-duration H-leg sign support (1 foot mounting height)



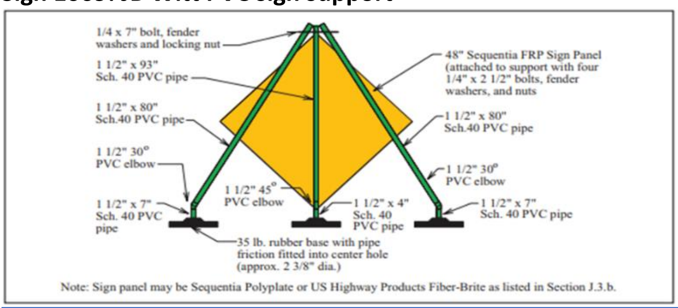
Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Sign 1008: X-base with single upright



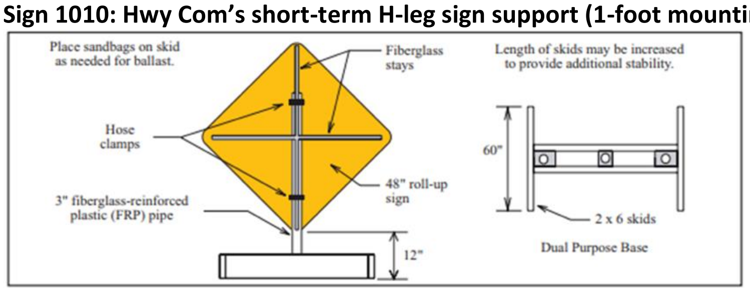
Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Sign 1009: JB Witt PVC sign support



Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Sign 1010: Hwy Com's short-term H-leg sign support (1-foot mounting height)



Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

7. If existing work zone sign support standards were to be modified, please list which methods would be preferred (check all that apply):

    i. Longer skid legs
    ii. More sand bags/ballasting
    iii. Restricting use of certain supports in high wind districts
    iv. Restricting use of certain supports based on duration of work
    v. Modified sign supports

Part III: Please Provide Information about New Technology and Materials.

8. Do you know some of the new technology and materials used as temporary signs?

- (●) Yes
- ( ) No

Itemize and rate them:

Temporary Sign	Performance Rating	Setup and Mobility Rating	Safety Rating	Comments/Observation

Your Contact Information (for the benefit of further contact of this project).

- Name

____

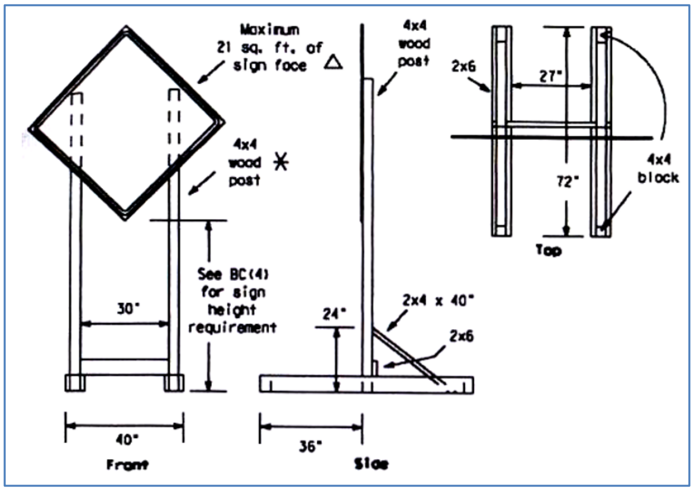
- Phone Number

____

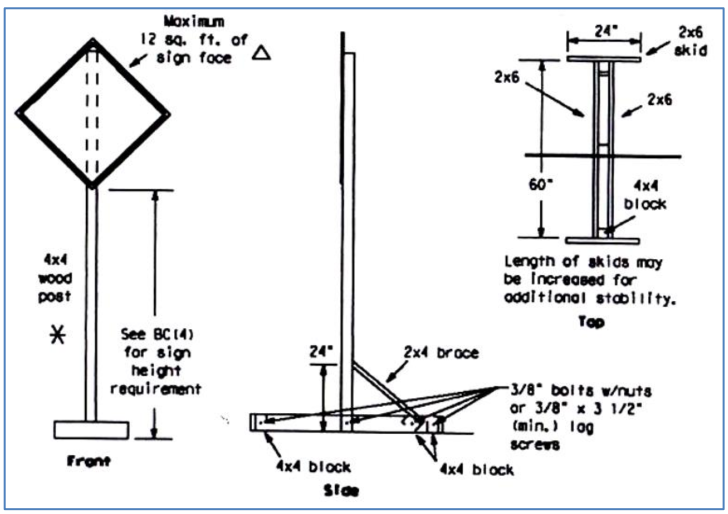
- E-mail

____

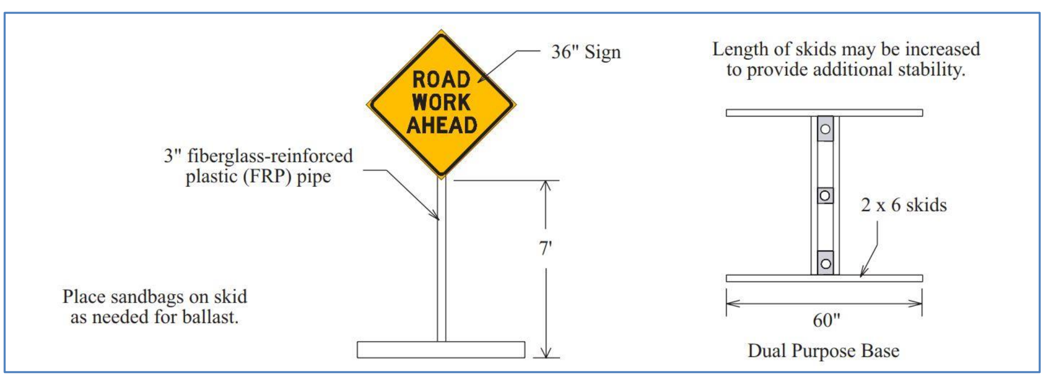
Appendix B: List of All Temporary Traffic Signs



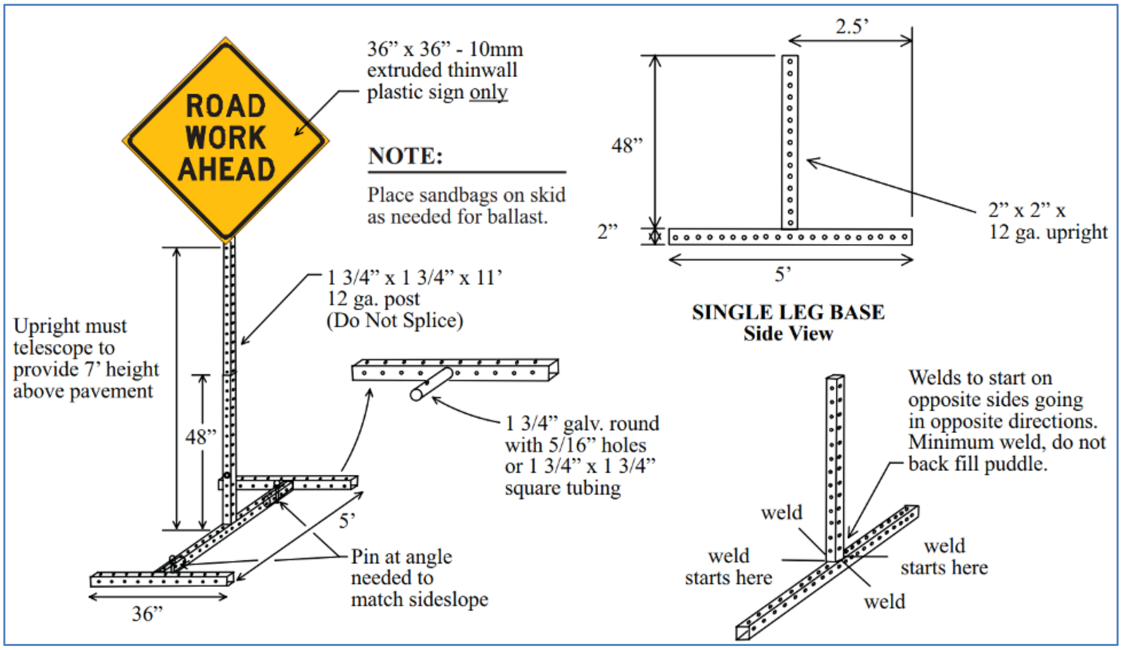
Sign 1000: Wooden Skid with 2 Wooden Legs Sign



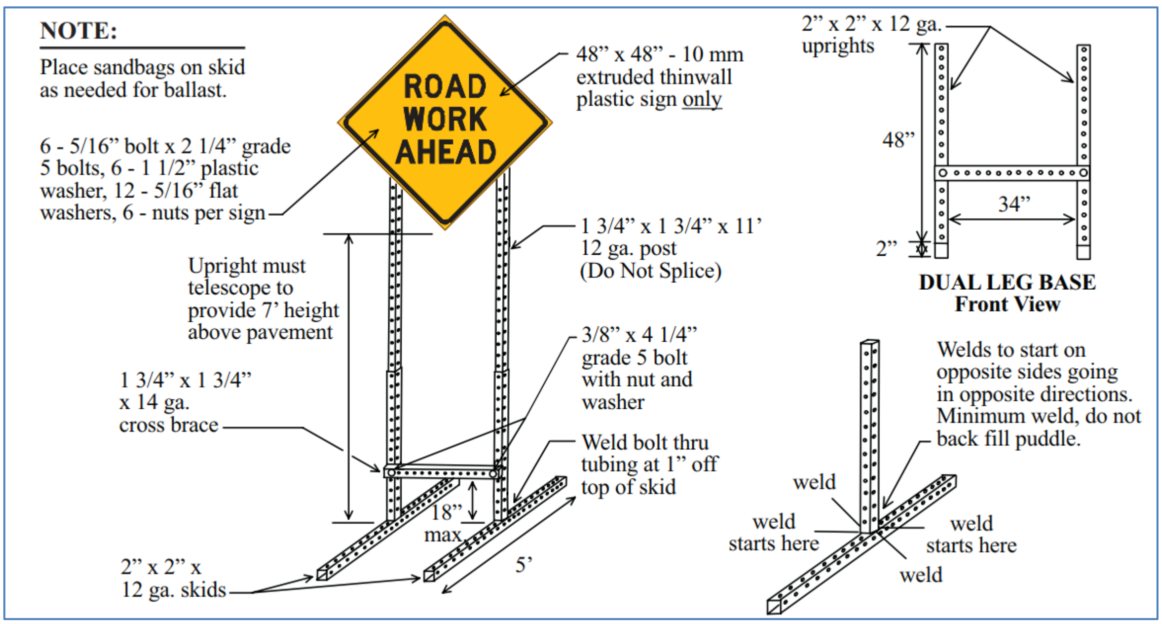
Sign 1001: Wooden long/intermediate-term Single Leg (H-leg) Sign



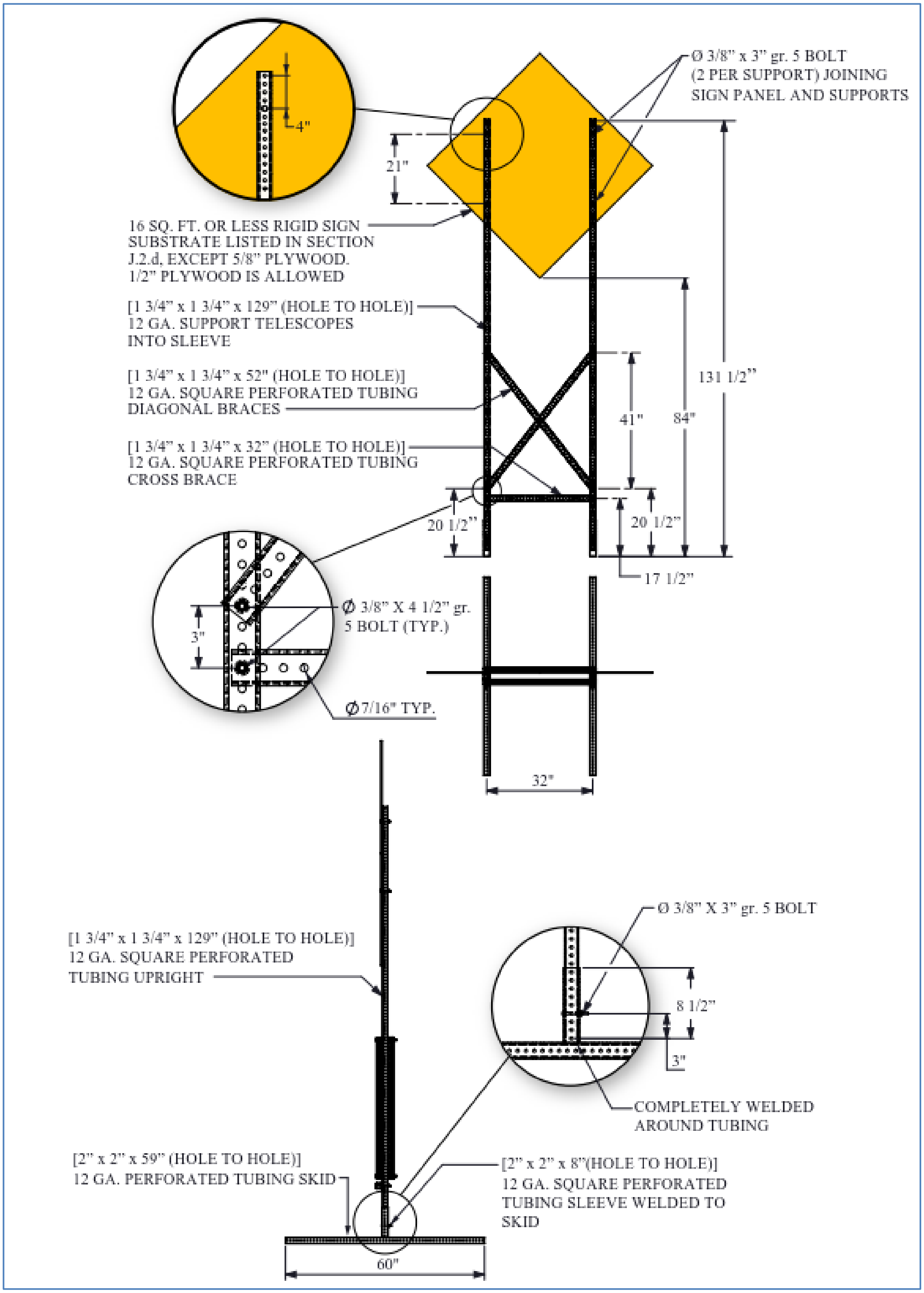
Sign 1002: Hwy Com's long/intermediate-term Single Leg (H-leg) Sign



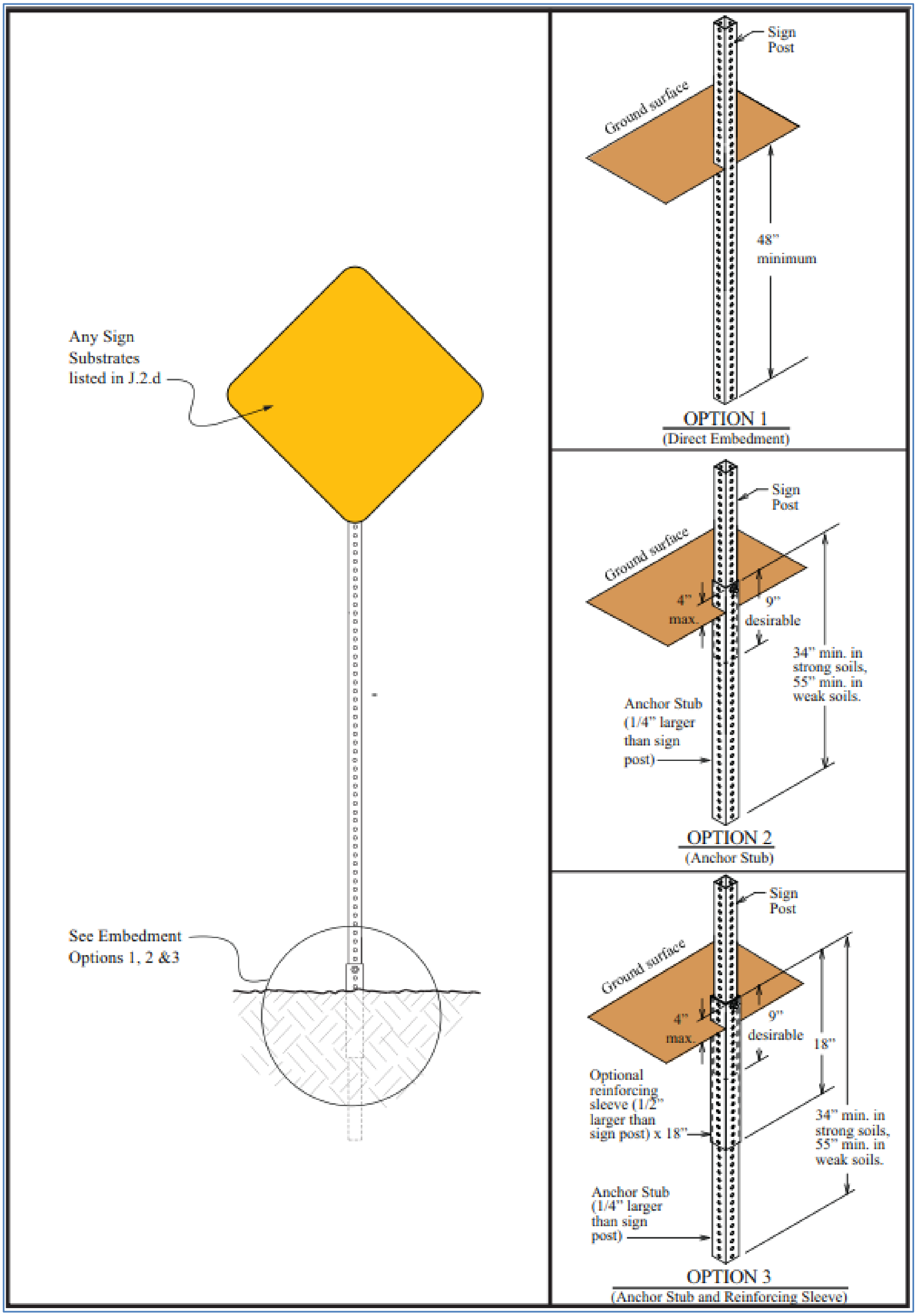
Sign 1003: H-base Single Upright with Leg PSST Skid Sign



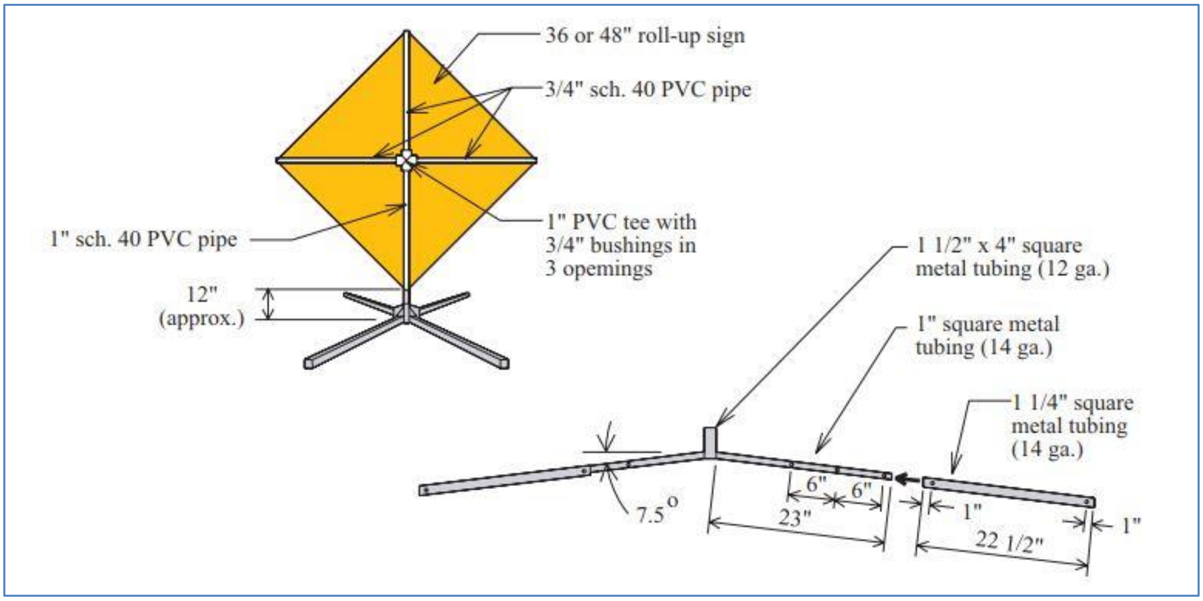
Sign 1004: Independent Dual Upright with Leg PSST Skid Sign



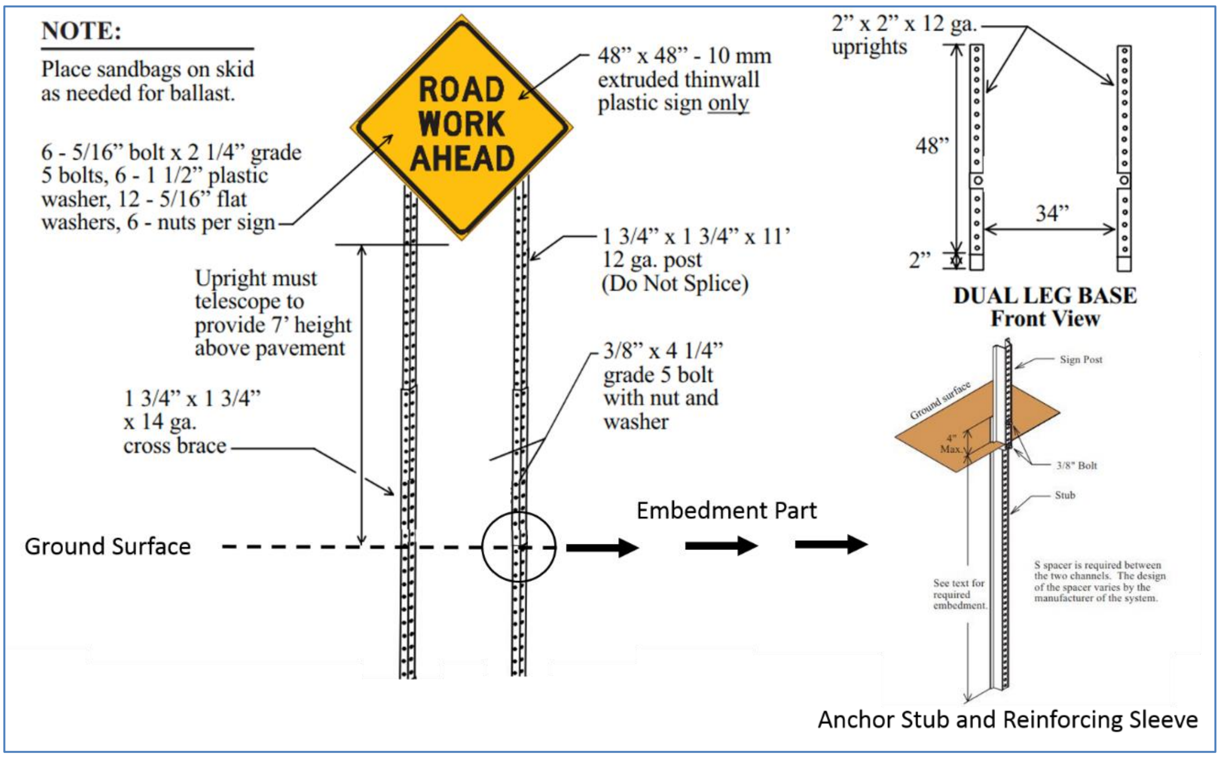
Sign 1005: Dual Leg PSST Skid Support Sign



Sign 1006: Perforated Square Metal Tubing with Anchor Sign



Sign 1008: X-base with Single Upright Sign



Sign 2000: Dual Leg Perforated Square Metal Tubing with Anchor Sign

References

AASHTO, Manual for Assessing Safety Hardware, American Association of State Highway and Transportation Officials, Washington, D.C., 2009.

Alan Taylor (2017). Photos: The aftermath of hurricane Harvey. https://www.theatlantic.com/photo/2017/08/photos-the-aftermath-of-hurricane-harvey/538143/ (accessed on April 01, 2018)

American Association of State Highway and Transportation Officials (AASHTO) (2013) Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals, American Association of State Highway and Transportation Officials, Washington, D.C., 2013.

Bligh, R. P., D. R. Arrington, and W. L. Menges, Temporary Large Guide Signs, Report FHWA/TX-13/0-6782-1, Texas Department of Transportation, 2013.

Connecticut Department of Transportation (DOT) (2017). 2017 work zone safety and mobility process review final report. http://www.ct.gov/dot/lib/dot/documents/dconstruction/wzs_reviews/2017_work_zone_process_review_final_report.pdf (accessed on April 01, 2018)

Dolce, C. (2017). Three category 4 Hurricanes Have made a U.S. Landfall in 2017.https://weather.com/storms/hurricane/news/hurricane-maria-irma-harvey-three-united-states-category-4-landfalls (accessed on April 1, 2018)

Impactrecovery.com (2018). MUTCD Guidelines for sign bases and posts. http://www.impactrecovery.com/resources/mutcd_guidelines_for_sign_bases_and_posts/ (accessed on April 01, 2018)

Manual on Uniform Traffic Control Devices (MUTCD) (2009). Chapter 6 Temporary Traffic Control. https://mutcd.fhwa.dot.gov/pdfs/2009r1r2/part6.pdf (accessed on April 01, 2018)

My Parking Sign (2018). Sign Bases-Portable, Cast Iron, and Wheeled Sign Bases. https://www.myparkingsign.com/sign-bases (accessed on April 01, 2018)

National Cooperative Highway Research Program (NCHRP) (1992). NCHRP report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features. Transportation Research Board of the National Academies, 2006.

National Cooperative Highway Research Program (NCHRP) (2006). NCHRP report 553: Crashworthy work-zone traffic control devices. Transportation Research Board of the National Academies, 2006.

National Weather Service (2017). Major Hurricane Harvey-August 25-29, 2017. https://www.weather.gov/crp/hurricane_harvey (accessed on March 20, 2018)

Roger P. Bligh, Dusty R. Arrington, Wanda L. Menges, and Darrell L. Kuhn. (2014). Skid-Mounted Support System for Temporary Guide Signs. Texas Department of Transportation Research Report: 0-6782-2. URL: http://tti.tamu.edu/documents/0-6782-2.pdf

Texas Department of Transportation (TxDOT) (2016). Texas Motor Vehicle CrashStatistics-2016. https://www.txdot.gov/government/enforcement/annual-summary.html (accessed on April 01, 2018)

Texas Department of Transportation (TxDOT) (2017). Compliant Work Zone Traffic Control Devices (CWZTCD). ftp://ftp.txdot.gov/pub/txdot-info/trf/pdf/cwztcd.pdf (accessed on April 01, 2018)

Texas Department of Transportation (TxDOT) (2018). Traffic Standards. Barricade and construction-general notes and requirements. ftp://ftp.dot.state.tx.us/pub/txdot-info/cmd/cserve/standard/traffic/bc-14.pdf (accessed on April 01, 2018)

Texas Manual on Uniform Traffic Control Devices (TMUTCD) (2011). Chapter 6 Temporary Traffic Control. https://mutcd.fhwa.dot.gov/pdfs/2009r1r2/part6.pdf (accessed on April 01, 2018)

Williams, B. (2014). Texas Dominates the wind energy industry. https://www.saveonenergy.com/green-energy/texas-dominates-the-wind-energy-industry/ (accessed on April 01, 2018)