The Kiewit Center for Infrastructure and Transportation

# Stopping Sight Distance

## Discussion Paper #1

by

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## DISCLAIMER

This paper represents the research and viewpoints of the author. It draws heavily on information previously prepared for the Oregon Department of Transportation (ODOT) in the Discussion paper 8A, “Stopping Sight Distance and Decisions Sight Distance,” for ODOT, by Dr. Robert D. Layton, The Kiewit Center for Infrastructure and Transportation, Oregon State University, September 2004.

## GENERAL GOAL

This and other background papers are prepared to provide background, enhance understanding and stimulate discussion among individuals representing a variety of groups, agencies and interests who have concern in Oregon’s highways.

## SPECIFIC OBJECTIVES

The specific objectives of this discussion paper are to:

1. Summarize the literature and traditional knowledge regarding stopping sight distance.

2. Summarize research and the current state of the art on the factors and elements of driver behavior and traffic operations that affect stopping sight distance.

3. Review current criteria on stopping sight distance within the context of access management.

4. Identify questions and issues regarding the appropriate criteria and use of stopping sight distance for access management.

# OVERVIEW

## Background

The safe operation of all highway facilities, including intersections, requires the consideration of three primary elements for safe roadway operations: the driver, the vehicle, and the roadway. An understanding and consideration of each of these elements is necessary to define appropriate sight distance criteria. Human factors associated with the driver's performance must take account of both physical abilities and psychological influences. The size, weight, and braking ability of vehicles are of particular importance for the safe operation and stopping of vehicles. The roadway geometric design features, obstacles to sight at the roadsides, pavement surface condition, and climatic conditions impact the safety on the roadway and sight distance requirements. Each of these elements and their interactions govern the development and specifications of sight distance criteria and standards.

The determination of stopping sight distance requires the definition and consideration of seven design variables:

Primary Stopping Sight Distance Factors

- Perception-reaction time
- Driver eye height
- Object height
- Vehicle operating speed
- Pavement coefficient of friction
- Deceleration rates
- Roadway grade

An important study on stopping sight distance was published as NCHRP Report 400, "Determination of Stopping Sight Distance" *(1)*. This reference presents recommended revisions to the AASHTO "Policy on Geometric Design" for the 2001, 2004 and 2011 Editions *(2,3,4)*.

Most of the recommended changes from NCHRP Report were included in the 2001 AASHTO "Policy on Geometric Design" (i.e., 2001 Greenbook). However, a number of state DOTs have opted to retain the 0.5 ft. (150 mm) height of object criterion from the 1990 and 1994 AASHTO Policies (1990 and 1994 Greenbooks), rather than accept the significant impact due to the change in height of object, from 0.5 ft. (150 mm) to 2.0 ft. (600 mm), for stopping sight distance *(5,6,7)*.

## Content

This background paper summarizes the literature, standards and traditional knowledge on stopping sight distance. The primary emphasis of this discussion is on the driver behavior and traffic operation conditions that influence the distance required for drivers to stop or maneuver their vehicles safely.

The discussion includes information drawn from policies, standards and current research. The primary sources of the policies and standards are the AASHTO Policy on Geometric Design, 1990 Edition (English Units), 1994 Edition (Metric units) and 2001 Edition (both units), and the Oregon Highway Design Manual. The standards and criteria for stopping sight distance have evolved since the 1920s. The changes in vehicle sizes and operating characteristics, driver experience and behavior, and highway technology cause a continued evolution of sight distance policies and standards.

## Issues

Sight distance criteria have impact on virtually all elements of highway design, many elements of the operation/control, and recently, access management implementation. The roadway geometric design features, presence of obstacles to sight at the roadsides and the pavement surface condition are fixed by sight distance requirements. The nature of traffic controls and their placement must take account of sight distance requirements. At times, the effects of traffic stream conditions, such as traffic queues, must be viewed from adequate distance to stop. The provision of roadside access and accommodation of pedestrian crossings must assure a safe stopping distance.

Adequate stopping sight distance must be provided on 100% of the street and highway system so a driver with the standard eye height can see an object of standard height with sufficient time to stop safely. This assumes a certain level of alertness on the part of the driver and no influence on a driver’s perception and reaction due to added complexity of traffic, control and local environmental conditions. Some research has indicated that driver behavior, expectations and alertness change with the type of area and with the operating conditions on the roadway.

The determination of stopping sight distance requires the definition of six of the seven primary design variables defined previously. It is not necessary to specify both deceleration rate and a design coefficient of friction because they both measure the required rate of slowing for the vehicle.

Under some conditions the added complexity of traffic, local activities and driver expectancy may require longer times to accommodate long perception-reaction times due to situation complexity, expectations and alertness, as well as longer distance for normal vehicle maneuvers of lane changing, speed changes and path changes, or for stopping. The current standards for stopping sight distance take these factors into account.

These increased perception-reaction times and longer maneuvering distances are accommodated by decision sight distance. Decision sight distance is applied where numerous conflicts, pedestrians, various vehicle types, design features, complex control, intense land use, and topographic conditions must be addressed by the driver. Stopping sight distance is applied where only one obstacle must be seen in the roadway and dealt with. Decision sight distance is different for urban versus rural conditions, and also for maneuvers ranging from stopping to speed, path or direction change within the traffic stream.

Stopping in the context of decision sight distance, as distinct from stopping sight distance, may be necessary to avoid a vehicle that is forced to stop for some traffic condition, such as a queue of vehicles, or roadside conflicts, such as, congestion in a driveway.

In view of the complexity and variations in drivers' expectancy for situations associated with access management, in general, decision sight distance is a more logical requirement for many access management situations than stopping sight distance, as currently defined. Decision sight distance is covered in a companion paper, "Decision Sight Distance: A Discussion Paper," Kiewit – 2012/03, OSU, March 2012.

## Stopping Sight Distance as a Design Measure and Access Management Measure

Stopping sight distance is required at all locations along the highway, to see an object in the roadway with enough distance to stop. The stopping sight distance is typically required through all intersections that are not "stop" or "yield" controlled. It is required at all pedestrian crossings.

For access management, stopping sight distance should logically be required at driveway approaches for vehicles entering, at height of headlight, or leaving, at the height of tail-light. Stopping sight distance has also been used as a criterion for safe driveway spacing on major arterials.

## Questions to be Answered

The selection and application of a sight distance criteria require that a number of questions be answered. The most important questions are identified as follows:

1. Should a safe coefficient of friction or acceptable deceleration rate be used to define the deceleration of vehicles? What deceleration rates are implied by the coefficient of friction used for design? What deceleration rates are typical and comfortable for drivers? What deceleration rates are acceptable for stopping of trucks?

2. What height of eye should be used for stopping sight distance? What proportion of the drivers should the height of eye criterion represent? What height of eye should be used for trucks?

3. Is a 2 ft. (600 mm) object reasonable for assessing stopping sight distance? Should the height of the object be different for decision sight distance? Should the height of the object be different for some situations where stopping sight distance is required, such as pedestrian crossings?

4. Should trucks be treated specifically or should the higher eye height be assumed to offset the longer stopping distance required?

5. Should the stopping sight distance be based on design speed, running speed or vary according to conditions?

6. Should the perception-reaction times specified in the AASHTO Green Book be accepted, or should they be specified according to the situation?

## PERCEPTION-REACTION TIMES

### PIEV Process

The perception-reaction time for a driver is often broken down into the four components that are assumed to make up the perception reaction time. These are referred to as the PIEV time or process.

PIEV Process

| | |
|---|---|
| • Perception | the time to see or discern an object or event |
| • Intellection | the time to understand the implications of the object's presence or event |
| • Emotion | the time to decide how to react |
| • Volition | the time to initiate the action, for example, the time to engage the brakes |

### Current Design Perception-Reaction Time

Human factors research defines the required perception-reaction times *(2,3,4,5,6)* as follow for:

| | |
|---|---|
| • design | 2.5 sec |
| • operations/control | 1.0 sec |

These perception reaction times were based on observed behavior for the 85th percentile driver; that is, 85% of drivers could react in that time or less. More recent research has shown these times to be conservative for design *(9,10,11,12)*.

Wortman and Mathias *(9)* reported both the "surprise" and alerted 85th percentile perception reaction times for control. The time perception-reaction was measured after the yellow indication until brake lights appeared, and was in an urban environment

The Wortman et al., research found:

| | |
|---|---|
| • alerted 85% perception-reaction time | 0.9 sec |
| • "surprise" 85% perception-reaction time | 1.3 sec |

### Perception-Reaction Time Research

Recent studies have checked the validity of 2.5 seconds as the design perception reaction time. Four recent studies have shown maximums of 1.9 seconds as the perception-reaction time for an 85th percentile time and about 2.5 seconds as the 95th percentile time *(9,10,11,12)*.

**Table 1. Brake Reaction Times Studies**

| | 85th | 95th |
|---|---|---|
| Gazis et al. | 1.48 | 1.75 |
| Wortman et al. | 1.80 | 2.35 |
| Chang et al. | 1.90 | 2.50 |
| Sivak et al. | 1.78 | 2.40 |

*Source: (9,10,11,12)*

### Perception-Reaction Times by Road Type

Some researchers have suggested that the perception-reaction should reflect the complexity of traffic conditions, expectancy of drivers and the driver's state. They suggest that the perception reaction times may be altered accordingly, as shown in Table 2 *(12)*.

**Table 2. Perception-Reaction Times Considering Complexity and Driver State**

| | Driver's State | Complexity | Perception-Reaction Time |
|---|---|---|---|
| Low Volume Road | Alert | Low | 1.5 s |
| Two-Lane Primary Rural Road | Fatigued | Moderate | 3.0 s |
| Urban Arterial | Alert | High | 2.5 s |
| Rural Freeway | Fatigued | Low | 2.5 s |
| Urban Freeway | Fatigued | High | 3.0 s |

*Source: (12)*

### 2011 AASHTO Policy on Brake Reaction Times

The basis for the design perception-reaction times, or "brake reaction times" in the 2011 AASHTO Policy on Geometric Design references the research by Johannson and Rumar for expected and unexpected events *(4,13)*. This study was based on data collected from 321 drivers. The following figure for the 85$^{th}$ percentile driver has been used to determine the design perception-reaction times for unexpected and expected event.

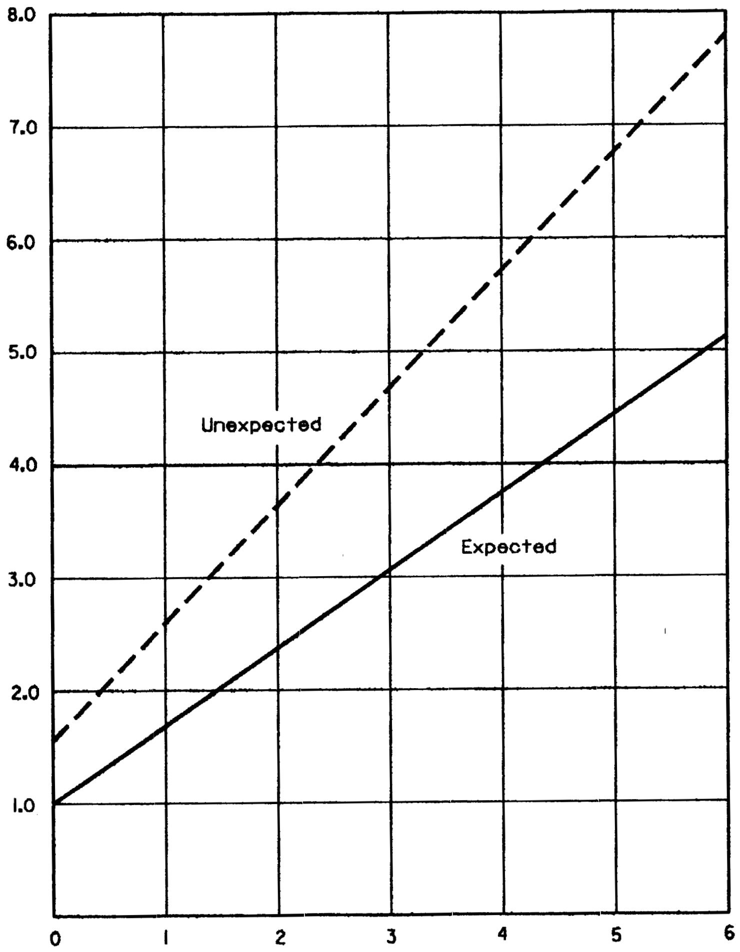


**Figure 1. 85th Percentile Driver Perception Reaction Time versus Information Content**
*Source: (6)*

For stopping sight distance an unexpected event, such as, an obstacle in the middle of the roadway would correspond to 1 information bit, and would give a perception-reaction time of 2.7$^s$. A design value of 2.5 seconds was set because it would accommodate 85% of drivers.

The perception-reaction time for traffic control would correspond to 0 information bits since the driver would see and understand the presence of the signal, and would be waiting for a change of its indication. This results in a perception-reaction time of 1 second for the expected condition. One study cited indicated an average alerted perception-reaction time of 0.64 seconds with 5% of the drivers requiring over 1 second *(14).*

It also references NCHRP Reports 600A, 600B and 600C dealing with consideration of human factors for roadway systems *(15,16,17).*

An appreciation and understanding of human factors, driver behavior and abilities are needed to determine the sight distance criteria. The physical abilities and psychological limitations of drivers impact these criteria, and should be reviewed here to obtain perspective.

### Perception-Reaction Times for the Elderly Driver

The perception-reaction times for elderly drivers have not been found to be significantly longer than the average younger driver. However, the changes in physical and cognitive abilities for the elderly could have significant impacts on their abilities to understand conditions and react safely. Consequently, AASHTO has recommended that a design perception-reaction time of 3.0 seconds be used *(18)*.

## HUMAN FACTORS

### Visual Acuity

The primary stimulus for operation and safe control of vehicles is eye sight. The physical composition of the eye and its functioning constitute limits that must be considered when developing sight distance criteria.

Visual Acuity

| | |
|---|---|
| 3-4° cone | best vision – can see texture, shape, size, color, etc. |
| 10° cone | clear vision – critical traffic control devices must be in this cone |
| 20° cone | satisfactory vision – regulatory and warning traffic control devices should be this cone of vision |
| ~ 90° cone | peripheral vision – only movement can be seen with this vision |

Drivers focus their attention down the roadway in the cone of clear vision at 3 to 4 times the stopping distance. They then shift their vision to the right and left to keep track of traffic conditions, pedestrians and local activities. The eye movement time includes the time required for a driver to shift their eyes and to focus on an object.

Eye Movement Time

| | |
|---|---|
| Shift to New Position | 0.15-0.33 sec |
| Fix or Focus on Object | 0.1-0.3 sec |

It takes roughly 0.5 second for a driver to shift his eyes and focus. Thus, a full cycle to right and back to the left takes about 1 second. If there is glare, it takes 3 seconds to recover full visual acuity and about 6 seconds to recover from bright to dim conditions.

## Visual Ability of the Older Driver

For drivers over 65, the average static visual acuity has dropped to 20/70 *(19).* The ability to see detail in signs, markings and geometric features is governed by the static visual acuity of the driver. The static visual acuity is dependent on the background, brightness, contrast and time for viewing.

Dynamic visual acuity is the ability to resolve the details of a moving object. Dynamic visual acuity is diminished as speed of the object increases, however it improves as time of viewing illumination and familiarity increase *(20).* Dynamic visual acuity related to crash involvement regardless of age. However, there is gradual deterioration of dynamic visual acuity with advancing age.

Contrast sensitivity is the ability of drivers to analyze contrast information and see patterns in the visual field. A study by M.S. Horswill, et al., *(21)* found that hazard perception-response time increases significantly with loss in contrast sensitivity. Contrast sensitivity is more important than visual acuity for night time driving safety and operations. Older drivers have less contrast sensitivity than younger drivers.

Research has found reduced contrast sensitivity and static visual acuity for elderly drivers when there is glare *(18).* The ability to assess distance or depth perception by shifting from near view to far view is lost to elderly drivers by the hardening of the optic lens and the weakening of the ocular muscle. This results in the inability of the elderly to judge speeds of oncoming vehicles, assess gaps between vehicles and determine the distance to roadside features. These losses in ability are critical for making left turns and crossing through traffic safely.

Virtually all vision measures deteriorate with lower levels of illumination. Less illumination is especially problematic for the elderly driver. Drivers by age 75 need about 32 times as much illumination to see well as they did at age 25 *(18)*.

## Working Memory Capability

Working memory capacity relates to the mutual cognitive ability to process new information while storing and analyzing known information. The working memory capacity is the amount of information that a driver can receive and process at a time. It is felt that the working memory capacity of the elderly is less than that for younger drivers. A rule of thumb estimates the average workload of seven items to roughly define the typical working memory capacity.

High volume, high speed arterials with multiple access points, numerous conflicts, median openings, pedestrians and traffic control can provide a workload that taxes the working memory capacity. As speeds and volumes increase, drivers pay less attention to activities in the periphery at the roadside, thus access management features require longer perception-reaction times.

Attention to the driving task is extremely important for safe driving. It has been estimated that 25-50% of crashes result from inattention *(22)*. Selective attention requires selection of the most critical information out of the volume of information presented. Selection and appropriate use of critical information is basic to safe driving. Elderly drivers have more difficulty selecting the critical information, and it takes them longer to process it. Care must be taken to provide adequate viewing and response time, where conflicts are numerous, conditions are complex, and speeds and volumes are high to limit driver workload to acceptable levels.

## Human Mind is a Sequential Processor

Humans are sequential processors; that is, drivers sample, select and process information one element at a time, though very quickly. Therefore, complex situations create unsafe or inefficient operations because it takes so long for drivers to sample, select and process the information. This means that as complexity increases, a longer perception-reaction time should be available. The visual acuity limitations, visibility constraints of glare/dimness recovery and complexity of traffic conditions, when taken together, require much longer perception-reaction times or decision times.

## Driver Expectancy

Drivers are led to expect a particular operation condition based on the information presented to them. They use both formal and informal information.

- Formal information – this includes the traffic-control devices and primary geometric design features of the roadway, but does not include the roadside features such as ditch lines, guardrail, and other street furniture.

- Informal information – this includes roadside features and also land use features, such as brush lines, tree lines, fences and information signing. It includes all information that is not formal.

Drivers develop expectations on how to drive a roadway through experience, training and habit. At times these expectations are in error because they use inappropriate informal information, or the formal information provided is not proper or gives mixed messages. Often, the information at a location is conflicting, and drivers who are familiar with the location will read traffic conditions differently than unfamiliar drivers. For example, driver error due to driver expectancy can occur where the location of pavement joints (informal information) conflict with lane markings (formal information). A driver may see and follow the pavement joints rather than the pavement striping, particularly on dark, wet nights.

Increased perception reaction time is needed to allow time for drivers to make the proper decision when information conflicts and driver expectancy may be in error.

Traffic conditions vary dramatically on major facilities; consequently, the information that drivers receive from other vehicles and traffic conditions is constantly changing. Therefore, high volume and high speed conditions with the added complexity and heavier driver workloads require longer decision times and compound any problems arising from driver expectancy.

## DRIVER EYE HEIGHT

The design driver eye heights for AASHTO 2004 and 2011 *(3,4)* are:

| | |
|---|---|
| Automobiles | 3.5 ft (1080 mm) |
| Trucks | 7.6 ft (2330 mm) |

The height of eye for design has decreased with time as the vehicle sizes and dimensions changed. The design height of eye up to the year 2000 was 3.5 ft. (1070 mm) (1,2). This has reduced from 5.5 ft. (1680 mm) in the 1920s to 3.75 ft. (1150 mm) in 1965. A moderate change in driver's eye height results in a small change in stopping sight distance and in the required length of vertical curves *(25).* Driver eye height for trucks is not normally of concern because they are significantly higher than passenger cars. The higher height of eye for trucks is assumed to compensate for their longer stopping sight distance. However, truck eye height may be an issue where the stopping sight distance is controlled by horizontal alignment, such as cut slopes, or other vertical sight obstructions, such as a hedge, overhanging limbs or signs. Typical values for height of eye for trucks are from 71.5 in. (1820 mm) to 112.5 in. (2860 mm) with an average eye height of 93 in. (2360 mm). In the past, height of eye of 8.0 ft. (2400 mm) has been used for design *(26,27)* for trucks.

The NCHRP Report 400 presented the results of some measurements made on height of eye for various vehicles. These results are shown in Table 3 *(1).*

**Table 3. Current Height of Eye Statistics**

| | Passenger Cars | | Multipurpose Vehicles* | | Heavy Trucks | |
|---|---|---|---|---|---|---|
| | (ft) | mm | (ft) | mm | (ft) | mm |
| Mean | (3.77) | 1149 | (4.86) | 1482 | (8.03) | 2447 |
| Standard Deviation | (0.18) | 55 | (0.43) | 130 | (0.35) | 107 |
| 5th Percentile | (3.48) | 1060 | (4.15) | 1264 | (7.56) | 2304 |
| 10th Percentile | (3.55) | 1082 | (4.28) | 1306 | (7.64) | 2329 |
| 15th Percentile | (3.59) | 1094 | (4.37) | 1331 | (7.68) | 2341 |

*These include pickups, utility vehicles, vans, etc.

*Source: (1)*

There was some indication that the height of eye adopted by AASHTO would be reduced to 1 meter, or 3.28 ft., since the passenger car fleet had continued to decrease in height. However, the increased use of pick-ups, SUVs and vans has caused the overall driver's eye height to increase. The NCHRP Report 400 recommended a height of eye of 3.54 ft. (1080 mm).

This change of height of eye of 3.54 ft. (1080 mm) was adopted in the 2001 AASHTO Greenbook; also the 2001 Greenbook adopted an eye height for trucks of 7.6 ft. (2330 mm), with a stated range of 6-8 ft. (1800 mm to 2600 mm). These recommended heights of eye are retained in the new 2011 Greenbook *(2,4)*.

## OBJECT HEIGHT

The object heights for stopping sight distance *(2,3,4)* are:

| | |
|---|---|
| AASHTO (2001, 2004 & 2011) | 2 ft. (600 mm) |
| CALTRANS, ODOT, WsDOT (SSD) | .5 ft. (150 mm) |
| Pavement SD | 0 ft. |
| Access points | 2 ft. (600 mm) (headlights) |

The object height that has been used for stopping sight distance has been 6 in. (150 mm) since 1965. The standards have required that a driver should be able to see and stop before hitting an object of 6 in. (150 mm) in height everywhere on the roadway. This arbitrary value recognized the hazard an object of that height or larger would represent, since 30% of the compact and sub-compact vehicles could not clear a 6 in. (150 mm) object *(28)*. It also suggested that the 6 in. (150 mm) object height was a rational trade-off between the need to see the pavement and the cost to provide that sight distance. Under some circumstances the height of the tail-light at 1.5 ft. (450 mm) to 2.0 ft. (600 mm) was recognized as a more appropriate object to be viewed, in particular at under-crossings, where a truck would be the design vehicle with its height of eye. A study undertaken by CALTRANS for sight distance on HOV lanes found an 85% tail-light height of 2.5 ft. (760 mm).

The 2001 AASHTO standard for object height increased to 2.0 ft. (600 mm) based on a car’s tail-light and safety statistics that do not show a high frequency of crashes with small objects in the roadway. This is retained in the new 2011 Greenbook. CALTRANS, ODOT and WSDOT retained the 0.5 ft. (150 mm) object height for both stopping sight distance and decision sight distance, recognizing all of the aspects of safe highway design and visibility that are provided by this lower height of object of 0.5 ft. (150 mm). Discussion of the safety implications of the use of a 2.0 ft. (600 mm) height of object is given in Appendix A.

The object height at intersections has been 4.25 ft. (1300 mm), which was the same required for passing sight distance *(5,6)*. This criterion assumed that being able to see the top or roof of a passenger car is adequate as the object for intersection sight distance. This ignores the difficulty in distinguishing the thin splinter of the car roof from other objects, particularly if the car is of an earth tone color. It also ignores the difficulty in seeing the car at night with the headlights at about 2 ft. (600 mm) height, even assuming some upward diffusion of the lights. A height of object of 3.5 ft. (1080 mm), the 2001 AASHTO standard for passing sight distance, would yield a target of 9-10 in. (220-250 mm) in height, which would assure an approaching vehicle would be seen. Where the object is the back of queue or vehicles elsewhere in the traffic stream, the object height may be either the height of the vehicle or the height of the tail-light. The height of tail-light according to NCHRP Report 400 must be no lower than 15 in. (380 mm) nor higher than 72 in. (1830 mm); the mean tail-light height was found to be 2.38 ft. (726 mm) for passenger cars. This would typically result in an object height of 1.5-2.5 ft. (460-760 mm). For vehicles entering the roadway at night, the height of the headlights may be used or 2 ft. (600 mm). The AASHTO standard for object height is 3.5 ft. (1080 mm) for both passing sight distance and intersection sight distance, according to the 2001 Greenbook; this standard is retained in the 2011 Greenbook *(2,4)*.

Pavement sight distance should be provided in channelized intersections, on turning roadways, or at locations where the alignment may take an unexpected direction. This is provided with an object height of 0.0 ft. (0.0 mm).

In summary:

| | **2001 & 2011 AASHTO** | **2009 CALTRANS** | **2001 ODOT** | **2011 WSDOT** |
|---|---|---|---|---|
| Object for stopping sight distance | 2.0 ft. (600 mm) | 0.5 ft. (150 mm) | 0.5 ft. (150 mm) | 0.5 ft. (150 mm) |
| Object for decision sight distance | 2.0 ft. (600 mm) | 0.5 ft. (150 mm) | 0.5 ft. (150 mm) | 0.5 ft. (150 mm) |
| Object for passing sight distance | 3.5 ft. (1080 mm) | 4.25 ft. (1300 mm) | 3.5 ft. (1080 mm) | 3.5 ft. (1080 mm) |
| Object for intersection sight distance | 3.5 ft. (1080 mm) | 4.25 ft. (1300 mm) | 3.5 ft. (1080 mm) | 3.5 ft. (1080 mm) |
| Object for access drives | 2.0 ft (600 mm) | | | |
| Pavement (SSD) | 0 | | | |

*Source: (2,4,7,23,24)*

## VEHICLE SPEED

The speed employed in the analysis of stopping sight distance is typically the design speed in Oregon and other states, in particular for vertical sight restrictions. Until the 2001 AASHTO Policy, AASHTO allowed the running speed to be used, since the design coefficient of friction was for wet pavements, and drivers were expected to slow on wet pavements. However, AASHTO indicates that recent data shows that drivers do not slow appreciably on wet pavement. The 2001 AASHTO Policy on Geometric Design has eliminated stopping sight distance based on running speed, and stopping sight distanced based on design speed is specified. Therefore, design speed should be used to determine sight distance criteria. When the facility is an existing facility, or design speed is not known, the operating speed on the roadway can be used.

The relationship between average speed, 85th percentile speed and design speed is not well understood. However, the approximate relationship can be defined as follows, based on the standard Normal Distribution. The design speed has been defined as about the 95th to 98th percentile speed; therefore:

Mean = Mode = Median

Average operating speed = mean speed

The normal distribution representing the distribution of speeds is symmetrical; therefore 50% of the area under the curve is on either side of mean, or median.

The 85th percentile speed (or minimum design speed) = mean speed + 1 std. deviation
(50% area) (33.7% area)

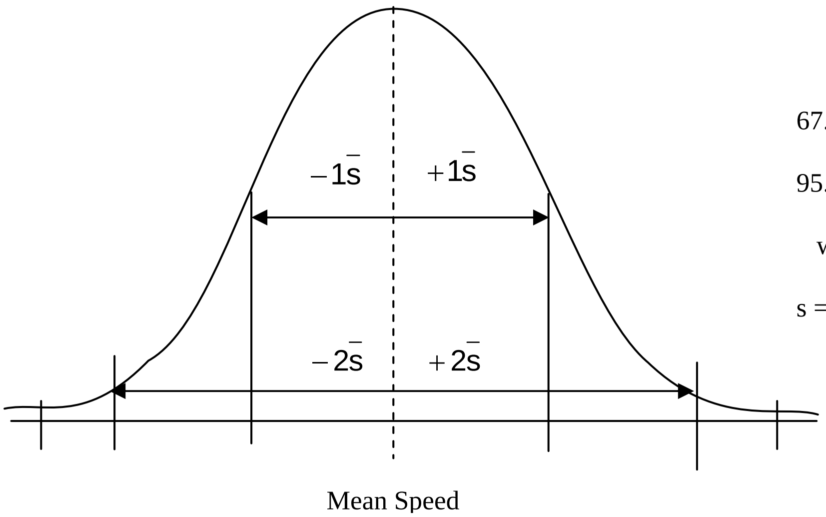
Design speed (98% speed) = mean speed + 2 std. deviations
(50% area) (47.8% area)

Typically, the standard deviation for speeds is about 5-7 mph. Thus, if the standard deviation is not known, a rule-of-thumb is:

The 85th percentile speed, or minimum design speed, is mean operating speed + 5 mph (10 km/h)

Design speed is 85th percentile speed + 5 mph (10 km/h)

Small variations in speed result in very large differences in stopping sight distance, since stopping sight distance varies as the square of velocity. Decision sight distance varies linearly with the speed, so the speed definition is not as critical.



67.4% are between -1s & +1s

95.5% area between -2s & +2s

where

s = standard deviation

**Figure 2. Normal Distribution of Speeds**

## PAVEMENT COEFFICIENT OF FRICTION AND DECELERATION

Historically, stopping sight distance was based on the frictional resistance of a poor, wet pavement *(1,2).* The 2001 AASHTO Policy, based on the research in NCHRP Report 400, based the stopping sight distance on an acceptable deceleration rate.

### Frictional Resistance of Pavements

The frictional resistance of pavements varies with tire characteristics (tire pressure, load, temperature, tread pattern, tire wear, etc.), pavement conditions (roughness, wear, aggregate type, etc.) and the presence of water. The skid resistance of the pavement is primarily a function of the micro-texture and the macro-texture. The micro-texture is comprised of the:

- fine scale grittiness or sandiness
- adhesion or chemical bonding between the tire and the surface
- particle surface texture

The macro-texture is provided by the:

- coarse surface texture of larger aggregate
- large scale asperities or mechanical interlock between the tire and the surface

The presence of water, oil and fines also reduces skid resistance. Contamination by road oils, accumulated fines and dust, and other debris creates a suck surface when light rains float them to the surface. Leaf slurry and other vegetative debris also reduce skid resistance.

High volumes of surface moisture can also result in hydroplaning. Hydroplaning occurs when a water film of sufficient depth floats the tire off the surface.

A number of studies are shown in Figure 2 that represents the behavior of pavements under various conditions. The conditions that were assumed for design until 2001 were:

- a bleeding asphalt surface in poor repair with poor tire tread
- or, a portland cement concrete surface with the friction coarse worn down to the surface aggregate

As seen in Figure 3, the skid resistance drops as design speed increases. The use of a constant deceleration for all speeds does not capture that phenomenon.

## Current 2011 Standard Stopping Based on Deceleration

The current standard AASHTO design deceleration rate is;

AASHTO (2001) 11.2 ft/sec$^2$ (3.4 m/sec$^2$)

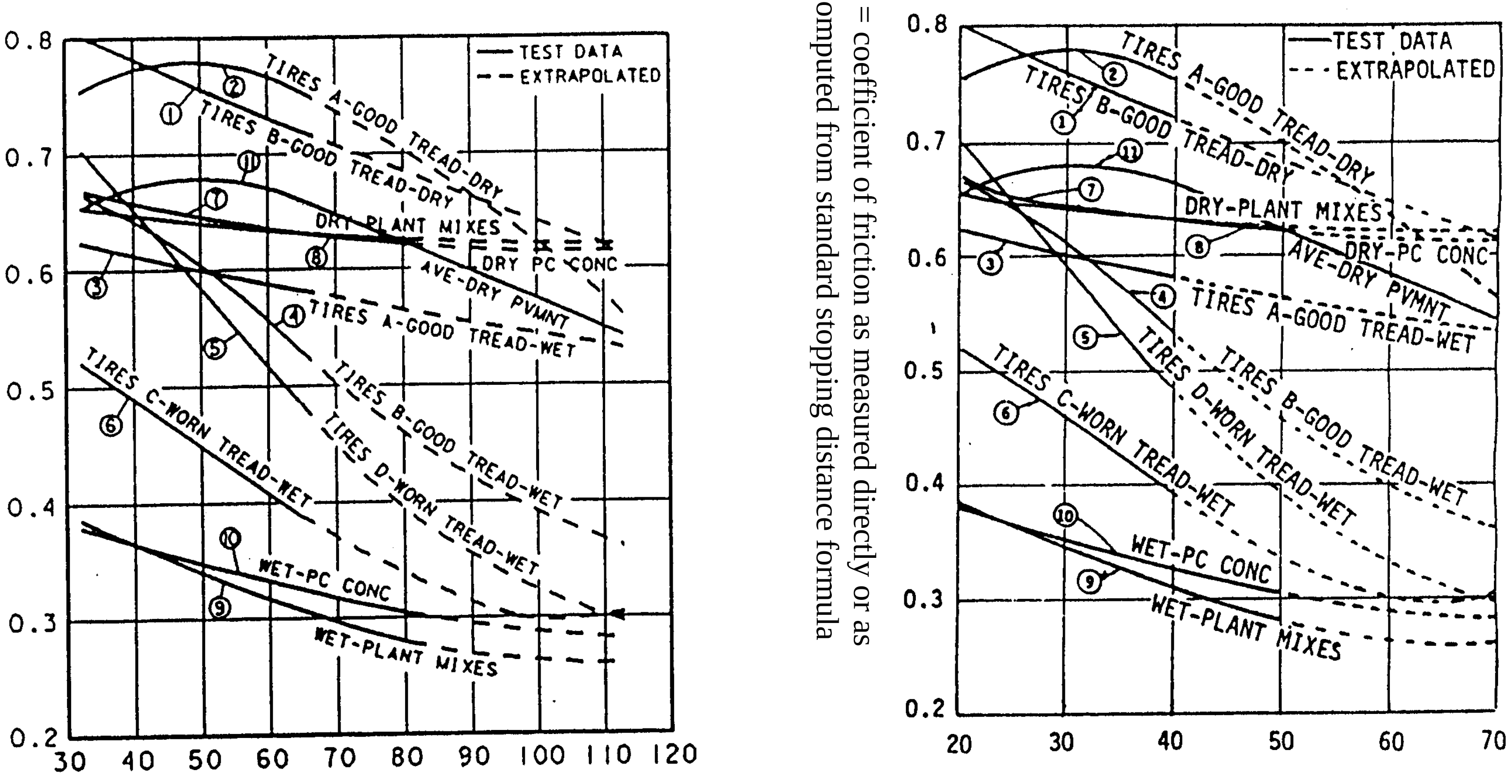
Until 2001, the coefficients of friction used for design on arterials or open highways in the 1990 and 1994 AASHTO Green Books (1) were based on the results of a number of studies that measured the locked-wheel skid resistance on poor wet pavements. These AASHTO design values corresponded to a comfortable deceleration rate of 6 to 8 mph/second (9.6 to 12.9 kph/sec); they are shown in Table 4.

With trucks the safe coefficient of friction for braking is less than for passenger cars because a truck can't safely make a locked-wheel stop without the risk of losing control *(29)*. Therefore, the deceleration rate when stopping is less for trucks than for passenger cars, on the order of 3.5 mph/sec (5.6 kph/sec) to 5.5 mph/sec (8.9 kph/sec); these decelerations correspond to "f" values of 0.16 to 0.25, respectively. Design coefficients of friction based on truck performance are given in the last column of Table 4 above. Note that the coefficient of friction corresponding to a deceleration rate is determined from the relationship:

$$f = \frac{a\,(\text{mph/sec}) \times 1.4667\ (\text{fps/mph})}{32.2\,\text{fps}^2} \quad \text{(U.S. Customary)}$$

$$f = \frac{a\,(\text{m}/\text{sec}^2)}{9.8\,(\text{m}/\text{sec}^2)} \quad \text{(Metric)}$$

The 2001 AASHTO Policy on Geometric Design recommended a deceleration criterion to determine the braking distance term for stopping sight distance of 11.2 ft/sec$^2$ (3.4 m/sec$^2$). This has been retrained in the 2011 Greenbook *(6)*.



f = coefficient of friction as measured directly or as computed from standard stopping distance formula

Speed of vehicle (km/h)
*Source: (6)*

f = coefficient of friction as measured directly or as computed from standard stopping distance formula

Speed of vehicle (mph)
*Source: (5)*

**Figure 3. Variation in Coefficient of Friction with Vehicular Speed**

## Table 4. 1990 and 1994 Design Coefficients of Friction for Stopping Sight Distance

| Design Speed | | Running Speed | | 1990 and 1994 AASHTO Coeff. of Friction for $f_{WET}$ | AASHTO Coeff. of Friction for trucks, $f_{TR}$ | Acceptable Deceleration for Trucks, $a_{TR}$ ft/sec$^2$ |
|---|---|---|---|---|---|---|
| (20 mph) | 30 kph | (20 mph) | 32 kph | 0.40 | 0.25 | 8.1 |
| (30 mph) | 50 kph | (28 mph) | 45 kph | 0.35 | 0.21 | 6.8 |
| (40 mph) | 65 kph | (36 mph) | 58 kph | 0.32 | 0.19 | 6.1 |
| (50 mph) | 80 kph | (44 mph) | 71 kph | 0.30 | 0.18 | 5.8 |
| (60 mph) | 100 kph | (52 mph) | 84 kph | 0.29 | 0.17 | 5.5 |
| (70 mph) | 115 kph | (58 mph) | 93 kph | 0.28 | 0.16 | 5.1 |

### 2011 AASHTO Policy Deceleration Rates for Stopping Sight Distance

The Greenbook reference research by Fambro et al., that showed most drivers decelerate at greater than 14.8 ft/sec$^2$ (4.5m/sec$^2$) when decelerating for an unexpected condition *(1)*. This corresponds to a pavement coefficient of 0.46, which cannot be provided by many wet surfaces. The standard deceleration rate of 11.2 ft/sec$^2$ (3.4 m/sec$^2$) proposed first in the 2001 Greenbook has been retained. This is expected to accommodate 90% of all drivers, and require an available pavement coefficient of function of 0.35. Most wet bleeding asphalt surfaces and wet polished concrete roadways should provide this much frictional resistance.

## STOPPING SIGHT DISTANCE

The stopping sight distance is comprised of the distance to perceive and react to a condition plus the distance to stop:

$$SSD = 1.47\ Vt + \frac{V^2}{30\left(\frac{a}{32.2} \pm g\right)} \qquad \text{(U.S. Cust.)}$$

or

$$SSD = 1.47\ Vt + \frac{V^2}{30\,(f \pm g)} \qquad \text{(U.S. Cust.)}$$

$$SSD = 0.278\ Vt + \frac{V^2}{254\left(\frac{a}{9.81} \pm g\right)} \qquad \text{(Metric)}$$

or

$$SSD = 0.278\ Vt + \frac{V^2}{254\,(f \pm g)} \qquad \text{(Metric)}$$

where SSD = required stopping sight distance, ft. or m ,
V = speed, mph or kn/n,
t = perception-reaction time, sec., typically 2.5 sec. for design,
f = coefficient of friction, typically for a poor, wet pavement,
g = grade, decimal,
a = deceleration rate, ft/sec$^2$ or m/sec$^2$.

The 1990 and 1994 AASHTO Greenbooks provided for a minimum and a desirable stopping sight distance *(5,6)*. The desirable stopping sight distance was provided based on the design speed and a coefficient of friction for a poor, wet pavement. The minimum stopping sight distance was provided based on the running speed and a coefficient of friction of a poor, wet pavement. The NCHRP Report 400 recommended new design criteria to AASHTO using a deceleration rate of 11.2 ft/sec$^2$ or 3.4 m/sec$^2$ (0.34 g) instead of the wet coefficient of friction *(1)*. The running speed is the average operating speed on the roadway and is typically less than design speed, about 83% to 100% of design speed for 20 mph to 70 mph (32 kph to 113 kph), respectively. As indicated previously, AASHTO has found that drivers do not slow on wet pavement so the use of running speed is not appropriate to determine stopping sight distances. Table 5 gives the stopping sight distances for a range of design speeds. For comparison, it also gives typical emergency stopping sight distances, with short emergency reaction times of 1 sec. and wet and dry pavement conditions. In this table, the coefficient of friction for a wet pavement is assumed to be those used for stopping sight distance in the 1990 and 1994 Greenbooks, and for dry pavement is assumed to be 0.6 *(5,6)*.

It is interesting to note that with low beam headlights, a driver may be able to see from 120 ft. to 350 ft. (37 m to 107 m) and with high beams from 200 ft. to 500 ft. (61 m to 152 m). Thus, drivers driving faster than 55 mph (88 kph) at night are overdriving their headlights *(30)*.

The 2001 and 2011 AASHTO Greenbooks recommend a minimum stopping sight distance based on design speed with a deceleration rate of 11.2 ft/sec$^2$ (3.4 m/sec$^2$) and a perception-reaction time of 2.5 seconds for design *(4,6)*. The “minimum” stopping sight distance based on running speed has been abandoned.

**Table 5A. Design Stopping Sight Distances and Typical Emergency Stopping Distances (U.S. Customary Units)**

| Speed | Stopping Sight Distance, (ft.) | | Typical Emergency Stopping Distance, (ft.) | |
|---|---|---|---|---|
| Design Speed (mph) | Calculated ($2.5^s$, a=11.2 FPS$^2$) | Design ($2.5^s$, a) | Wet Pave. ($1^s$, $f_{wet}$) | Dry Pave. ($1^s$, $f_{dry}$) |
| 20 | 111.9 | 115 | 63 | 52 |
| 25 | 151.9 | 155 | 92 | 71 |
| 30 | 196.7 | 200 | 130 | 94 |
| 35 | 246.2 | 250 | 172 | 120 |
| 40 | 300.6 | 305 | 225 | 148 |
| 45 | 359.8 | 360 | 284 | 179 |
| 50 | 423.8 | 425 | 357 | 212 |
| 55 | 492.4 | 495 | 417 | 249 |
| 60 | 566.0 | 570 | 495 | 288 |
| 65 | 644.4 | 645 | 581 | 330 |
| 70 | 727.6 | 730 | 686 | 375 |

**Table 5B. Design Stopping Sight Distances and Typical Emergency Stopping Distances (Metric Units)**

| Speed | Stopping Sight Distance, (m) | | Typical Emergency Stopping Distance, (m) | |
|---|---|---|---|---|
| Design Speed (km/h) | Calculated ($2.5^s$, a=3.4 m/sec$^2$) | Design ($2.5^s$, a) | Wet Pave. ($1^s$, $f_{wet}$) | Dry Pave. ($1^s$, $f_{dry}$) |
| 30 | 31.2 | 35 | 17.1 | 14.2 |
| 40 | 46.2 | 50 | 27.7 | 21.6 |
| 50 | 63.5 | 65 | 42.0 | 30.3 |
| 60 | 83.0 | 85 | 59.6 | 40.3 |
| 70 | 104.9 | 105 | 81.7 | 51.6 |
| 80 | 129.0 | 130 | 106.1 | 64.2 |
| 90 | 155.5 | 160 | 131.2 | 78.1 |
| 100 | 184.2 | 185 | 163.4 | 93.4 |
| 110 | 215.3 | 220 | 200.6 | 110.0 |
| 120 | 248.6 | 250 | 235.7 | 127.9 |

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## Evaluation of 2 ft. (600 mm) Height of Object Criteria

This appendix evaluates the efficacy of using a 2 ft. height of object for analyzing stopping sight distance, as proposed in the new 2001 AASHTO Greenbook. The new 2001 AASHTO Greenbook sets the 2.0 ft. (600 mm) height of object for stopping sight distance because it represents the height of tail light for an automobile, the object that is most likely to be hit in an accident. This object of height on the surface seems reasonable and prudent. However, there are a number of issues that must be considered when raising the object height from 0.5 ft. (150 mm) to 2.0 ft. (600 mm), including;

1. The most frequently hit object on the roadway is an automobile, because it is the most frequently found object on the roadway.

2. Other objects of 0.5 ft. (150 mm) to 2.0 ft. (600 mm) are not frequently hit because the previous stopping sight distance standards provide sight distance to see an object of 0.5 ft. (150 mm) or more.

3. Objects of less than 0.5 ft. (150 mm) do not typically cause accidents because an automobile can drive over them, or they do not have sufficient mass to give major problems.

4. Design elements on the roadway are not visible from an adequate preview distance to accommodate safe operations on the roadway for roadway geometrics designed based on a 2.0 ft. (600 mm) object height.

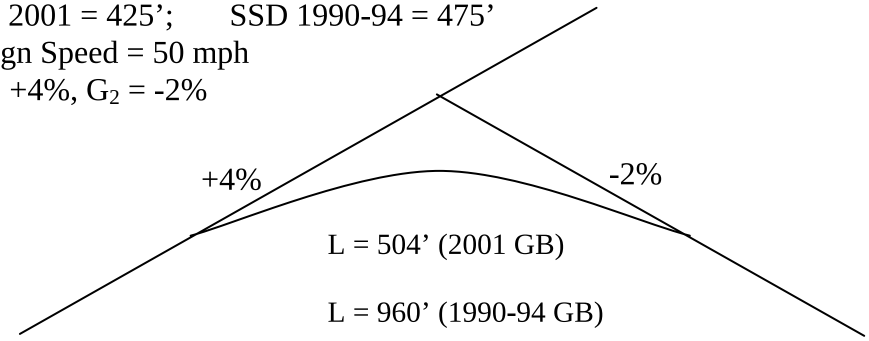
5. Headlight sight distance over a crest vertical curve at night is severely restricted, and dangerous for vertical curves designed based on a 2.0 ft. (600 mm) object height.

The roadway section that is visible to a driver at stopping sight distance is reduced appreciably, that is, the side slopes, ditch sections and other visual cues that drivers use to operate their vehicle are not available. Consequently, unfamiliar drivers might be expected to slow at such locations. Other drivers are going to have less time to react and adjust to roadway conditions.

A comparison of the preview distance to a 0.5 ft. (150 mm) object for a vertical curve designed under the 2001 criteria, versus the 1990-94 criteria, shows how restricted operations become under the new criteria.

## Example – Comparison of a Typical 50 mph Vertical Curve Design

Given: SSD 2001 = 425’; SSD 1990-94 = 475’
Design Speed = 50 mph
$G_1 = +4\%$, $G_2 = -2\%$



<u>Vertical Curve Design:</u>

2001 Greenbook Design

L =KA; L = 84 x 6

L = 504’

1990-94 Greenbook Design:

L =KA; L = 160 x 6

L = 960’

<u>Preview Distance Calculation:</u>

Preview distance with an

Object height = 0.5’:

Equation relating length and sight distance for vertical* curves:

$$S < L: \quad L = \frac{AS^2}{100\left(\sqrt{2h_1} + \sqrt{2h_2}\right)^2}$$

$$504 = \frac{6S^2}{100\left(\sqrt{2x3.5} + \sqrt{2(.5)}\right)^2}$$

$$S = 333\,\text{ft.}$$

<u>Required Length of Vertical Curve:</u>
The length of vertical curve is nearly cut in half with the new criteria, 504 ft. versus 960 ft.

<u>Distance to Stop before a 0.5 ft. (150mm) Object Height for 2001 Curve Design (with 2.0 ft. Object:</u>
The available preview distance is 333 ft. to see a 0.5 ft. object, where stopping sight distance under the 1990-94 criteria requires 475 ft. to stop, and 425 ft. for the 2001 criteria.

<u>Minimum Available Maneuver Time:</u>
If we assume the vehicle can maneuver around the 0.5 ft. object with a comfortable lateral movement, only 4.5 seconds travel time are available for this maneuver, as the vehicle travels 333 ft at 50 mph;

$$TT\,Prov = \frac{333}{1.47(50)} = \underline{\underline{4.5^s}}$$

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* See AASHTO Geometric Design Greenbook or a Route Surveying text for equation development

## Total Required Maneuver Time

The total distance required to maneuver around an object is the perception / reaction distance plus the maneuver distance. Typical lateral movement velocities of 3-4 ft/sec have been observed. The required maneuver time for the example curve, for both rural and urban areas, is longer than available, by 1 second urban and 2 seconds rural, respectively, as shown below.

| | PRT | | Maneuver Time | | |
|---|---|---|---|---|---|
| Urban | $2.5^S$ | + | $\frac{12\,\text{ft}}{4\,\text{FPS}}$ | = | $\underline{\underline{5.5^S > 4.5^s}}$ |
| Rural | 2.5 | + | $\frac{12\,\text{ft}}{3\,\text{FPS}}$ | = | $\underline{\underline{6.5^S > 4.5^s}}$ |

If we assume that we need a preview distance that is equal to stopping sight distance, it is also inadequate. As shown, 5.8 seconds is required compared to 4.5 seconds provided.

Preview Distance = SSD

$$\text{Preview Time} = \frac{425}{1.47(50)} = \underline{\underline{5.8^s > 4.5s}}$$

Further, if we look at the pavement sight distance condition with a height of object equal to “0”, the available pavement sight distance is;

$$S < L : L = \frac{AS^2}{100\left(\sqrt{2h_1} + \sqrt{2h_2}\right)^2}$$

$$504 = \frac{6S^2}{100\left(\sqrt{2x3.5} + \sqrt{2x0}\right)^2}$$

$$S = 242\,\text{ft.}$$

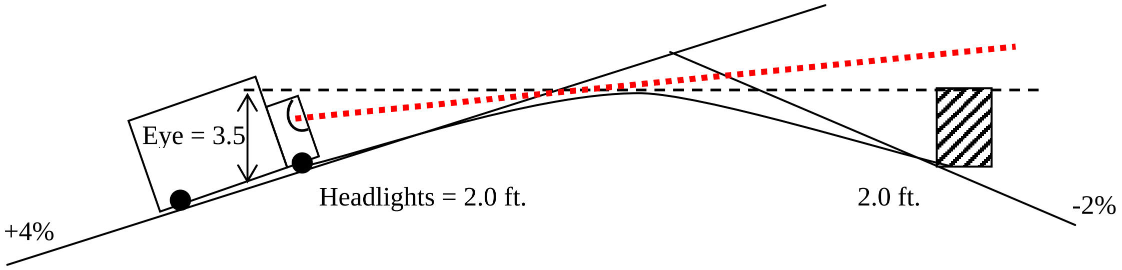
with a travel time available for maneuvering of;

$$TT_{PROV} = \frac{242}{1.47(50)} = 3.3\,\text{sec.}$$

Only 3.3 sec. of travel time and 242 ft. of travel distance are available for a driver to see the pavement, react and maneuver the vehicle. Clearly, very short by the maneuver distance or the stopping sight distance standard.

## Headlight Sight Distance over a Crest Vertical Curve

The headlight sight distance over a crest vertical curve has been accommodated, somewhat, by the more conservative height of object criteria of 0.5 ft. (150 mm). However, the headlight sight distance over a crest vertical curve is restricted for vertical curves designed with a 2.0 ft. (600 mm) object height. For the previous curve example, it provides only 366 ft. to a vehicle that is stopped without tail lights lit, where the reflection of the tail lights from the vehicle's headlights shows as the object. Notice for the example curve, an object must be 3.5 ft. (1080 mm) high to be visible with the headlights at the stopping sight distance of 425 ft.; no objects shorter than 3.5 ft. (1080 mm) would be lit by the headlights at 425 ft. Therefore, there is not adequate stopping sight distance at night for any objects shorter than 3.5 ft. (1080 mm).



Headlight S.D. over the "2001" Example Crest Vertical Curve with Headlight Height of 2 ft. (600 mm) for an Object Height of 2 ft. (600 mm):

$$L = \frac{AS^2}{100\left(\sqrt{2h_1} + \sqrt{2h_2}\right)^2}$$

$$504 = \frac{6S^2}{100\left(\sqrt{2x2} + \sqrt{2x2}\right)^2}$$

$$S = 366 \text{ ft} < 425 \text{ ft}$$

with a travel time of

$$TT_{PROV} = \frac{366}{1.47(50)} = 5.0\,\text{sec} > 4.5\,\text{sec}$$

Thus, the travel time of 5.0 sec. required to see and stop before a 2 ft. (600 mm) object is only slightly larger than the necessary available maneuver time to avoid the object.

Headlight S.D. with 2 ft. Headlight and 0.5 ft. Object over the “2001” Example Vertical Curve:

The headlight sight distance to a 0.5 ft. object in the roadway is:

$$L = \frac{AS^2}{100\left(\sqrt{2h_1} + \sqrt{2h_2}\right)^2}$$

$$504 = \frac{6S^2}{100\left(\sqrt{2x2.0} + \sqrt{2x0.5}\right)^2}$$

$$S = 275\,\text{ft.} < 425\,\text{ft.}$$

with a travel time of

$$TT_{PROV} = \frac{275}{1.47(50)} = 3.7\ \text{sec.} < 4.5\ \text{sec.}$$

The driver cannot see a 0.5 ft. object until he/she is 275 ft. away, with a required stopping sight distance of 425 ft. The travel time of 3.7 sec. to the object is less than the required maneuver time of 4.5 sec. to avoid the object.

**Headlight S.D. to Pavement from Headlight over the “2001” Example Vertical Curve:**

The distance from which the pavement can be seen is;

$$L = \frac{AS^2}{100\left(\sqrt{2h_1} + \sqrt{2h_2}\right)^2}$$

$$504 = \frac{6S^2}{100\left(\sqrt{2x2.0} + \sqrt{2x0}\right)^2}$$

$$S = 183\,\text{ft.} < 425\,\text{ft.}$$

with a travel time of

$$TT_{PROV} = \frac{183}{1.47(50)} = 2.5\,\text{sec.} < 4.5\,\text{sec.}$$

This provides time for the to perception / reaction time for design, but leaves no time for the action to steer to avoid a condition in the pavement, such as, a pothole. The available time to perceive, react and follow the lane comfortably is not sufficient.