FINAL REPORT

A DETERMINATION OF THE APPROPRIATENESS OF VIRGINIA'S RETROREFLECTIVE SIGN SHEETING SPECIFICATION FOR FLUORESCENT ORANGE CONSTRUCTION AND MAINTENANCE SIGNS

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ABSTRACT

To ensure the safe and efficient movement of traffic through a highway network during nighttime conditions, traffic signs are either illuminated or made retroreflective. Since illuminating all highway signs is not practical or energy efficient, the majority of traffic signs are retroreflective. The Virginia Department of Transportation (VDOT) requires that retroreflective sheeting used on construction and maintenance activity signs be a fluorescent prismatic lens type capable of being retroreflective at entrance angles as great as 50 degrees with observation angles of 0.2 and 0.5 degree. Because the validity of the 50-degree entrance angle requirement was questioned, this research was conducted to determine if VDOT's specification is appropriate.

Since this project was concerned with fluorescent orange construction and maintenance signs, 232 work zones in Virginia for the 1999 construction season were identified and inventoried. From these sites, 1,865 signs were investigated. The information collected included position, offset, height, shape and dimensions, whether tilted forward or back, rotation and twist, and the number of approach lanes facing the sign. This information was compiled in a spreadsheet, and a vector-based model was developed to determine the entrance, observation, rotation, and orientation angles for each sign.

The results indicated that VDOT's 50-degree entrance angle requirement is not appropriate for fluorescent orange construction and maintenance signs. However, the results also indicated that more emphasis should be placed on observation angle requirements than on entrance angle requirements. Every motorist on the approach to a sign will have an observation angle of 0.2, 0.5, 1.0, 1.5, and possibly 2.0 degrees depending on the type of vehicle being driven. The study recommends that VDOT specify a 40-degree entrance angle and a 1.0-degree observation angle for prismatic fluorescent orange work zone signs. In addition, the study recommends that the specification include requirements for orientation and rotation angles.

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INTRODUCTION

The purpose of a traffic sign is to convey a message to drivers that will result in the orderly and predictable movement of traffic. Drivers are exposed to three basic types of signs: regulatory, warning, and guide signs. Each type should elicit a different driving behavior or maneuver. To ensure safe and efficient movement of traffic through a highway network during nighttime conditions, traffic signs are either illuminated or made retroreflective. Since illuminating all highway signs is neither practical nor energy efficient, the majority of traffic signs are retroreflective.

The process to make traffic signs retroreflective has evolved from using reflector button copy, to using glass beads, to using sign sheetings with micro-cube corners (prismatic sheeting). As sign sheeting has evolved, so have its retroreflective characteristics. Retroreflectivity results when light rays are emitted from a source (typically a vehicle's headlights), strike the surface of a sign, and then return toward the source. Sign sheeting materials are measured or compared against their coefficient of retroreflection (R_A) at various specified angles. The more efficient a material is at returning light to its source, the higher its R_A value. Typically, the higher the R_A value, the brighter the material appears to motorists.

A material's retroreflectivity is dependent on its angularity. For prismatic materials, angularity can be described using the Application System provided in the American Society for Testing and Materials' (ASTM) specification ASTM E-808-99a, which is also the standard practice for describing retroreflectivity.[1] The system is composed of four angles: an entrance angle (β), an observation angle (α), a rotation angle (ε), and an orientation angle (ω_s).[1] The entrance angle is the angle formed by a light beam striking the surface of a sign and a line normal to the surface of the sign. The observation angle is the angle between the light beam striking the surface of the sign and the driver's line of sight to the sign. The rotation and orientation angles are defined with respect to the datum axis of sign material. Figure 1 depicts the interrelationship of the four angles. When signs are not installed plumb and perpendicular to the roadway, all four angles change as the distance from the sign changes.

The angularity of a sign generally refers to the range of angles at which a sign will remain retroreflective, hence visible to a motorist. Sign sheetings that have an entrance angle of 30 degrees have been typically regarded as being "wide angle."[2] A wide observation angle is considered anything greater than 2 degrees.[2] The Virginia Department of Transportation's (VDOT) *Road and Bridge Specifications,*[3] however, require that the sheeting used on orange construction and maintenance activity signs be a fluorescent prismatic lens type of sheeting

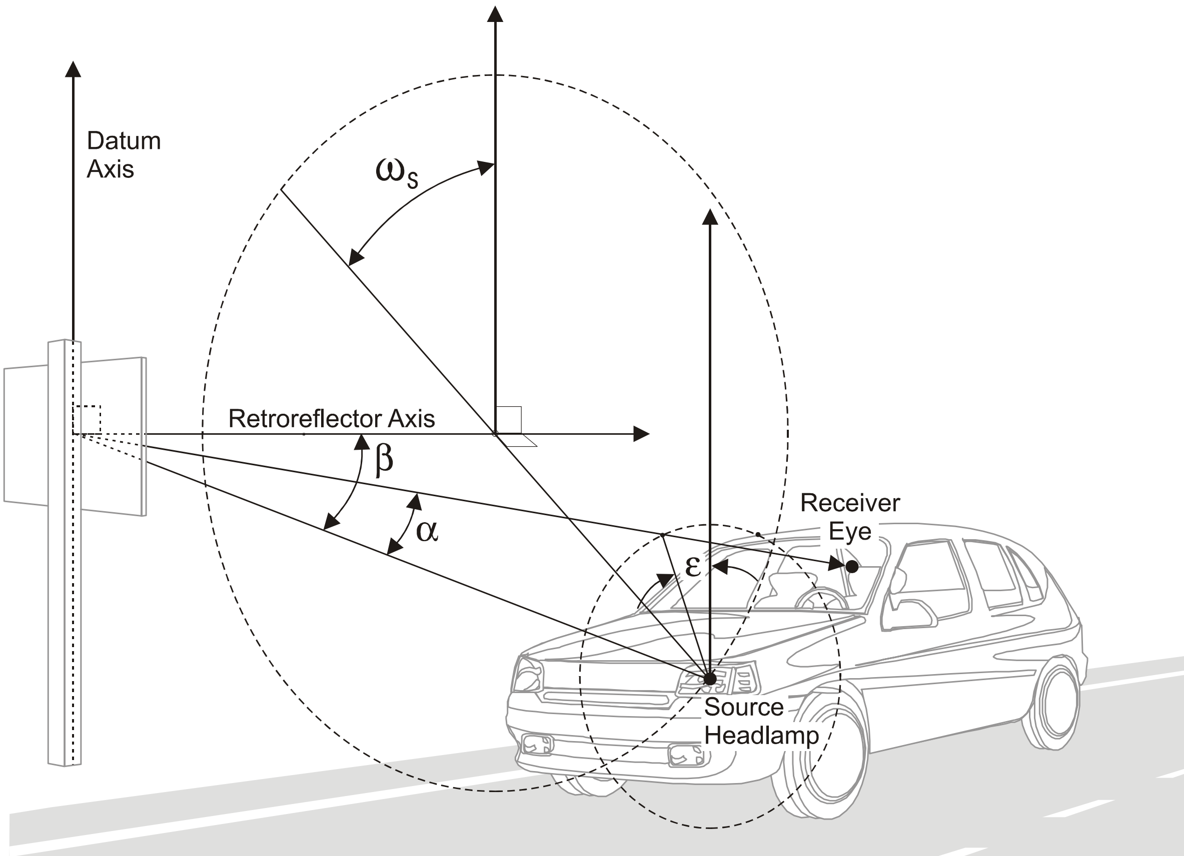

Figure 1. Interrelationship of Application System Angles

capable of being retroreflective at entrance angles of –4, +30, and +50 degrees with corresponding observation angles of 0.2 and 0.5 degree.[3] VDOT's purpose for specifying such a wide angle sheeting is to provide a factor of safety for misaligned signs that will ensure they remain visible to motorists despite misplacement. Because the validity of the 50-degree entrance angle requirement was recently questioned by a number of sign sheeting manufacturers that could not meet VDOT's specification, research was needed to determine if this specification was appropriate.

PURPOSE AND SCOPE

The purpose of this research was to determine whether VDOT's wide angle sheeting specification for fluorescent orange construction and maintenance signs was appropriate.

To achieve this purpose, the following objectives were established:

- Collect appropriate data for Virginia's fluorescent orange construction and maintenance signs.

- Develop a vector-based model to determine the frequency and distribution of the entrance, observation, rotation, and orientation angles where such signs exist in the field.

- Analyze the data to determine the appropriateness of the specification.

This research investigated signing in work zones, both temporary and long term, that included both day and nighttime activities. Retroreflective fluorescent orange roll-up and rigid signs were the only sign types considered. The research was limited to the 1999 construction season and presents only a "snapshot" of the signs' angles as they appeared in the field. This is because a work zone is a dynamic setting where signs are continuously moved or relocated depending on the maintenance of the traffic plan in force. Therefore, the position of the signs investigated could have changed the next day, and thus their angles could have changed after the initial measurements. No attempts were made to re-inventory any signs after the initial investigation.

METHODOLOGY

Five tasks were completed to meet the objectives of this study: literature review, site selection, data collection, model development, and analysis of findings.

Literature Review

A computerized literature search was conducted to identify research on sign angularity, sign placement, driver field of view, eye-scanning behavior, changes in the vehicle fleet, headlight designs and evolution, legibility indices, older driver requirements, and other variables that would enter into determining the appropriateness of VDOT's specification.

Site Selection

Since this project was concerned with fluorescent orange construction and maintenance signs, all work zones in Virginia for the 1999 construction season were initially considered for this study. However, because of logistics with data collection efforts and the potential that motorists would be exposed to these types of signs only during daytime conditions, four criteria for inclusion of a work zone were imposed : (1) a duration of more than 1 day, (2) the presence of at least one sign that was erected or visible to motorists at night, (3) work other than district permit work being conducted, and (4) work other than routine daily maintenance activities by VDOT forces being conducted. Work zones that failed any of the four criteria were eliminated from further consideration..

In March 1999, VDOT's Mobility Management Division (previously Traffic Engineering Division) identified 404 construction projects and 173 maintenance projects in progress.[4] Prior to inventorying a district, the research team contacted the district safety officer to verify which projects were ongoing for the particular time frame and which met the established criteria.

Based on the criteria, the initial total of 577 construction and maintenance sites was reduced to 313.

The actual number of construction and maintenance signs that are used in the field is dependent on several variables, including the location of the work zone, type of roadways affected, length of the work zone, and type of construction or maintenance activities ongoing. The researcher was unable to arrive at a universal number of signs that might be in the field at any given time. Therefore, a sample size could not be determined, and the researcher decided to attempt to inventory all of the fluorescent orange signs in the work zones that met the study criteria for the 1999 construction season.

Data Collection

After the applicable work zones were identified, a two-person team collected information for each sign in each work zone. The information included sign position (left or right mounted), type of mounting device (portable sign stand or post mounted), sign offset from the roadway, sign height, type of sign (rigid or roll-up), shape and dimensions, sign tilt (forward or back), sign rotation about its vertical axis (right or left), sign twist (facing toward or away from traffic), number of approach lanes facing the sign, lane widths, posted speed limit, and environmental setting (urban or rural).

Prior to any field measurements, the researcher defined a sign convention using the “right-hand rule.” This was done to ensure consistency in data collection and future analysis. A sign mounted on the right-hand side of the roadway was considered to have a positive twist when facing away from traffic, a positive rotation when rotated to the left, and a positive tilt when leaning backward.

The lateral offset for each sign was measured from the edgeline of the curb lane to the center of the sign. The mounting height was measured from the surface of the roadway to the bottom of the sign. Sign tilt and rotation, both in degrees, were measured using a carpenter’s “angle indicator,” or inclinometer. All measurements, distance and angular, were rounded to the nearest whole number.

The data collection team also measured the horizontal angle component for each sign that would be used to calculate the twist. This was accomplished by using an optical device designed by the Federal Highway Administration (FHWA)[5] (see Figure 2) and a traffic cone. The traffic cone was placed on top of the edgeline of the curb lane at a distance of 100 ft from the sign. The optical device was then placed flush on the sign’s face at its horizontal center, and the device’s telescope was pointed at the traffic cone (see Figure 3a). When the crosshairs in the telescope were aligned with the high visibility mark on the cone, the angle was read directly from the protractor on the device and its value recorded.

The vertical angle component of each sign was measured using a similar procedure to calculate the approach slope of the roadway (see Figure 3b). In this case, the optical device was rotated 90 degrees to the vertical, and the center of the device was located at the bottom of the

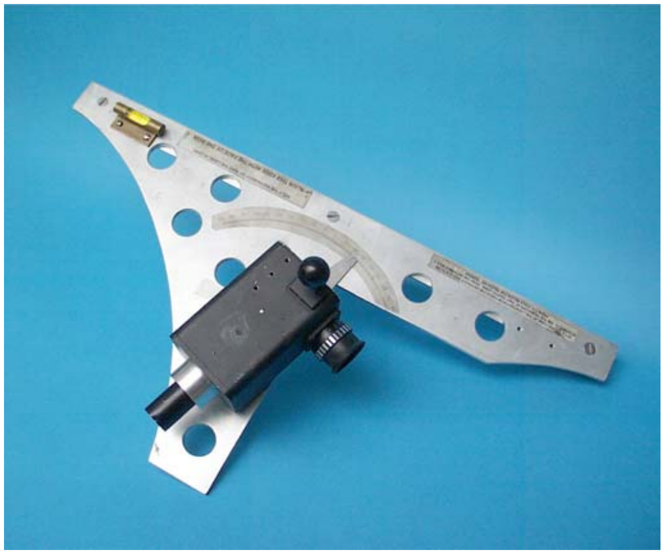

Figure 2. Optical Device Used in Data Collection

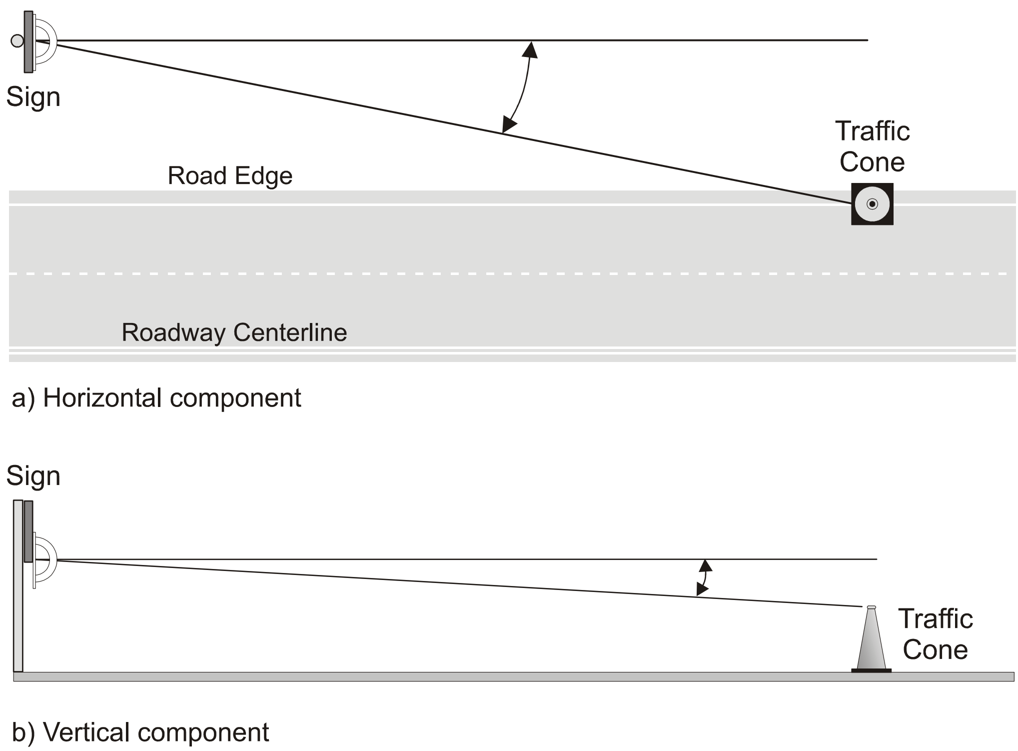

Figure 3. Horizontal and Vertical Components

sign face. The telescope was then rotated until it was pointed at the traffic cone. Once the telescope's crosshairs were centered on a high visibility mark on the cone that was 2.16 ft above the pavement surface, the angular measurement was read directly off the protractor and recorded.

The height of the mark on the cone was originally supposed to represent the height of a vehicle's headlights above the pavement.

Once the data collection team collected all of the necessary information for a sign, they went to the next sign in the work zone and repeated the process.

Model Development

The data collected were placed into an Excel spreadsheet. A vector-based mathematical model was then developed in the spreadsheet to determine the entrance, observation, rotation, and orientation angles for each sign inventoried. For each sign, the model produced values for each of the four angles for the left and right headlights based on the sign's potential range of viewing (multilane facilities) and a set of viewing distances from the sign. The appropriate statistical analyses were then performed.

Analysis

The results of the literature review and the model were examined to determine whether VDOT's wide angle sheeting specification for fluorescent orange construction and maintenance signs was appropriate.

RESULTS

Literature Review

Sign Placement

The *Virginia Work Area Protection Manual* has a general rule that construction and maintenance signs should be located on the right-hand side of the roadway.[6] For divided roadways with a median of 8 ft or greater, both the left and right sides should be signed. The signs can be mounted on portable supports or posts or on or above barricades.[6] The 1988 *Manual of Uniform Traffic Control Devices* (MUTCD) recognizes that the optimal position cannot always be attained in practice but that signs should be placed on the right-hand side of the roadway, where the driver is looking for them. On multilane facilities where traffic in the right-hand lane might obstruct the view of a sign, it may be beneficial to post a supplementary sign on the left side of the roadway.[7]

The *Virginia Work Area Protection Manual* and the 1988 edition of the MUTCD provide further guidance for post-mounted signs. These documents indicate that signs should be erected at a height of at least 7 ft, measured from the bottom of the sign to either the near edge of the pavement or from the sidewalk or curb for pedestrian clearance. To be crashworthy, the top of the sign is to be a minimum of 9 ft above the ground elevation at the base of the sign. The height to the bottom of a secondary sign mounted below another sign may be 1 ft less than the 7-ft requirement.[6,7] The Millennium Edition of the MUTCD reduced the 7-ft mounting requirement for rural conditions to 5 ft, except for when increased visibility is required.[8]

The lateral placement of construction and maintenance warning signs in rural areas is stipulated to be a minimum of 6 ft from the edge of the shoulder to 12 ft from the edge of the pavement to the nearest corner of the sign. In urbanized locations, this lateral placement must be no less than 2 ft from the face of the curb to the sign.[6-8]

When signs are placed on portable supports (sign stands) for short-term conditions, the bottom of the sign is required to be no less than 1 ft above the pavement elevation.

Sign Orientation

Several documents provide guidance on how to orient traffic signs for approaching motorists. For the most part, they are consistent with one another.

FHWA's Traffic Control Devices Handbook

The FHWA's *Traffic Control Devices Handbook*[9] provides guidance on how signs should be oriented. Post-mounted signs that are 12 to 14 ft from the edge of the pavement should be turned slightly away from the roadway (93 degrees) to prevent glare. Signs mounted 30 ft or more from the edge of the pavement should be mounted 87 degrees to approaching traffic. For signs mounted on roadways with grades, it might "be desirable to tilt a sign forward or back from vertical to improve the viewing angle."[9]

Institute of Transportation Engineers (ITE) Traffic Signing Handbook

The ITE's *Traffic Signing Handbook*[10] states that signs should generally be installed at approximate right angles to the direction of the traffic they are intended to serve. For straight sections of roadway, the face of the sign should be rotated about 3 degrees toward approaching traffic instead of being exactly perpendicular to the edge of the roadway. Signs fabricated with a high-performance retroreflective sheeting material should be oriented approximately 3 degrees away from the perpendicular to prevent specular glare.

Specular glare is inevitable for curved sections of roadway, and ITE recommends that small signs be at right angles to a driver's line of sight when the driver is about 250 ft from the signs. Larger signs on curves should be perpendicular to a driver in the right lane when the driver can first read the sign. The maximum readability (legibility) distance is recommended to be 40 ft/in of letter height.

Signs should normally be installed vertically; however, on steep grades, signs can be tilted forward or back from the vertical (plumb) to improve the viewing angle.

Maryland State Highway Administration

The Maryland State Highway Administration (MDSHA) provides guidance on sign placement and orientation in each of their plan sets.[11] They stipulate that signs be erected such that their face is vertically plumb.

With regard to horizontal alignment, MDSHA has requirements for tangent sections and for inside and outside horizontal curves. On tangent sections of roadway and when signs are mounted within 30 ft of the travel way, the sign face should be rotated 93 degrees away from traffic. Signs located more than 30 ft from the travel way should be perpendicular to approaching traffic.

On facilities that have inside horizontal curves, MDSHA suggests that the sign face be positioned such that it forms a 90-degree angle with a cord between a point at the near edge of the pavement at the sign and a point on the edge of the pavement 500 ft in advance of the sign. For facilities with outside horizontal curves, the sign face should be oriented such that it is at a right angle to the tangent of the curve at the sign location.

3M Company

The 3M Company provides suggestions on how to orient signs during installation.[12] They recommend that a sign be erected so that its vertical axis is plumb and its horizontal axis is at an angle of 93 degrees with the traffic lane the sign serves.

On horizontal curves, 3M recommends that the sign be positioned such that the vertical axis is plumb and the horizontal axis is at an angle of 93 degrees with a straight line between the sign and the point at which the sign is to be read (i.e., 40 ft/in of letter height).

Legibility Distance Requirements

The placement and orientation of signs are important aspects of signing; however, determining when a sign is legible is important to traffic engineers when determining where to place the sign. Legibility has been more heavily researched than any other factor related to signing, and each study has concluded with varying results.

A report published in a 1955 *Highway Research Board Bulletin* stated that the legibility distance for different combinations of factors resulted in ranges from 22 to 92 ft/in of letter height.[13] A 1958 study indicated that observers with approximately 20/20 vision were capable of reading scrambled letters at about 56 ft/in of letter height.[14]

More recent research suggests legibility distances similar to those of the 1958 study but also noted that a more conservative approach should be taken to accommodate older drivers. Sign letter height has been pointed out to be a problem area for older motorists, and the currently accepted standard for legibility of 50 ft/in of letter height may not be adequate for this population.[15] Results from a 1988 report indicate that if signs are to provide adequate visibility for older drivers, Series D and E letters should be based on an assumed legibility of 40 ft/in of letter height and not 50 ft/in.[16-18]

Effects of Sign Position and Distance on Sign Luminance

A 1956 study related sign position, distance, and the reflective characteristics of the sign material to sign brightness.[19] To determine the brightness, or luminance, of a sign in place on the highway, the researchers found it necessary to take into account the reflective characteristics of the sign material; the trigonometric relationships among the car, the sign, and the roadway; and the illumination reaching the sign from the headlamps. Since the sign, the headlamps, and the driver's eyes are not at the same level, the problem needed to be solved in three dimensions rather than two.

The study also indicated that signs made of most retroreflectorized materials were brightest when facing the light squarely, that is, when the entrance angle was 0. As the sign was rotated (twisted) so that the entrance angle increased, the brightness of the sign decreased. The luminance for a sign was relatively low at short distances away from a sign since the divergence (observation) angles were large and the sign was out of the intense portion of the headlamp beam. In fact, for any given sign position, each angle will change continuously as the car approaches the sign.

The study found that luminance falls off rapidly at near distances. The low luminance at near distances was due not only to the entrance angle but also to the divergence (observation) angle characteristics of the material. Any bright material concentrates its light into a beam with a small divergence angle. There is, then, little light returned at the large divergence angles encountered at near distances, and the high-brightness materials did not perform at their best except at greater distances.

The study also found that a 5-degree clockwise rotation did not affect luminance very much but that a 10-degree clockwise rotation brought about a substantial reduction in luminance at all but very near distances. A counterclockwise rotation (twisting of a sign away from the road) caused even greater reductions.

The authors recommended that signs erected on curves be aimed toward where they should be viewed. However, for 5- or 6-degree right curves, signs should be aimed at a point no further than 400 or 500 ft down the road to avoid serious loss in luminance at near distances.

Field Angularity Research

In 1993, the Connecticut DOT published the results of a study that examined the validity of the maximum entrance angle specification (30 degrees) for retroreflectorized traffic signs.[5] The 30-degree entrance angle had been considered to be the widest entrance angle for signs; however, the 45-year-old specification had not been substantiated by empirical data.

The study noted that the current specifications for minimum R_A values for new sign sheetings are specified using only two entrance angles: –4 and +30 degrees. The –4 degree angle was intended for signs that are close to a straight road but turned slightly away from traffic to prevent glare and that the +30 degree angle has traditionally been considered to be the widest angle at which signs would commonly be seen on curved roadways.

The Connecticut DOT attempted to collect empirical data to evaluate the need for a new maximum specification. The researchers used a customized computer software program developed for the DOT's photo log laser videodisc retrieval system. The software, SEAMS (Sign Entrance Angle Measurement System), allowed the measurement of entrance angles for a large sample of in-service traffic signs in an office environment.

The researchers collected the sign entrance angle measurements at distances of 100 and 200 ft based on previous last-look distance research. The researchers stated that the 200-ft distance for the freeways and the 100-ft distance for non-freeways would provide a conservative estimate of sign entrance angles.

Researchers made four assumptions when making measurements with the SEAMS program. First, the photo log van always tracked in the center of the lane. Second, the photo log camera was located in the center of the truck. Third, the placement of a sign was always at a right angle to a point on the roadway shoulder line. Fourth, the vertical component of the entrance angle was insignificant.

The study's goal was to collect data for 200 signs for each roadway type (six types). Data for a total of 1,142 signs were collected. The researchers made a special effort to capture signs situated on the left side of freeway facilities.

Results indicated that none of the 1,142 signs had an entrance angle greater than 30 degrees. Only 10 of the signs had an entrance angle greater than 25 degrees. For freeway roads, the 99th percentile was 20 degrees, and for non-freeway facilities was 27 degrees. (However, the non-freeway and freeway signs were measured at different distances.)

The researchers concluded that the current maximum entrance angle requirement, 30 degrees, included a margin of safety to compensate for signs that were twisted, poorly placed, bent, or leaning out of plumb. As a general entrance angle specification, 30 degrees is valid. The researchers also indicated that a lower specification, 20 degrees, could be used for signing on freeways with no adverse effect.

Changes in the U.S. Vehicle Fleet

Changes in vehicle fleets and the "design" vehicle are continuous and have accelerated over the past two decades. Of particular interest is the ratio of automobiles to light trucks and how it has changed in the last 20 years. The changes in vehicle fleet composition could affect when and where a sign is detectable, legible, and no longer visible. For example, there appears to have been a proliferation of sport utility vehicles (SUV) on roadways throughout the nation over the last decade.[20,21] It is plausible that individuals driving SUVs experience a reduced amount of light being returned to them from signs as compared with individuals seeing the same signs at the same distances driving conventional automobiles. This reduction is due to the larger separation between the driver's eye and the vehicle's headlights as compared with a conventional automobile.

The literature reviewed in this section investigated trends in vehicle registrations and the trends in vehicle sales. Vehicular registrations were disaggregated by automobile registrations and light truck registrations. Automobile registrations included mini-compact, subcompact, compact, midsize, large, and two-seater types. Light truck registrations included small pickup, large pickup, small van, large van, small utility, and large utility types. All classes of vehicles encompassed the domestic and import variety.

Pre-1994 Registration Trends

Not until 1994 were light trucks classified separately from automobiles in the FHWA's *Highway Statistics Series.*[20] Figure 4 depicts the yearly national automobile and truck registrations from 1976 to 1993.[20]

In 1976, there were slightly more than 110 million registered automobiles in the United States, and by 1993, the number had increased by 15.6 percent to 127 million. During this time frame, automobile registrations peaked in 1989 to more than 134 million registrations. From 1989 to 1993, automobile registrations dropped by 5.4 percent.

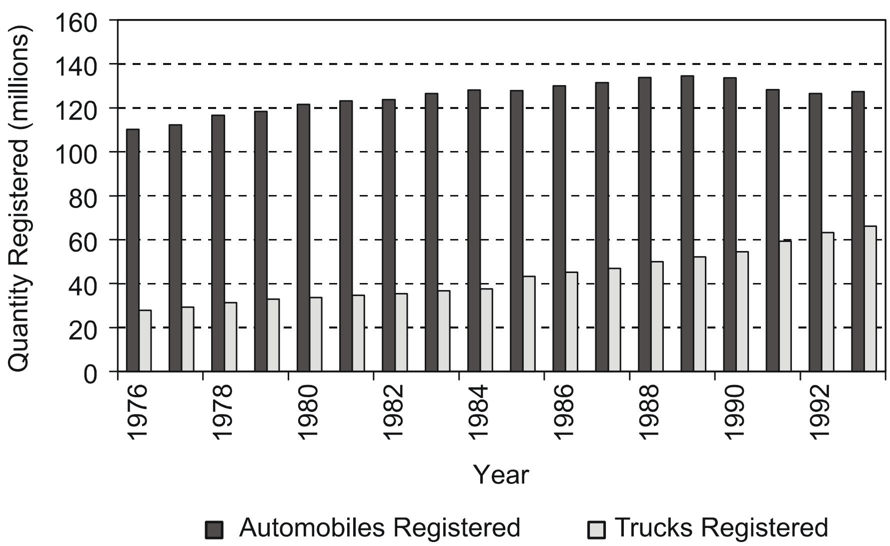

Figure 4. Automobile vs. Truck Registrations by Year. Prior to 1994, the Federal Highway Administration included light trucks (under 10,000 lb) in the automobile category. This would include sport utilities, vans, and pickups.

Total truck registrations increased from almost 28 million in 1976 to 66 million in 1993, an increase of 137 percent. Truck registrations from 1989 to 1993 are in contrast to automobile registrations in that truck registrations increased 26.7 percent.

Post-1994 Registration Trends

In 1994, FHWA separated light trucks from automobiles and created a separate classification. Further, light trucks were broken down by type, which included pickups, vans, and sport utilities. Figure 5 shows automobiles and light truck registration trends from 1994 to 1998.[20]

As shown, in 1994 there were almost 134 million automobiles registered compared to nearly 132 million in 1998. This continued the decrease in automobile registration. Over this same time period, pickup truck registrations increased by more than 31.3 percent, van registrations by more than 50.3 percent, and SUVs by more than 119 percent to slightly more than 16 million vehicles. Although SUVs showed the largest increase, this class of vehicle represented only 8 percent of the total number of registered vehicles.

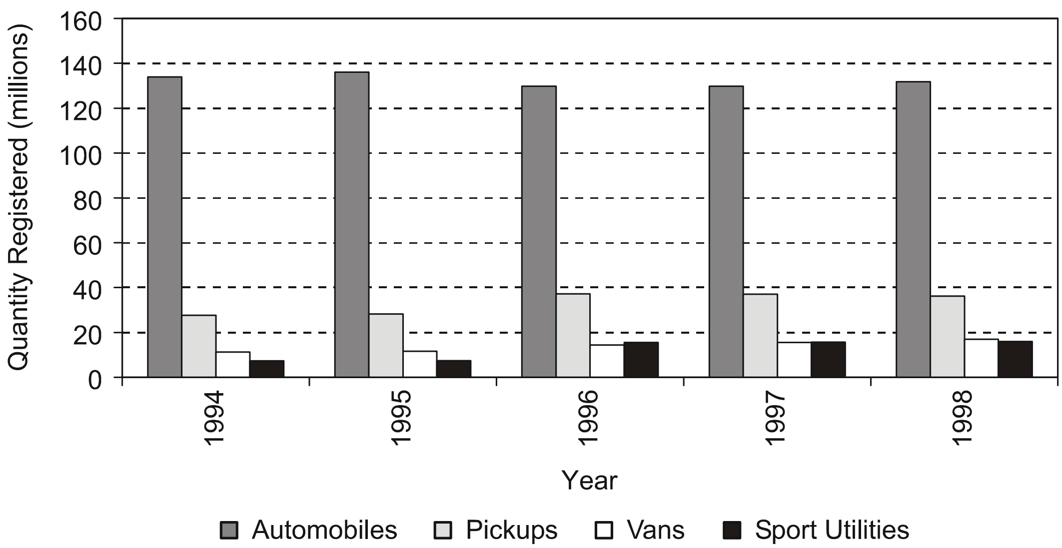

Figure 5. Motor Vehicle Registrations from 1994 to 1998

Vehicle Sales Trends

Motor vehicle sales were also examined. A study by the Oak Ridge National Laboratory investigated sales of new domestic and international automobiles and light trucks.[21] Figure 6 shows the distribution of sales of automobiles versus light trucks from 1976 through 1997.

As Figure 6 depicts, automobile sales overall decreased by nearly 15 percent from 1976 through 1997. Light truck sales, on the other hand, increased by more than 170 percent for the

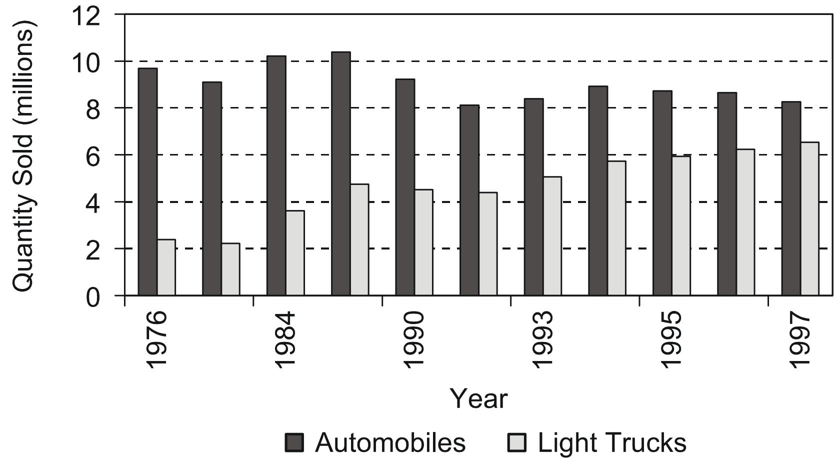

Figure 6. Sales of New Domestic and Import Automobiles and Light Trucks

same period. For the 4-year span from 1994 through 1997, automobile sales dropped by 7.4 percent and light truck sales increased by 14 percent.

Figure 7 shows the breakdown of types of light trucks sold in the United States from 1976 to 1997, i.e., small pickup, large pickup, small van, large van, small utility, and large utility. Small pickup sales peaked in 1988 and have decreased steadily since. Large pickups have annually been the highest selling vehicles. Small vans have shown a steady increase from 1976 to their peak in 1994; however, sales have shown a slight decrease since 1994. Sales of large vans have remained fairly constant through the years, with slight peaks in 1976 and 1984.

The light trucks with the most significant increase in sales have been the small and large utility vehicles. In 1976, a total of 4,716 small utilities were sold, and by 1997, the sales totaled 1.7 million. Large utility vehicle sales increased dramatically from 1992 to 1996, representing an increase of 281 percent, but leveled off from 1996 to 1997.

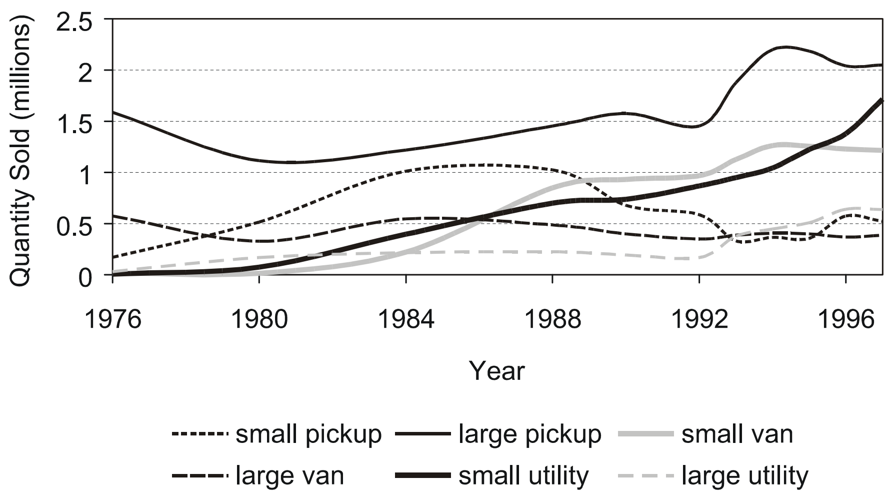

Figure 7. Distribution of Light Truck Sales

Headlamps and Driver Eye Positions

The vehicle fleet is constantly changing, and the percentage of light trucks and SUVs has been increasing. A part of this change has been the mean placement of headlamps and driver eye positions within the vehicle fleet. It is important to understand these changes because the locations of headlamps and driver eye positions are critical in estimating the efficiency of a retroreflective material.[22] This is because the efficiency is an inverse function of the observation angle.[23]

Tables 1 and 2 show the locations of headlamps and driver eye heights in the 15 best-selling automobiles and 15 of the best-selling light trucks/vans. These 30 vehicles accounted for 52 percent of all vehicles sold for calendar year 1995.

Headlamp heights and driver eye heights are directly related to the amount of light reflected back to the eye of the driver. Zwahlen and Schnell noted that at a viewing distance of almost 500 ft, the amount of light reflected back to the eye of a driver in a light or heavy truck could be reduced by 75 percent compared to the light reflected back to a driver of an automobile.[24]

Table 1. Locations of Low-Beam Headlamps[22]

Dimension	Distance (ft)	
	Car	Light trucks and vans
Vertical to ground[a]	2.03	2.72
Lateral to centerline of vehicle[a]	1.84	2.13
Longitudinal to front of bumper[b]	0.66	0.59

[a]Measured from the center of the headlamp.
[b]Measured to the lens of the headlamp.

Table 2. Locations of Centroid of Driver Eye Positions[22]

Dimension	Distance (ft)	
	Car	Light trucks and vans
Vertical to ground	3.64	4.66
Lateral to centerline of vehicle	1.15	1.38
Longitudinal to front of bumper	7.68	7.41

Site Selection

Table 3 shows the distribution of study sites by construction district. Because of the timing associated with the inventory of any single district, some projects had not started or had been completed prior to the district's inventory. However, more than 74 percent of the construction and maintenance projects slated for 1999 that met the study criteria were inventoried.

Table 3. Distribution of Construction and Maintenance Projects by District

District	Not Inventoried	Inventoried	Total
NOVA	1	10	11
Bristol	6	37	43
Salem	6	29	35
Lynchburg	6	24	30
Richmond	3	48	51
Suffolk	2	27	29
Fredericksburg	33	18	51
Culpeper	18	18	36
Staunton	6	21	27
Total	81	232	313

Figure 8 depicts the distribution of inventoried work zones by county and construction district. As shown, the sites inventoried are well distributed across the Commonwealth and can be considered geographically representative of all work zones statewide.

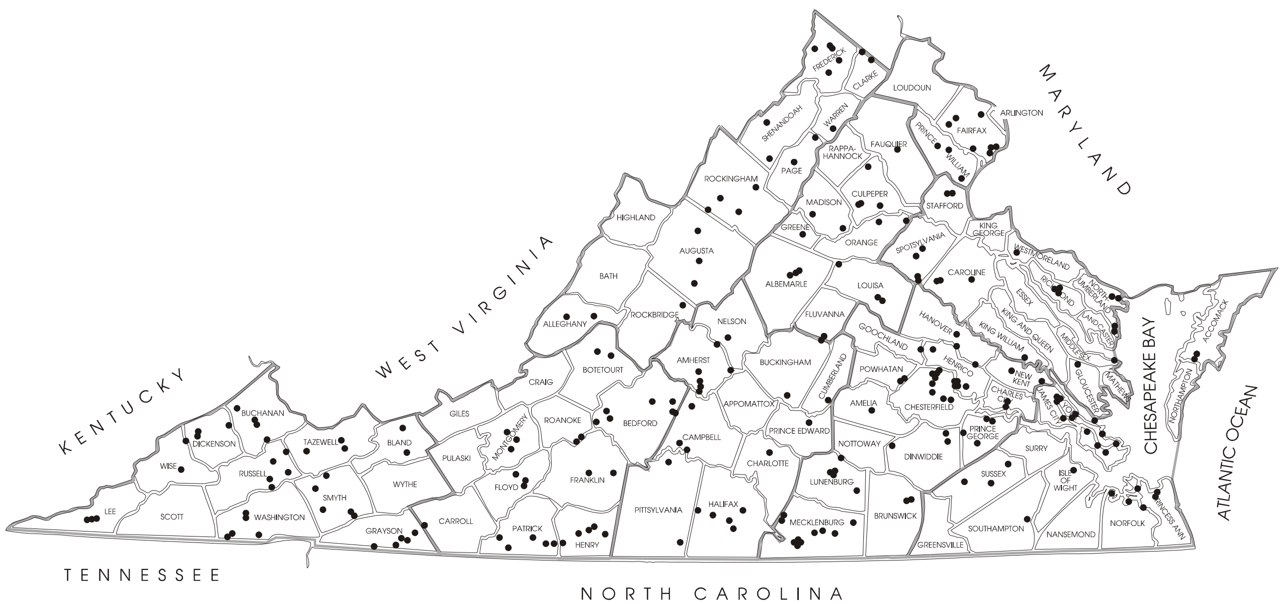

Figure 8. Statewide Distribution of Work Zones Inventoried

Sign Data and Viewing Conditions

A total of 1,865 signs were inventoried in the 232 work zones surveyed statewide for the 1999 construction season. No overhead construction and maintenance signs were found. Only one roll-up sign was found in use in the field; the rest were conventional rigid signs. All of the signs inventoried were classified as being mounted on either the right-hand side or the left-hand side of the road and as being in a rural or urban environment.

Sign Location

The majority of signs inventoried, 87 percent (1,617), were mounted on the right-hand side of the road. Of these, 716 were in rural environments and 901 in urban settings.

The remaining 13 percent (248) of the signs were mounted on the left-hand side of the road. Of these, 57 were in rural areas and 191 in urban settings.

Sign Supports

The majority (91 percent) of construction and maintenance signs inventoried were mounted on wood posts. Signs mounted in sign stands accounted for 8 percent of the supports, and barricade-mounted signs were the least prevalent, at 1 percent.

No significant difference was found between the types of sign supports used in rural and urban areas. Ninety to 93 percent of the signs were post mounted. The use of portable sign stands was slightly higher in urban areas at 9 percent than in rural areas at 6 percent. Signs mounted on barricades were the least common in both settings, accounting for approximately 1 percent of sign mounting devices used.

Lateral Offset from Roadway

The lateral offsets for each sign were measured from the edgeline of the curb lane to the center of the sign. Figures 9 and 10 show the minimum, maximum, and average lateral offsets measured in the field for left- and right-mounted signs. As these two figures depict, the minimum and maximum offsets occurred in urban environments with signs having no offset to signs placed as much as 526 in, almost 44 ft, off the edge of the roadway.

Figure 11 shows the distribution of sign offsets by environment and mounting location. For rural right-mounted signs, 95 percent were within 218 in (18.2 ft) of the roadway. For urban right-mounted signs, 95 percent were within 235 in (19.6 ft) of the edge of the roadway.

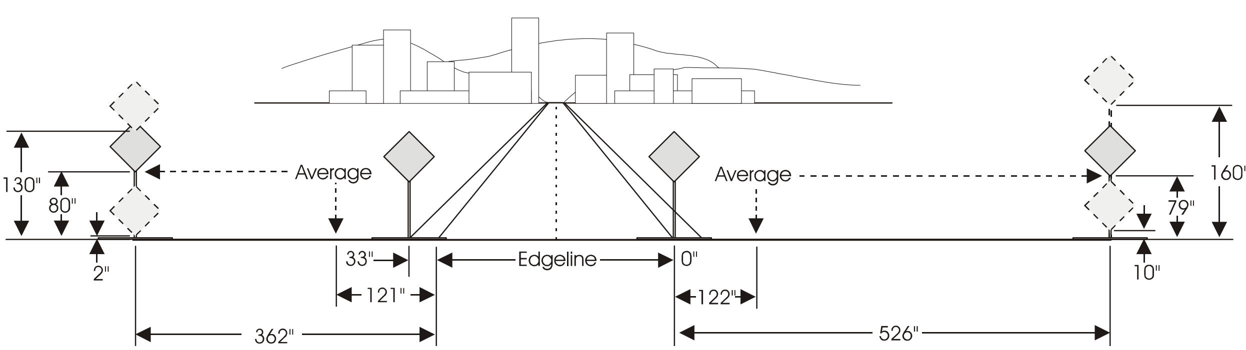

Figure 9. Urban Sign Mounting Conditions

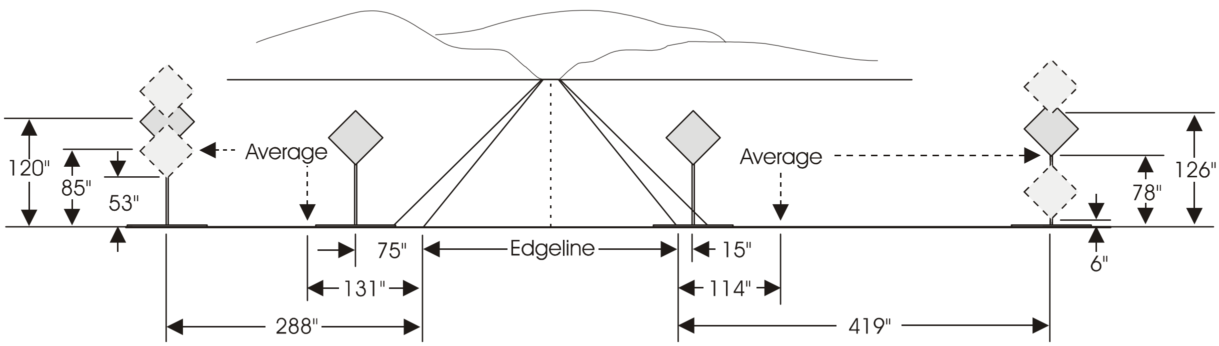

Figure 10. Rural Sign Mounting Conditions

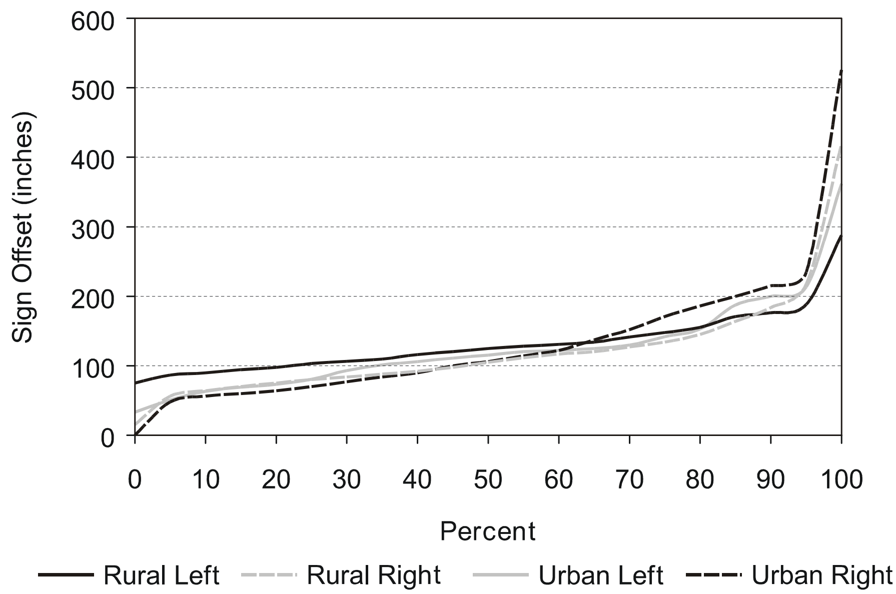

Figure 11. Distribution of Sign Offsets

Figure 11 also shows that 95 percent of the rural left-mounted signs were within 188 in (15.7 ft) of the roadway, and 95 percent of the urban left-mounted signs were within 213 in (17.8 ft) of the edge of the roadway.

Even though the average offsets between left and right mounted and urban and rural settings varied by only a matter of inches, sign placement was more variable in urban rural settings.

Sign Stand Placement

As one could assume, sign stands were typically placed closer to the roadway than their post-mounted counterparts. Rural areas with right-mounted signs had an average offset of almost 84 in (7 ft), whereas the urban areas had an average offset of 81 in (6.8 ft). No sign stands were encountered in rural areas for left-mounted signs. In urban areas, sign stands averaged 73 in off the left side of the roadway.

Sign Mounting Heights

The mounting height was determined by measuring from the surface of the roadway to the bottom of the sign. Figures 9 and 10 show the minimum, maximum, and average sign mounting heights measured in the field for left- and right-mounted signs. As these two figures depict, the minimum and maximum mounting heights occurred in urban environments, ranging from 2 in for a left-mounted sign to 13.3 ft for a right-mounted sign.

Figure 12 shows the distribution of sign mounting heights by environment and mounting location. For rural right-mounted signs, 90 percent were mounted at or below 94 in (7.8 ft) of the roadway; for urban right-mounted signs, 90 percent were within 96 in (8 ft) of the surface of the roadway.

Figure 12 also shows that 90 percent of rural left-mounted signs were within 99 in (8.3 ft) of the surface of the roadway, and 90 percent of urban left-mounted signs were mounted at a height of 98 in (8.2 ft).

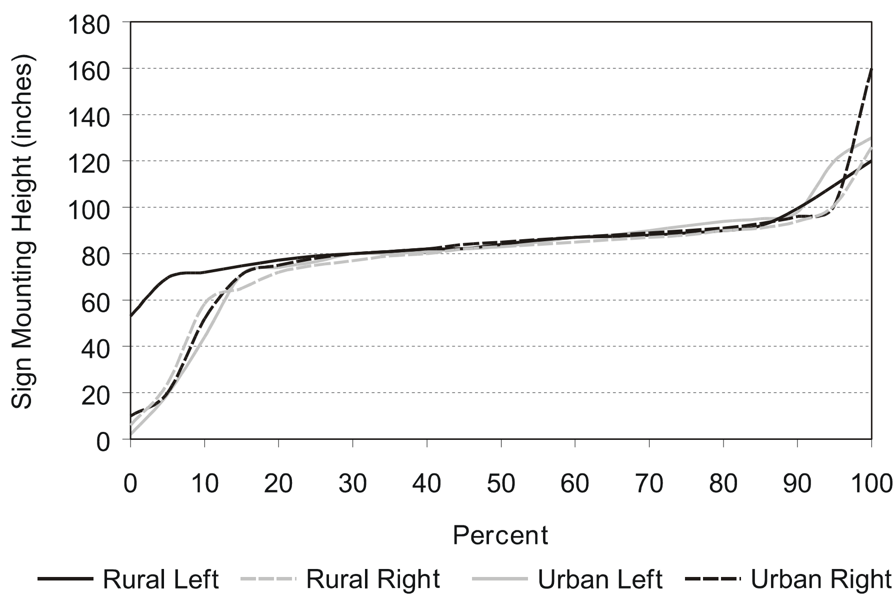

Figure 12. Distribution of Sign Mounting Heights

Sign Types

Sixty-one percent of signs used within the work zones surveyed were rectangular. These signs were typically “Road Under Construction” and “End Construction” (G20-2). Thirty-five percent were diamond shaped, and only 4 percent were square. The square signs were typically supplemental speed plaques used in conjunction with diamond-shaped signs.

The representation of rectangular signs being nearly twice that of diamond-shaped signs should not be surprising since motorists are typically exposed to rectangular signs at the beginning and the end of a project. Projects that have side roads also have the "Road Under Construction" and "End Construction" signs on every approach to and every departure from the work zone. The more side roads a project has, the more rectangular signs will be used.

Perceived Tilt

The tilt of a sign as measured in the field is not entirely indicative of what a driver may see. This is because a sign may be perfectly upright with respect to the earth's gravitational force, but because of the approach slope of the roadway, a motorist may view the sign as being tilted back or forward. When the approach slope and tilt of a sign are taken into account, the sign may be tilted further back or forward than originally thought. None of the signs was perceived as being plumb. However, in a number of cases where the slope of the roadway had offset the tilt of the sign, the "perceived tilt" was in the thousandths of a degree. In these cases, the sign should be considered plumb.

Perceived Tilt Back

The majority of signs, 62 percent, were perceived as being tilted back anywhere from 0.04 degree to slightly more than 16 degrees. Signs that had a perceived tilt back averaged 2.28 degrees. The maximum and minimum occurred in urban conditions.

Perceived Tilt Forward

Only 38 percent of the signs investigated were perceived to be tilted forward, with the minimum being 0.004 degree to a maximum of almost 27 degrees. The minimum could be considered as being plumb. The signs that had a perceived forward tilt had average values in the low 2-degree range.

Sign Rotation

Signs were measured to determine their rotation about the vertical axis since some prismatic sheetings must be oriented in a particular way. No determination was made of whether the sign sheeting was installed properly. It was assumed that all signs had been manufactured in accordance with the manufacturer's specifications.

Forty-two percent of all the signs inventoried had no rotation. The remaining 58 percent had rotations from a little as 1 degree to as much as 29 degrees. On average, sign rotations were small, just above 1.5 degrees. It should be noted that 95 percent of the signs had rotations of 5 degrees or less. The two maximum rotations are anomalies caused by severe warping of the wood posts.

Sign Twist

Sign twist was calculated from the field data for use in the model. More than 80 percent of the right-mounted signs were twisted toward traffic, with an average twist of approximately 8 degrees. The remaining 315 right-mounted signs were twisted away from traffic on the average of 4 degrees.

The majority of left-mounted signs, 54 percent, were twisted away from traffic on average of slightly more than 6 degrees. The other 46 percent had an almost 8-degree twist toward traffic.

Number of Approach Lanes

The number of approach lanes a roadway has determines the potential number of viewing conditions a sign could have. That is, a sign mounted on a three-lane facility could be viewed in as many as three lanes. Each lane would therefore have different angles associated with each position. This could affect the associated angles to which drivers are exposed.

As Figure 13 shows, almost 90 percent of the signs inventoried were posted on roadways having two or fewer approach lanes viewing the signs. The majority of signs, 57 percent, had one approach lane, 32 percent had two, 9 percent had three, and only 2 percent (32 signs) had four lanes viewing them.

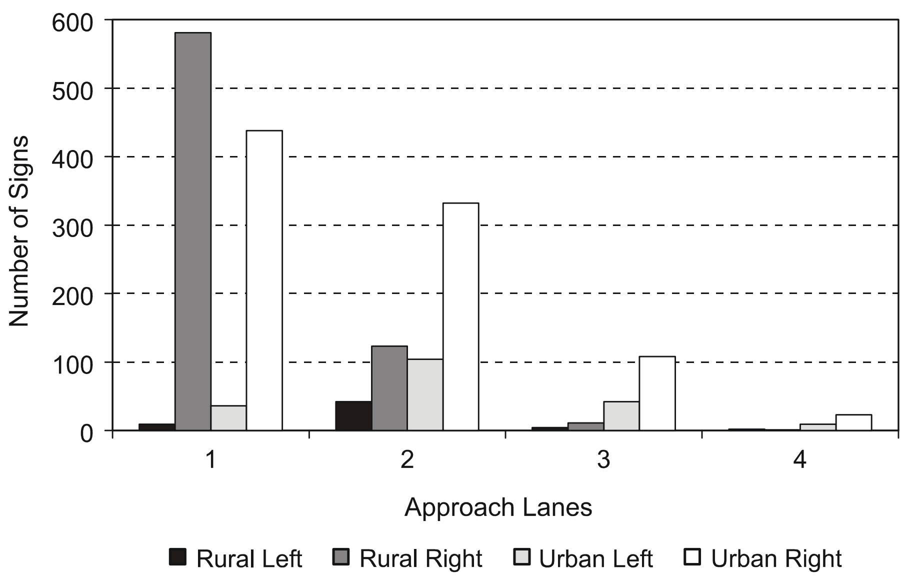

Figure 13. Number of Signs vs. Number of Approach Lanes

As one would expect, more of the left-mounted signs were found in urban areas than in rural areas. This because urban areas had more multilane facilities, thus requiring supplemental left-mounted signs. The number of signs used on single approach lanes in rural areas is due to the number of side streets and entrances and exits to construction operations. The rural areas tended to have more ingress and egress than the limited access facilities in the urban areas. The number of signs used in urban areas remains high simply because of the amount of information drivers in these areas require.

Lane Widths

More than 64 percent of the lanes approaching the signs inventoried were 11 or 12 ft in width. In the rural environment, the majority of widths varied between 8 and 12 ft, with an average width of 11 ft. In the rural condition, 27 percent of widths were 8 or 9 ft. In the urban environment, 75 percent of the lane widths were 11 or 12 ft, with less than 4 percent being 8 or 9 ft. The average lane width in the urban setting was 12 ft.

Posted Speed Limits

Posted speed limits were recorded for each sign inventoried. No attempt was made to determine actual speeds along any segment of roadway. There were some fairly large differences in posted speed limits between rural and urban areas as shown in Figure 14. For example, 68 percent of the signs in rural areas had speed limits posted at 55 mph whereas only 30 percent of the signs in urban areas had speed limits posted at 55 mph.

In urban areas, however, the distribution of signs in each category of posted speed limit was more uniform. That is, 13 percent of the signs had a posted 25 mph speed limit, 16 percent 35 mph, 20 percent 45 mph, 30 percent 55 mph, and 16 percent 65 mph.

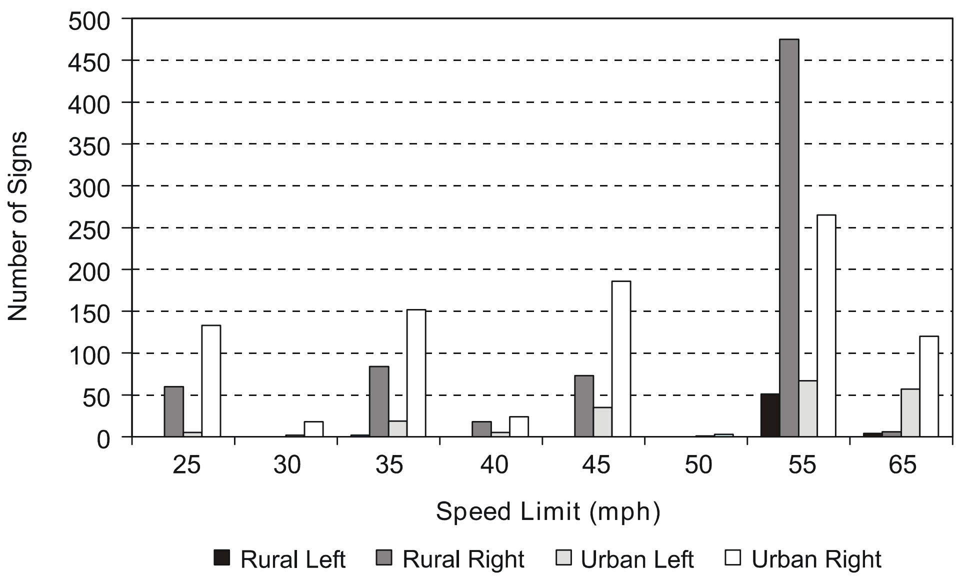

Figure 14. Posted Speeds Limits

Model Development

The data collected were placed into an Excel spreadsheet. To determine the entrance, observation, rotation, and orientation angles for each sign inventoried, the sign twist, roadway approach slope (grade), and perceived tilt needed to be calculated.

Sign Twist Calculation

Twist was determined by (1) assuming the sign in the field was mounted perpendicular to the roadway, (2) knowing the actual offset, and (3) knowing the distance to the traffic cone (100 ft). A calculation was then made to determine the angle formed by a line from the traffic cone to a line normal to the sign's face (see Figure 15). This calculated angle was then subtracted from the horizontal angle measured in the field. The resulting value determined whether the sign was twisted and, if so, the degree to which it was twisted and its direction (away from or toward traffic). For example, a right-mounted sign with a measured offset of 7 ft would have a calculated horizontal angle of 4 degrees (Tan^{-1} [7/100]). The same sign in the field might have had a horizontal angle measured to be 6 degrees. Therefore, the calculated sign twist would be 2 degrees facing away from traffic (based on the researcher's sign convention). Should the calculated twist value have been negative, the sign would have been twisted toward traffic.

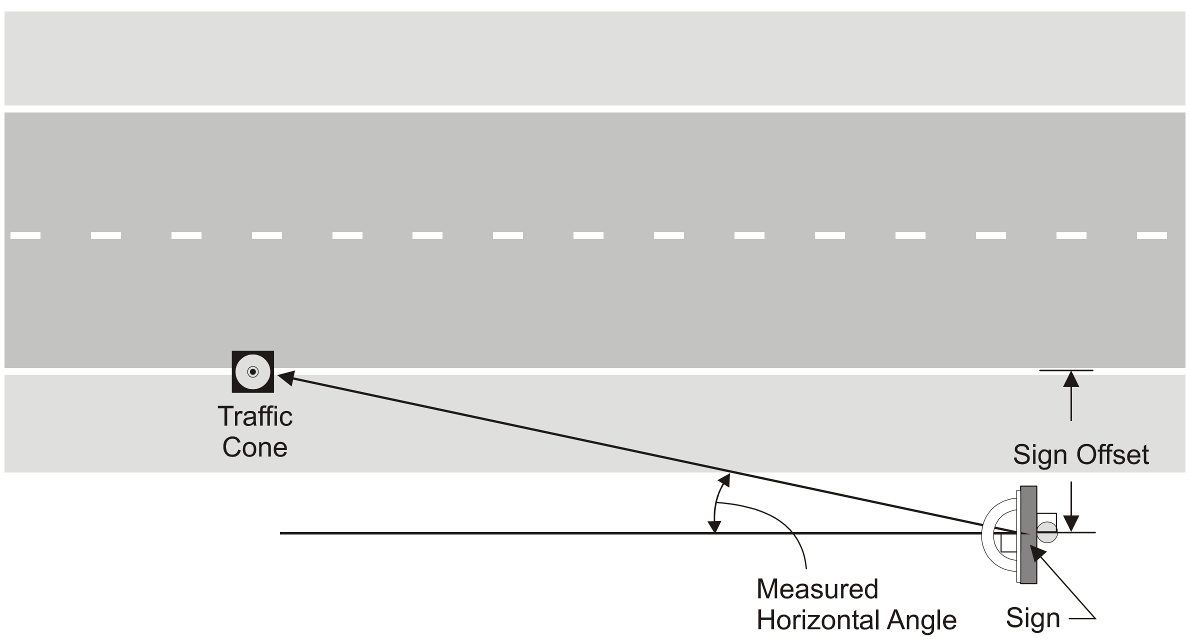

Figure 15. Sign Twist Determination

Roadway Approach Slope

Knowing the slope of the roadway could increase or decrease the perceived tilt (back or forward) of a sign. For example, a driver on a roadway with a 2-degree downhill slope viewing a sign that was tilted forward by 2 degrees would actually be viewing a sign that was tilted forward by 4 degrees.

Slope was calculated by knowing (1) the vertical angle measured in the field, (2) the sign's measured tilt, (3) the sign's mounting height, and (4) the traffic cone's height above the road surface (2.16 ft) (see Figure 16). A calculation was then made to determine the angle formed by a line from the traffic cone to a line normal to the sign's face. The sign's measured tilt was then subtracted from the vertical angle measured in the field. If the resulting value was equal to the calculated vertical angle, the road's approach slope was level; if the value was negative, the approach slope was downhill; if the value was positive, the approach slope was uphill.

Once the slope was determined, a calculation was made to determine the perceived tilt of the sign when the roadway's approach was resolved as being level. This was accomplished by simply adding the calculated slope value to the field measured tilt. If the resulting value was negative, the sign had a perceived tilt forward; if it was positive, the sign had a perceived tilt backward.

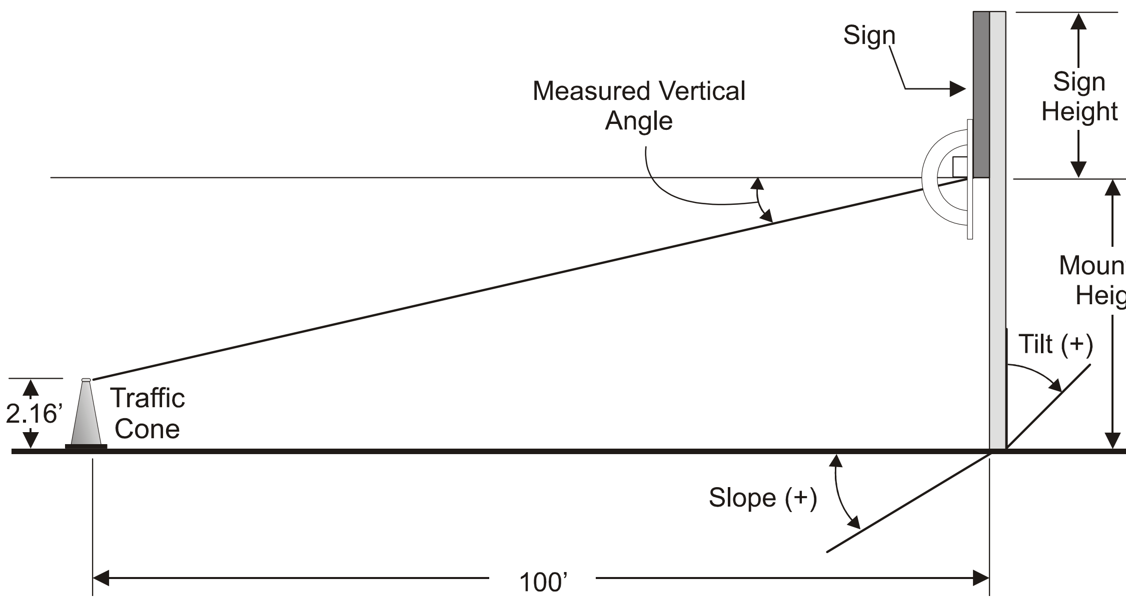

Figure 16. Slope Determination

Model

Using the data collected in the field and the calculated sign twist and perceived tilt, a vector-based mathematical model was developed in the same spreadsheet. This model allowed the researcher to describe each sign's angularity using the Application System as described in ASTM E-808-99a.[1] Although the *Exact Road Geometry Output Program* (ERGO)[25] already exists, the researcher did not use this program because of the potential appearance of bias toward one sign sheeting manufacturer. The model developed in this research used the basic vector relationships as presented by Johnson in 1998.[26]

The model used the edgeline of the curb lane as the origin and assumed that the vehicle was always placed in the center of the lane. For each sign, the model produced values for each of the four angles for the left and right headlights to the center of the sign based on (1) the sign's potential range of viewing (multilane facilities), (2) a set of viewing distances from the sign, and (3) each type of vehicle analyzed.

Potential Range of Viewing

A total of 1,865 signs were inventoried, and they had the potential to be viewed at 2,901 viewing arrangements (i.e., multilane roadways) for each distance from the sign analyzed.

Viewing Distances

The viewing distances used in the model were 100, 240, 280, 350, 500, and 1,000 ft. Since only one distance was inventoried, it was necessary to assume that the roadway's geometry and terrain remained constant from 100 ft to the 1,000-ft mark. The 100-ft distance was initially thought to be the last time a driver would look at the sign, and the hypothesis was that this distance would result in the largest entrance angle.

Almost all of the signs inventoried had either a 6- or 7-in letter height. By applying a conservative legibility index of 40 ft/in of letter height, the 240- and 280-ft distances were determined (6*40 = 240). The 350-ft distance was determined by assuming a legibility index of 50 ft/in with a 7-in letter height. In certain circumstances, the signs inventoried were abnormally large. These signs had larger letter heights that would increase their legibility distance. For simplicity, the model did not take into account these special circumstances.

Since signs are typically detected at greater distances than they are capable of being read, the distances of 500 and 1,000 ft were selected.

Vehicles Used in the Model

Four types of vehicle were used in the model: (1) a 1999 Honda Civic EX, (2) a 1999 Chrysler Town and County Minivan, (3) a 1998 Ford Expedition, and (4) a 1985 Peterbilt 379 Class 8 tractor. These vehicles were selected to be representative of the current vehicle fleet. The Appendix contains the vehicle dimensions and associated driver eye placements used in the model.

RESULTS OF MODEL

Entrance Angle

The model calculated the entrance angles (β) for each sign inventoried, for each distance, for each lane the particular sign could be viewed from, and for each of the four vehicles' right and left headlights. The right and left headlight values were averaged to produce a single entrance angle for each distance, lane, and vehicle type.

The results of the model indicated that entrance angles do not vary significantly between different types of vehicles. The results presented in Tables 4 through 7 were the maximum entrance angles produced by any of the four vehicles and not necessarily by any single vehicle for each distance. In addition, the maximum angles presented were across all travel lanes inventoried. That is, if a roadway had four lanes of travel, all four lanes were reviewed to determine the greatest entrance angle.

Left-Mounted Signs

The model revealed that no left-mounted signs inventoried had a 50-degree entrance angle from 100 ft from the sign to 1,000 ft. The maximum entrance angle produced was almost 47 degrees at a distance of 100 ft. Table 4 shows the maximum entrance angles and second greatest entrance angles generated.

Since no signs produced entrance angles greater than 50 degrees, the data were reviewed to determine how many signs had entrance angles greater than 30 degrees from 100 to 1,000 ft from the sign. Table 5 shows the results of the left-mounted signs having an entrance angle of 30 degrees or greater. Of the 248 left-mounted signs, which can be viewed from 519 positions, a maximum of 24 signs (9.7 percent) had entrance angles greater than 30 degrees at a distance of 100 ft from the signs. As the distance from the signs increased, the number of signs with angles greater than 30 degrees decreased.

Further review of the results identified that all but four signs inventoried had entrance angles less than 40 degrees at a distance of 100 ft. In fact, all of the left-mounted signs inventoried had entrance angles less than 40 degrees from 210 to 1,000 ft from the sign.

Table 4. Left-Mounted Sign Maximum Entrance Angle

Distance (ft)	Maximum Entrance Angle (degrees)	Second Greatest Entrance Angle (degrees)
100	46.6	45.3
150	42.3	41.4
200	40.1	39.4
240	39.0	38.4
280	38.3	37.9
350	37.4	37.3
500	36.9	36.2
1,000	36.2	35.7

Table 5. Left-Mounted Signs Having Entrance Angle Greater Than 30 degrees

Category	Distance (ft)					
	100	240	280	350	500	1,000
Number of Signs	24	8	8	8	8	7
% of Signs	9.7	3.2	3.2	3.2	3.2	2.8
% of Viewing Conditions	4.6	1.5	1.5	1.5	1.5	1.3

Right-Mounted Signs

The model revealed that a 50-degree entrance angle does exist at a distance of 1,000 ft. Table 6 shows the maximum entrance angles and second greatest entrance angles generated. It is interesting to note that the maximum values depicted increased rather than decreased with distance. This is because the signs in question were rotated toward traffic such that when traffic approached them, the entrance angles were reduced.

The data were reviewed to determine how many signs had entrance angles greater than 30 degrees from 100 to 1,000 ft from the sign. Table 7 shows these results. Of the 1,617 right-mounted signs, which could have been viewed from 2,382 positions, only 18 signs had entrance angles greater than 30 degrees at a distance of 100 ft from the signs. As the distance from the signs increased, the number of signs with entrance angles greater than 30 degrees decreased.

Upon further review of the results, only three signs had entrances angles of 40 degrees or more at a distance of 100 ft. The entrance angles of two of the three signs decreased below 40 degrees at a distance of 130 ft. Only one sign had an entrance angle greater than 40 degrees from 100 to 1,000 ft. The sign in question was on a ramp in an urban setting. No other sign had an entrance angle of 40 degrees or more for distances greater than 130 ft.

Table 6. Right-Mounted Sign Maximum Entrance Angle

Distance (ft)	Maximum Entrance Angle (degrees)	Second Greatest Entrance Angle (degrees)
100	41.6	39.9
130	42.5	39.0
240	46.6	34.8
280	47.4	34.5
350	48.2	35.4
500	49.2	36.5
1,000	50.4	38.9

Table 7. Right-Mounted Signs with Entrance Angle Greater than 30 Degrees

Category	Distance (ft)					
	100	240	280	350	500	1,000
Number of Signs	18	8	8	8	7	7
% of Signs	1.1	0.5	0.5	0.5	0.4	0.4
% of Viewing Conditions	0.8	0.3	0.3	0.3	0.3	0.3

Observation Angle

The model calculated observation angles (α) for each sign inventoried, at each distance, for each lane from which the sign could be viewed, and for the right and left headlights of each of the four vehicles. The right and left headlight values were averaged to produce a single observation angle value for each distance, lane, and vehicle type.

Left-Mounted Signs

The results of the calculations for the left-mounted signs are shown in Figure 17. This figure shows the 99th percentile of the greatest observation angles calculated for each vehicle from 100 to 1,000 ft from the sign. The results are not surprising in that the Honda Civic had the smallest observation angles for the entire approach, ranging from 0.17 degree at 1,000 ft to 2.30 degrees at 100 ft. The angles for the SUV and minivan remained relatively equal, ranging from 0.2 degree at 1,000 ft to 0.54 degree and 0.53 degree, respectively, at approximately 400 ft. The observation angles for these two vehicles diverged from this point for the remainder of the approach to the signs.

As expected, the Class 8 tractor was associated with the largest observation angles along the entire approach, ranging from 0.32 degree at 1,000 ft to 3.47 degrees at 100 ft. The Honda had an observation angle of 1.0 degree at approximately 200 ft from the sign, whereas the minivan, SUV, and the Class 8 tractor had a 1.0-degree observation angle at approximately 220, 225, and 320 ft, respectively, from the sign.

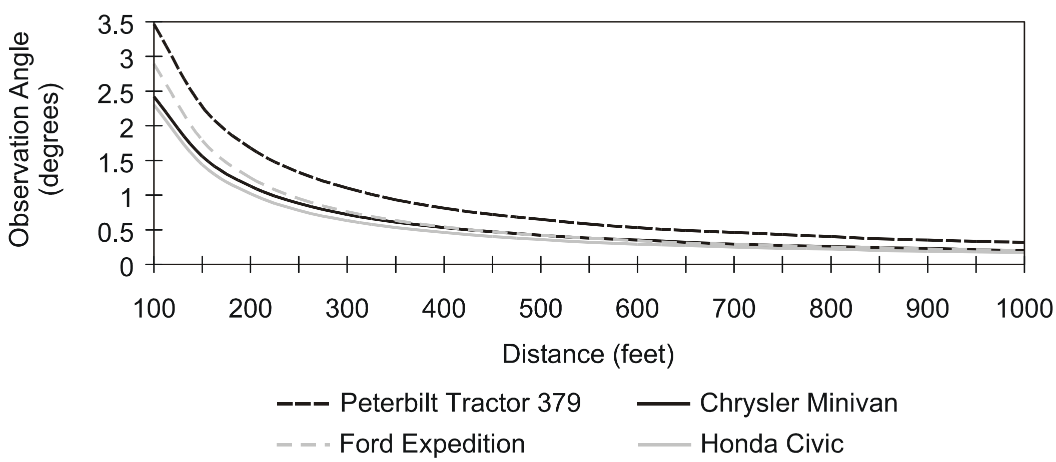

Figure 17. Observation Angles of Left-Mounted Signs

Right-Mounted Signs

The results of the calculations for the right-mounted signs are shown in Figure 18, which shows the 99th percentile of the greatest observation angles calculated for each vehicle from 100 to 1,000 ft from the sign. These results are similar to those for the left-mounted signs in

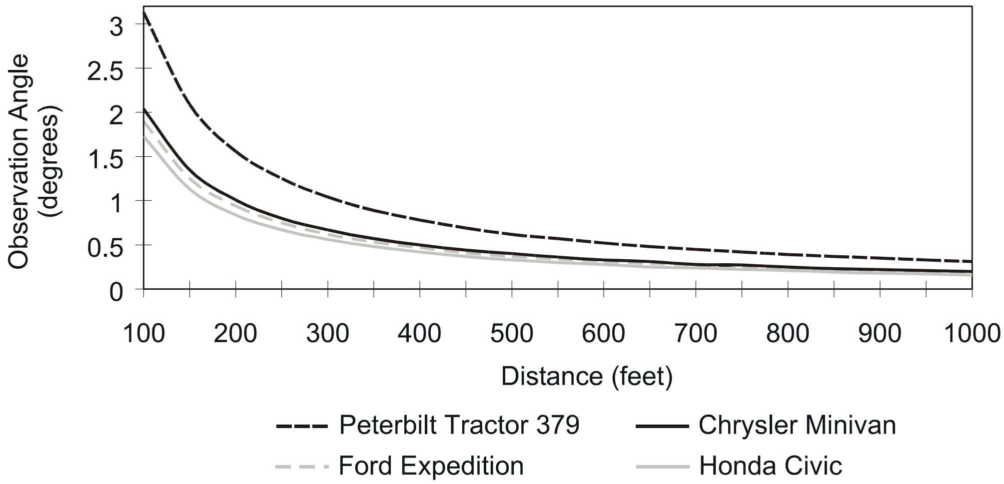

Figure 18. Observation Angles of Right-Mounted Signs

that the Honda Civic had the smallest observation angles for the entire approach, ranging from 0.16 degree at 1,000 ft to 1.73 degrees at 100 ft. The SUV observation angles ranged from 0.19 degree at 1,000 ft to 1.90 degrees at 100 ft, whereas the angles for the minivan over the same distance ranged from 0.20 to 2.04 degrees. It is interesting to note that the angles for the minivan were consistently larger than for the SUV over the entire approach. The Class 8 tractor again had the greatest observation angles along the entire approach, ranging from 0.31 degree at 1,000 ft to 3.13 degrees at 100 ft.

The Honda had an observation angle of 1.0 degree at approximately 130 ft from the sign, whereas the SUV, minivan, and Class 8 tractor had a 1.0-degree observation angle at approximately 190, 205, and 310 ft, respectively, from the sign.

Orientation Angle and Rotation Angle

Since prismatic sheetings lack rotational symmetry, it was important to analyze the orientation angle (ω_s) and rotation angle (ε) that were produced by the model based on the field data. Each of the angles (ω_s and ε) was developed for each distance, vehicle, and headlight. The resultant values for the right and left headlights were then analyzed.

It is well known that the rotation angle has some effect on retroreflectivity of prismatic materials at all entrance angles, whereas retroreflectivity is dependent on the orientation angle only for large entrance angles (β >30 degrees). To be conservative, the orientation and rotation angles were recorded for each vehicle type and lane placement in 50-ft intervals from 100 to 1,000 ft from each sign installation when entrance angles were greater than or equal to 25 degrees. This resulted in more than 6,400 data points. The corresponding observation angles ranged from 0.16 degree to 3.47 degrees, which are the minimums and maximum values previously discussed.

Since construction and maintenance signs can be right mounted or left mounted, the individual sign-mounting location results were combined for both the orientation angle and the rotation angle, as shown in Figure 19.

As Figure 19 indicates, negative orientation angle (ω_s) values ranged from –63 degrees to as much as –99 degrees, and the positive values ranged from +61 degrees to +144 degrees. The orientation angle values above +90 and below –90 degrees should be considered outliers in the data set but are shown here since they do occur in the field. These outliers are the results from four extremely poorly positioned signs with excessive lean that are not indicative of how signs are typically placed. With these signs removed from further consideration, orientation angles of ±75 and ±90 degrees represent almost 80 percent of the calculated values. The median value for both the positive and negative orientation angles approached 80 degrees.

Figure 19 also shows that the rotation angle ranges from –78 degrees to +79 degrees for signs having an entrance angle greater than or equal to 25 degrees. The grouping of the results suggests that rotation angle values of ±60, ±30, and 0 degrees are more representative of how these signs function in the field when the entrance angles are greater than 25 degrees.

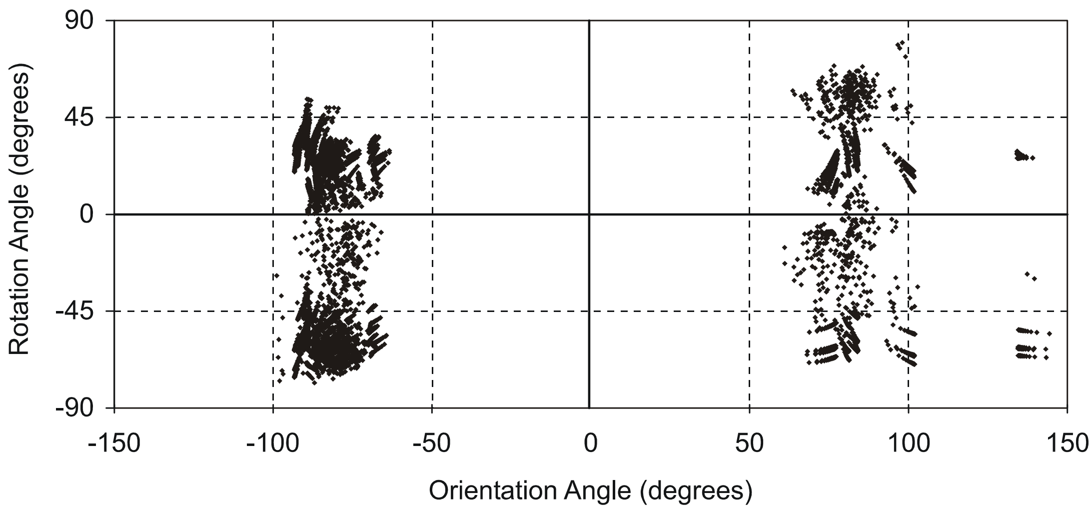

Figure 19. Orientation Angle vs. Rotation Angle for Entrance Angles ≥ 25 Degrees

DISCUSSION

The ability of a sign to function, during both day and night, is based on a complex relationship among the driver, the vehicle, and the roadway environment. Each factor has a number of associated elements, e.g., the vehicle could be a passenger car or an SUV, the sign might be 5 or 10 ft from the roadway, or the vehicle might be 250 or 500 ft from the sign. What might appear to be subtle differences in vehicle types, lateral offsets, or distance can have a significant impact on a sign's performance, especially at night. For example, a sign's placement (height above the road, offset, rotation, right or left mounted, etc. affects its ability to return light back to the vehicle. As a vehicle approaches a sign, the brightness of the sign increases because more light from the vehicle's headlamps is reaching the sign. But, as the observation angle (and generally entrance angle) increases, the resulting brightness decreases because of the characteristics of the sign sheeting and the headlamp aiming.

To increase the complexity of the situation, the perceived brightness of a sign will also be dependent on the type of vehicle approaching the sign. The driver of a passenger car approaching a sign at night will perceive it to be brighter than the driver of an SUV or tractor-trailer viewing the same sign at the same distance in the same travel lane. This is because the eyes of the driver of the passenger car are closer to the headlight (smaller observation angle) and more light is being returned to its source, whereas the driver of the SUV or tractor-trailer is positioned higher above the headlamps and less light is returned to these heights. A sign that is visible and legible to the driver of a passenger car may not be visible to the driver of an SUV or a tractor-trailer at the same distance.

As this phenomenon was previously discussed, for a given sign, the observation angle of a small passenger car can be 0.2 degree at 1,000 ft and that of a tractor-trailer can be more than 0.3 degree. As both of these vehicles approach the same sign, the observation angles will continue to increase. At issue is not only where the sign is detected, but also where it is legible. The legibility distances associated with the majority of work zone signs inventoried for this study were from 240 to 350 ft. Table 8 depicts the resultant observation angles for these legibility distances for the four vehicles types investigated.

Table 8. Legibility Distances and Corresponding Observation Angles by Vehicle Type

Distance (ft)	Honda Civic	Minivan	SUV	Tractor-Trailer
240	0.70	0.84	0.78	1.30
280	0.60	0.71	0.67	1.12
300	0.56	0.67	0.62	1.04
350	0.48	0.57	0.53	0.89

As the table shows, the minivan, SUV, and tractor-trailer will have greater observation angles than the passenger car. With the significant increase of SUVs and minivans in the vehicle fleet over recent years,[20,21] this finding indicates the need to change the current sign sheeting specification practices that are attempting to accommodate predominately the passenger car and develop specifications at driver-relevant geometries. To ensure a higher probability that work zone signs remain visible and legible to the full range of vehicles on Virginia's roadways, the current observation angle requirement should be increased.

As for the placement of signs, the literature provided guidance on the placement of construction and maintenance signs. However, the results of the field data analysis indicated that these signs are not always placed in accordance with the MUTCD.[7,8] Lateral placement tended to vary significantly from recommended practice. For the most part, signs were placed where they could be located safely to avoid temporary barriers, ditches, guardrail, and underground utilities and where they would not impede construction activities or reduce driver awareness. Even though the placement of these signs was less than ideal, this did not adversely affect the entrance angles at multiple distances. In fact, the vast majority of the signs investigated had entrance angles less than 30 degrees from 100 to 1,000 ft from the sign. However, in a number of instances, signs did have entrance angles greater than 30 degrees. Although the number was small, this indicates a need for work zone signs to be capable of performing at entrance angles greater than 30 degrees and that the current 50-degree entrance requirement is not appropriate.

The sign mounting heights did not vary significantly between urban and rural conditions. In fact, the average heights were relatively close to the recommended practice. This suggests that sign crews are less constrained at ensuring proper vertical placement than the restrictions imposed on them when locating these signs laterally.

Another interesting finding was that a considerable number of the work zone signs investigated appeared to be "aimed" toward the approaching motorist. This twisting of the sign face toward the oncoming vehicle resulted in smaller entrance angles than expected. In this situation, as a vehicle approaches a sign, the entrance angles get smaller. Therefore, the theory that maximum entrance angles occur only when a vehicle is closest to a sign is not valid.

CONCLUSIONS

- *For signs to be effective in work zones, they must be capable of performing under a variety of situations depending on the maintenance of traffic plan in force. Most of these situations can be considered less than ideal.*
- *When performance-based material specifications for work zone signs are being developed, it is not appropriate to rely solely on standards (e.g., the MUTCD) or guidelines for sign placement.* Real-world conditions present logistical problems in sign placement, and field engineers must often overcome these limitations. Material performance specifications must be able to account for work zone sign placement that is less than ideal.
- *Maximum entrance angles do not always occur when a vehicle is closest to a sign*. They can occur when a vehicle is furthest from a sign.
- *VDOT's current specification for retroreflective sheeting used on orange construction and maintenance activity (work zone) signs is not appropriate.* This is because for a prismatic lens retroreflective sheeting material, the specification should include values for the material's orientation and rotation angles, in addition to its entrance and observation angles. The findings of this study indicate that the current entrance angle requirement of 50 degrees is too large and the current observation angle requirement of 0.5 degree is too small.
- *Not every motorist will be exposed to construction and maintenance signs that are associated with large entrance angles, such as 40 degrees. But every motorist will experience a 0.2, 0.5, 1.0, 1.5, and possibly a 2.0-degree observation angle on the approach to a sign depending on the type of vehicle being driven.*

- *Because of the asymmetrical nature of prismatic retroreflective materials, orientation and rotation angles are important components of a sheeting's performance, in addition to entrance and observation angles.*

RECOMMENDATIONS

1. *VDOT's Mobility Management and Materials Divisions should modify the specification for construction and maintenance sign sheeting*. The entrance angle requirement should be reduced to 40 degrees, and the observation angle requirement should be increased to 1.0 degree. The reduced entrance angle will still allow a factor of safety for misaligned signs or signs with placements that are less than ideal, and the increased observation angle will better ensure that these signs remain visible to a greater range of vehicle types (passenger cars, SUVs, minivans, and tractor-trailers).

2. *VDOT's Mobility Management and Materials Divisions should consider modifying the specification for fluorescent orange construction and maintenance sign sheeting to include appropriate orientation and rotation angles*. Four angles are required to describe a prismatic lens retroreflective material. Using the Application System,[1] the specification should have requirements for entrance, observation, orientation, and rotation angles. Table 9 provides the recommended test points.

3. *VDOT's Mobility Management Division should continue to emphasize the importance of proper sign placement in work zones*. This would reduce the likelihood of signs being placed 44 ft from the edge of the pavement or signs being tilted back 26 degrees, as was found during the conduct of this study.

4. *The Virginia Transportation Research Council should continue this research for permanent ground-mounted signs on Virginia's interstate, primary, and secondary facilities to validate current sheeting specifications.*

COST IMPLICATIONS

The costs associated with implementing the recommendations of this study are unknown. The sign sheeting materials for which the evaluation criteria were developed may not have been manufactured as of yet. In the short term, costs associated with such a product might be higher since one manufacturer might be capable of producing the product first. The long-term costs could be less since the specifications are based on user requirements and not product specifications. This should allow for competition in the construction and maintenance sign sheeting industry.

Table 9. Proposed Test Points for Work Zone Prismatic Sheeting Using the Application System

Entrance Angle (β)	Rotation Angle (ε)	Orientation Angle (ω_s)	Orientation Angle (ω_s)	Orientation Angle (ω_s)	Orientation Angle (ω_s)	Orientation Angle (ω_s)
5	–60			0		
5	–30			0		
5	0			0		
5	30			0		
5	60			0		
15	–60			0		
15	–30			0		
15	0			0		
15	30			0		
15	60			0		
30	–60	–90	–75		75	90
30	–30	–90	–75		75	90
30	0	–90	–75		75	90
30	30	–90	–75		75	90
30	60	–90	–75		75	90
40	–60	–90	–75		75	90
40	–30	–90	–75		75	90
40	0	–90	–75		75	90
40	30	–90	–75		75	90
40	60	–90	–75		75	90

Note: The Application System is described in ASTM E808-99a.[1] Observation angles (α) for testing must consist of 0.2, 0.5, and 1.0 degree.

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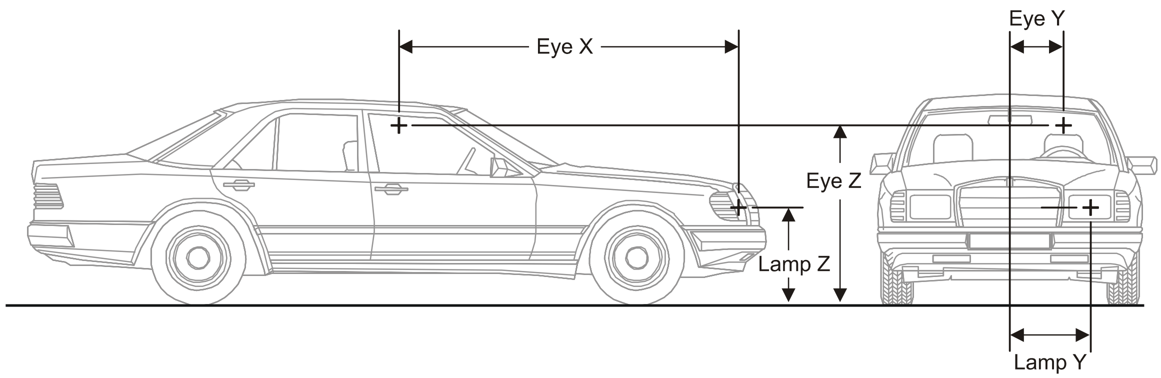
APPENDIX
VEHICLE DIMENSIONS AND DRIVER EYE HEIGHTS



Vehicle Dimensions and Driver Eye Position (ft)

Vehicle	Eye Setback (X)	Eye Lateral (Y)	Eye Height (Z)	Lamp Setback (X)	Lamp Lateral (Y)	Lamp Height (Z)
1999 Honda Civic	6.424	1.125	3.957	0	1.916	2.001
1999 Chrysler Town & Country Minivan	6.168	1.250	4.751	0	2.333	2.375
1998 Ford Expedition	8.333	1.667	5.249	0	2.165	3.166
1995 Peterbilt 379 Class 8 Tractor	8.415	1.332	8.061	0	3.084	3.707