CEDR Transnational Road Research Programme
Call 2013: Safety

funded by Netherlands, Germany, UK and Ireland

European Sight Distances in perspective – EUSight

Literature review report

Deliverable No D2.1
November 2014

Arcadis, Netherlands

SWOV, Netherlands

TRL, UK

TNO, Netherlands

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CEDR Call 2013: Safety
EUSight
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Due date of deliverable: 30.08.2014
Actual submission date: 14.09.2014
Revised final submission: 18.11.2014

Start date of project: 01.05.2014 End date of project: 26.02.2016

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Version: Final revised 13/03/2015

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Executive summary

Part of the CEDR Transnational Road Research Programme Call 2013: Safety is the research project European Sight Distances in perspective – EUSight. The objective of this research project is to conduct a detailed examination of the subject of stopping sight distance (SSD) and its role and impact on highway geometric design, taking into account differences (and similarities) between EU Member States.

Sight distance (SD) means the unobstructed visibility that is needed to be able to safely and comfortably perform the driving task and to avoid conflicts or collisions with objects or other road users. Stopping sight distance (SDD) means the distance over which a driver needs to be able to overlook the road to recognize a hazard on the road and stop his vehicle in time.

This report describes the result of Work package 2 of the EUSight project. It describes both an international literature study and a review of road design guidelines for motorways of a selection of EU member states on SD and SSD related aspects. This research considers stopping sight distance from different (related) aspects: human factors ('the driver'), road characteristics, vehicle characteristics and conditions (like wet, darkness or environment).

The literature review revealed that there are many studies available on Perception–Reaction Time (PRT). Obviously, there are differences in PRT between and within drivers. Hence, PRT is characterised by a distribution rather than by a constant value. For SSD, the common approach is to use percentiles of the PRT distribution. The 85th percentiles that have been reported range from 1.4 to 1.9 s; 90th or even 99th percentiles may range from 1.8 to 2.5 s. But which percentile should be used for SSD calculations does not follow from the literature review. Ultimately, this is a trade-off between safety and comfort on the one hand and cost/space travel time and adaptation to landscape on the other.

Brake assist and similar systems can help improve the response time of the vehicle and of the brake performance of the driver-vehicle system. It can be expected that more of these systems will become available over the coming years. Still, for the years to come, SSD criteria have to be based on a vehicle fleet containing vehicles without such systems. As a consequence friction is speed dependent.

The classical road condition used in SSD calculations is a wet surface. As a consequence, the road friction should be considered as a function of speed and of water depth. Further, at higher speeds, the friction coefficient is a function of the tyre tread depth. The existing surface types (concrete / dense asphalt / porous asphalt) are characterised by different micro and macro structures and by different water draining characteristics, accumulating to different friction coefficients in rain. These characteristics should be taken into account when choosing SSD parameters later on in the project.

The review of the road design guidelines for motorways on SSD considered the guidelines from Denmark, France, Germany, Ireland, the Netherlands, Switzerland and the United Kingdom. It was found that the SSD requirements are very similar for most countries except for the UK and Ireland, where the preferred SSD requirements are about one third higher than for the other countries. The UK and Irish guidelines give little or no insight into driver reaction times, deceleration values, braking coefficients, etc. and therefore these differences cannot be explained from just a guideline review. However, indications from the literature review indicate that the UK has adopted a PRT value that is comparable to those used in other countries but the standard deceleration rate applied may be conservative by comparisson. For the remaining countries there are some differences concerning the details on driver, vehicle and road characteristics, although these differences are most often small and thus reslultsin similar values for SSD.

Considering the small differences between the SSD requirements it can be concluded that there is a wide spread consensus on the SSD requirements between the country design guidelines. As the oldest guidelines of the selection reviewed is dated in 1983, it can be concluded that the requirements have not changed much over time.

List of definitions

Driver eye height

The vertical distance between the road surface and the position of the driver's eye.

Obstacle

A stationary obstacle on the road that requires a stopping manoeuvre. Examples of obstacles are a stationary vehicle (represented by the tail lights of a car) and an obstacle on the road (lost load of a truck).

Perception-Reaction Time (PRT)

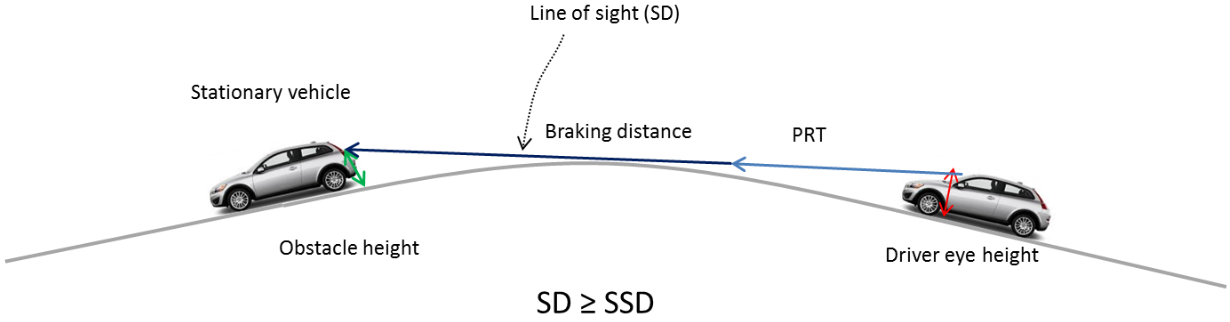
The time it takes for a road user to realize that a reaction is needed due to a road condition, decides what manoeuvre is appropriate (in this case, stopping the vehicle) and start the manoeuvre (moving the foot from the accelerator to the brake pedal).

Sight distance (SD)

This is the actual visibility distance along the road surface, over which a driver from a specified height above the carriageway has visibility of the obstacle. Effectively it is the length of the road over which drivers can see the obstacle, given the horizontal and vertical position of the driver and the characteristics of the road (including the road surroundings).

Stopping Sight Distance (SSD)

SSD is nothing more than the distance that a driver must be able to see ahead along the road to detect an obstacle and to bring the vehicle to a safe stop. It is the distance needed for a driver to recognise and to see an obstacle on the roadway ahead and to bring the vehicle to safe stop before colliding with the obstacle and is made up of two components: the distance covered during the Perception-Reaction Time (PRT) and the distance covered during the braking time.



1 Introduction

In the process of road design, sight distances are of great importance for traffic flow and traffic safety. Adequate sight distance is needed to enable drivers to adapt speed to the alignment of the road; to stop in front of a stationary obstacle; to overtake a slower vehicle safely on a carriageway with two-way traffic, to merge with (or cross) traffic at an intersection comfortably; and to process roadside information on traffic signs.

Part of the CEDR Transnational Road Research Programme Call 2013: Safety, is the research project European Sight Distances in perspective – EUSight. The objective of this research project is to conduct a detailed examination of the subject of stopping sight distance (SSD) and its role and impact on highway geometric design, taking into account differences (and similarities) between EU Member States. This research considers stopping sight distance from different (related) approaches: human factors ('the driver'), road characteristics, vehicle characteristics and conditions (like wet conditions, darkness or tunnels). Since SSD is related to many different aspects, multiple approaches and methodologies are needed to determine state-of-the-art parameter values.

This report describes the result of Work package 2 of the EUSight project. It describes an international literature study concentrating on the three aspects most relevant to determining sight distance, namely the driver (perception reaction times; alertness; workload etc.), the vehicle (braking, tyres, position of brake lights etc.), and the road environment (road surface, skid resistance; weather, objects on road etc.). The literature review focusses on human factor research concerning sight distances; traffic safety studies in relation to sight distances; pavement research; research into vehicle technology development (with a focus on braking and tyre-road interface); and research on international highway geometric design. The report also presents a review of recent road design guidelines of selected EU Member States and presents these results in the form of country specific factsheets. The report concludes with a section summarising the key findings and discussing the relevance of the various aspects describing the calculation of stopping sight distance in current design guidelines.

1.1 Background

Many aspects have to be taken into consideration when developing a geometric road design. The road capacity and the level of service are important as well as road safety, construction and maintenance costs, the environmental impact and the fitting of the road into the landscape. None of these aspects should be considered separately. Optimising a design in terms of one aspect may impact negatively on other aspects. Designing roads is a complex task requiring an optimal balance between all relevant design elements. In road design, sight distances are of great importance to, for example:

- avoid a collision with a possible obstacle downstream on the carriageway, the stopping sight distance. The obstacle can be an object or a stationary vehicle on the road (because of lost load, a breakdown or a queue of vehicles);
- given traffic conditions and other stimuli that complicate the driving task, adapt speed and steer the vehicle in accordance with the course of the road, the orientation or decision sight distance;
- Safely overtake a slower vehicle on a carriageway with two-way traffic, the overtaking sight distance;

- comfortably merge with or cross traffic at an intersection, the approaching and the intersection sight distance;
- process roadside information on traffic signs, the information processing sight distance.

Some international guidelines and handbooks (e.g. AASHTO Green Book) explicitly distinguish the type of obstacle: stopping for an object on the road is referred to as stopping sight distance (SSD), avoiding potentially dangerous situations (such as stopping for a queue of vehicles) is referred to as decision sight distance (DSD). The difference between SSD and DSD lies in the fact the SSD is based on a relatively simple process of events in a relatively simple traffic situation whereas DSD is more appropriate to more complex traffic situations where a driver needs more time to process information and take avoiding action. DSD is more forgiving but results in a more forgiving design that can increase the cost of a project. In this research the focus is on SSD although DSD (and the German Orientation Sight distance) are also briefly mentioned and discused.

Almost all handbooks for road design emphasize the importance of sight distance for traffic safety (AASHTO, 2004; Lamm, 1999). A study on two-lane rural roads in Germany by Krebs and Kloeckner (1977) concluded that accident risk decreases with increased sight distances. This study showed that sight distances of less than 100m can be associated with the highest accident rates. Sight distances between 100 and 200m result in accident rates which are about 25% lower than those associated with sight distances less than 100m.
On the other hand, large sight distances could result in expansive road designs, because sight distances are directly related to horizontal and vertical curve radii. Therefore, it is important to use appropriate sight distances, based on representative driver, vehicle and road characteristics. Technological advances in road and vehicle design have an impact on certain parameters relevant to SSD calculation (i.e. braking distance, deceleration rates, and skid resistance) and these may change in time. It is therefore essential that these parameters are regularly reviewed and updated to take into account such changes, especially since these changes could materially affect SSD. Regular updating of these parameters will ensure that designs meet current and future needs and will prevent resulting designs being based on outdated information leading to overdesign, leading to unnecessarily high requirements on space and costs.

The EUSight project focusses on the stopping sight distance (SSD). The project comprises 8 work packages (one of which is project management). This report presents the results of the first of the technical work packages, namely the literature review (Work Package 2). This report serves as an internal project report and the results provide essential input into the other work packages. Of importance is that this project, and therefore the WP, focusses on specifically SSD and does not deal with sight distance requirements relating to intersections and overtaking requirements.

2 Study objectives

The overall objective of this CEDR research project is to conduct a detailed examination of the subject of stopping sight distance (SSD) and its role and impact on highway geometric design, taking into account differences (and similarities) between EU member States. Sight Distances (in their broadest sense), and specifically SSD, are the result of interactions between a driver, the vehicle and the road given a set of (environmental, traffic etc.) conditions (Figure 2.1). Consequently, this research considers stopping sight distance from all of these interrelated aspects and focusses on these individually and/or collectively.

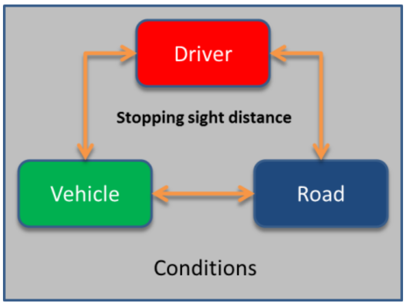


Figure 2.1: SSD-research in three aspects

Given the above, the specific objectives of WP 2 are:
1. To review international state-of-the-art literature related to sight distance (vehicle, driver, road given prevailing conditions)
2. To compare EU Member States road design guidelines on SSD definitions, parameters, parameter values, backgrounds and regulations
3. To identify relations between stopping sight distance parameter values and road design elements

3 Methodology

Work package 2 comprises three primary tasks:

- *Task 2.1: Review of sight distance related aspects*
- *Task 2.2: Review of EU-Member States road design guidelines*
- *Task 2.3: Reporting*

An earlier comparison of road design guidelines of selected European countries showed a variety of SSD definitions and parameters (Broeren, Van Delden & Stegeman, 2011). For instance, different definitions for the stationary object were found: some countries use the brake lights of a passenger car, some use the third brake light whilst others use an object on the road surface for calculating the available stopping distance. Also the position and dimensions of the object on the road and in the lane differ.

The results of Work Package 2 are dealt with in two primary sections:

- An introduction to the concept of SSD, Stopping Distance (SD) and Orientation Sight Distance (OSD – which is also known as orientation sight visibility or orientation visibility (OV) and similar in concept to the American Decision Sight Distance (DSD) and a description of the relation with crash rates and most recent insights into sight distance related aspects, applications and conditions.

- A selected number of country reports containing definitions, parameters, parameter values, conditions, regulations, SSD values (for various design speeds) and corresponding geometric design elements (crest curve radii and horizontal curve radii) related to SSD calculation.

In all cases specific reference will be made to driver, vehicle and road related aspects relevant to SSD, SD and OSD/OV. The results will be supported by table forms and graphs (with links to background information).

3.1 Literature study – review of sight distance related aspects

Because stopping sight distance is an important basis for road design and is closely related to road safety, this subject has been studied intensively over the years. Most of these studies are based on analysis of road geometry, driving simulator studies, evaluating sight distance in the road design stage and equipped vehicle measurements. This research and related studies will be screened and, if relevant, will be incorporated into this project.

Recently, the aspect of orientation sight distance or orientation visibility (OV) was introduced as a new approach on sight distance in Germany (Lippold & Schultz, 2007). Since changes in driver behaviour and improvements in vehicle and road design technology may result in short SSD requirements, the OSD/OV approach considers the driver workload and driver behaviour in relation to sight distance with the premise that shorter SDs might lead to a higher driver stress. Similar to DSD, OV takes into account the complexity of the traffic situation and allows for an added safety margin by relating reaction times to driving workloads.

WP2 included an international literature review focused on human factor research concerning sight distances, traffic safety studies in relation to sight distances, road surface and skid resistance research and international highway geometric design symposia publications (TRB, TRA, etc.). From the literature, statistical data of the sight distance related characteristics like the height of braking lights, share of cars with third braking light, drivers eye height, road surface characteristics, are reviewed. The literature review is directed at driver, vehicle and road parameters that are relevant to SSD.

The international literature review is based on an international search of the most relevant scientific publications on the subject of sight distances and stopping sight distances and their relation to driver behaviour, to road design and vehicle characteristics. The search was internet based and initially directed at publications in English and not more than ten years old (unless a founding document or practice). The search has been refined by reviewing abstracts and selecting the most relevant publications, limited to no more than 50 publications, and covering mainly Europe, the United States and Australia. The review was focussed on parameters for highway and motorway design. Urban road design did not form part of the review.

3.2 Review of EU-Member States road design guidelines

Besides reviewing relevant research studies, the road design guidelines of selected EU Member states will be studied with specific attention to the different definitions, parameters and parameter values of SSD, SD and OV. In addition, the design of geometric elements (crest curves and horizontal curves with sight obstructions) will be reported. The results will be tabulated, allowing for easy comparison of the SSD, SD and OV elements between selected EU Member States.

The parameter values in the SSD, SD and OV model must represent the driver, vehicle and road characteristics. As stated before, these conditions can vary per country. Background information of the road design guidelines, should give information about the representative vehicle and driver characteristics. In total the guidelines of 5 EU Member States, representing the different regions of the EU, will be reviewed and discussed.

3.3 Reporting

The final task entails integrating the results into an internal project report comprising:
- Introduction of the SSD, SD and OV, presented in chapter 4
- A literature review presenting the most recent insights on road, car and driver characteristics related to sight distance focused on the stopping site distance, presented in chapter 5.
- A review of design guidelines on SSD for a selection of EU member states, considering: definitions, parameters, parameter values, conditions, regulations, SSD values (for various design speeds) and corresponding geometric design elements (crest curve radii and horizontal curve radii), presented in chapter 6.

Together, the results of the literature and guidelines review are integrated into the conclusions, presented in chapter 7.

4 Background to sight distance

4.1 Stopping sight distance

Stopping sight distance is the most basic requirement in geometric design since a design must at any single point along a road provide enough sight distance for a driver to be able to safely stop in front of an unexpected obstacle on the carriageway. SSD is nothing more than the distance that a driver must be able to see ahead along the road to detect a hazard or object and to bring the vehicle to a safe stop. SSD is affected by both the horizontal and vertical alignment. Within curves the cross section and the roadside space might have an impact too.

SSD is the sum of the distance during the driver perception-reaction time and the vehicle braking distance. Essentially this is the distance required for a vehicle traveling at or near design speed to be able to stop before reaching the object/hazard. Stopping sight distance depends on :

- the time required for a driver to perceive and react to the stopping requirement; and
- the time needed for the driver to complete the braking manoeuvre

A basic SSD formula (Fambro, Fitzpatrick, & Koppa, 1997) is given in equation (1).

$$SSD = 0.27\, V\, t_{RT} + 0.039\, \frac{V^2}{a} \qquad (1)$$

Where :
V is the design speed (km/h),
t_{RT} is the reaction time (s) and
a is the average deceleration level (m/s^2).

This initial formula is fairly basic in that the geometry and condition of the road are not considered as independent variables, mainly due to the fact that the model was developed for a range of roads covering a range of conditions. More complexity stems from the “constants” in this equation are not truly constants but correlated with other factors, and also stochastic in nature.

When considering all parameters concerning SSD, one has to distinguish the *minimum* SSD according to the road design guideline (usually referred to as SSD) and the *available* sight distance on the road (SD). Both are closely related to traffic safety and road design.

Table 1 shows all the parameters relevant to determining SSD and SD.

Parameter	Influenced by	Relevant for
Speed	Driver (, condition)	SD, SSD
Perception reaction time	Driver (, condition)	SSD
Deceleration rate	Driver, vehicle, road surface, condition	SSD
Drivers eye height	Driver, vehicle	SD, SSD
Drivers lateral position	Vehicle, road design	SD, SSD
Stationary object definition	Vehicle, condition, country definitions	SSD
Horizontal alignment	Road design	SD, SSD
Vertical alignment	Road design	SD, SSD
Cross section	Road design	SD, SSD
Road side objects	Road design	SD, SSD

Table 4.1 sight distance parameters

A parameter particularly relevant to SD and SSD is the definition of an object and/or of the situation requiring the stop to be made. This definition has a material effect on the outcome of the SSD required, generally the smaller the object the bigger the SSD required. It is therefore not unimportant to base this definition on what really constitutes a threat to a driver and what must really be detectable at a given speed and allow the driver to safely come to a stop. In some countries the rear brake lights of cars define the object height and in others an inanimate object on the carriageway (such as a box).

The parameter values may vary between EU Member States, since:

- The vehicle fleets and driver population in the individual EU Member States may vary, which may result in different driver's eye height and acceleration/ deceleration rates etc.
- The driving behaviour in the different countries may vary too, resulting in different perception reaction times, speeds and deceleration rates.
- The physical geographical conditions differ per country; the impact of SSD on road design in mountainous countries (like Austria) is bigger than in flat countries (e.g.the Netherlands), resulting in more expansive road designs.
- The road infrastructure differs per country, e.g. the width of the traffic lanes (and thus the position of the vehicle on the road), the width of the hard shoulders, the distance between both roadside obstacles as well as barriers to the traffic lane, the minimum roughness of the surface required.
- The regulations could differ, e.g. the maximum speed allowed, the minimum deceleration rate, the minimum tyre profile depth, the minimum friction coefficient of the road surface, ambient lighting, etc.

4.2 Orientation Sight Distance or Orientation Visibility

In Germany a behaviour based approach called orientation sight distance has been introduced (Lippold & Schultz, 2007). The orientation sight distance supplements geometric parameters used in assessing sight distances with so called psycho-physiological criteria that allow for the extra demand placed on drivers (and their perception reaction times) by conditions on the road. This relationship was measured by looking at driving and viewing behaviour such as braking retardation, gaze at the road and time spend at a secondary task. Shorter SDs resulted in an extra demand of workload placed on drivers.

The design guidelines in Germany now include a standard methodology to check the 3 dimensional alignment of a road during design (Kuhn and Jha, 2010) and this takes into account the constraints mentioned with regards to sight distance and driver reaction/perception.

OSD or OV is further discussed in later chapters.

4.3 Developments in relation to sight distance

Sight distances are impacted by many different aspects and changes to any of these may result in the SD requirements changing. It is therefore important to regularly evaluate the criteria used in SD and SSD calculation to establish whether these are still relevant given the driver and vehicle population using the road network. Table 4.2 lists a number of factors that through change can impact on SD requirement from a driver, vehicle or road environment perspective.

Aspect	Driver	Vehicle	Road
Technological development of vehicles (ABS, ESP, brakes, etc.)	X	X	
Road surface characteristics (higher friction coefficient)			X
Quality of tyres (higher friction coefficient)		X	
Cross-border traffic in Europe (cars and especially trucks).	X	X	
Road safety equipment (managed roads, dynamic traffic management)			X
Third brake light		X	
Aging driving population (more elder drivers (60+) on the road)	X		
In-car technology (both assisting and distracting drivers)	X	X	
Increasing complexity of road configurations (self explaining roads versus special configurations)	X		X
Economic crisis in some EU-countries: less budget for maintaining road infrastructure and design of new roads as well as less budget for modern and well equipped vehicles		X	X

Table 4.2: Examples of sight distance related developments that may impact sight distance requirements

Chapter 5 presents the current state of art as found in the literature on these developments and if and to what extend these developments are influencing SDD and SD.

4.4 Accident factors and assumed relationship

Sight distances are reported to have a negative relationship with run off the road accidents and to a lesser extent with head-on accidents. The accident rate decreases as the sight distance increases. The relationship between accident rate and sight distance is not linear since the rate is seen to decrease rapidly until a certain critical distance (Fambro, Fitzpatrick & Koppa, 1997).

On rural roads, sight distances less than 200 m require a higher attention of drivers,
At sight distances less than 150 m the impact is much higher (Lippold & Schultz, 2007), the critical sight distance is in the order of 90-100 m

5 Literature review of sight distance factors

This literature review presents the latest insights on sight distance (SD). Several resources have been used for this literature review. As databases / search engines, mainly Scopus and Google Scholar have been used with the following (combination of) keywords: Perception Reaction time (PRT), sight, corners, visibility, brake light, guardrail, driver eye height, brake assist, physiological development, elderly drivers, aging, road surface, friction, geometric design, wear/maintenance.

Next to these keyword guided searches, searches by reference from a couple of key review papers have been used. Two of the review papers on stopping sight distance that have recently been published (Layton & Dixon, 2012; Young & Stanton, 2007) are used as a basis for this text. For some details we will refer to the original papers.

If the text of these review papers is quoted literally, the text is presented in italics with a reference at the end of the section to the specific paper.

In addition, other literature already available with the project partners was used.
Initially the search was aimed at relatively new material, from 2010 or later. However, some older work was incorporated as well when this was needed to fill elements that would otherwise remain empty, or for material that was judged to be fundamental.

In the following sections, the factors important to stopping sight distance that are mainly related to driver aspects, vehicle aspects or road aspects can be found. The factors to which attention is given, can be found in chapter 4 (see Table 4.1).

5.1 Factors related to the drivers

This section gives an overview of the literature on factors related to drivers with respect to stopping sight distance.

5.1.1 Perception Reaction times(PRT)

Perception Reaction time (PRT) is the time it takes for the driver to perceive an object and to initiate an appropriate action to deal with its presence. PRT time is often divided into the following components:

- Perception: the time to see or discern and to focus 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;
- Reaction (or Movement Time or Volition): the time to initiate the action, for example, the time to move the right foot from the gas pedal to the brake pedal (human aspects) and the time for the brakes to engage (vehicle aspects).

Perception Reaction time is also described as braking reaction time (BRT) and movement time (MT). Brake reaction time corresponds to the first three components and Movement Time to the fourth component described above. The sum of BRT and MT is sometimes called

Total Braking Time (TBT), which corresponds one to one with PRT. In this report, PRT will be the preferred term.

In human factors research, PRT is classically measured using observed behaviour, taking the reaction time of the 85th percentile driver as ‘the’ reaction time (meaning that 85% of the drivers are able to react within that time).

In the UK, SSD is based on a driver Perception Reaction time of 2 seconds and a deceleration rate of 2.45 m/s^2. The stopping distance in the Highway Code (UK) assume a driver reaction time of 0.67 seconds and a deceleration rate of 6.57m/s^2 for emergency braking. A review by Harwood et al. (1995) showed that the perception reaction on which the UK has based SSD is conservative by comparison elsewhere.

The American Association of State Highway and Transportation Officials recommends to use a PRT of 2.5 seconds (AASHTO, 2001). The reaction, or volition component, is estimated to take 1.0 seconds by AASHTO (2001).

Sohn and Stepleman (1998) recommended to use the 85th or even the 99th percentile value for PRT. In a meta-analysis they reported values as listed in Table 5.1.

	85th percentile (s)	99th percentile (s)
USA	1.92	2.52
Non-USA	1.40	1.52

Table 5.1: PRT percentiles from Sohn and Stepleman (1998)

Sohn and Stepleman’s (1998) study revealed considerable variation in Total Braking Time (which is equivalent to Perception Reaction Time) distributions, which were influenced by both the country of origin (US drivers tended to be slower than non-US drivers) and the awareness of the driver (responses are generally slower where the driver is not aware of the hazard). The components of TBT (i.e. BRT + MT) can therefore be affected by a combination of factors involving the driver, the vehicle and the situation (cf. Warshawsky-Livne & Shinar, 2002). (Young & Stanton, 2007)

Green (2000) examined various factors that influence PRT: expectation, urgency, age, gender and cognitive load. He conducted a meta-analysis using 40 different reports or papers. He found expectation to be the dominant factor. He stated that with high expectancy and little uncertainty, the shortest PRT is about 0.70 to 0.75 s. With normal signals such as brake lights, expected mean PRTs are about 1.25 s. For surprise intrusions, he reported a mean of 1.5 s. The urgency to take evasive action also plays a role: drivers respond faster when Time To Collision is smaller. Green did not report percentiles or standard deviations. Therefore, drawing conclusions in terms of percentiles is not feasible.

Layton and Dixon (2012) give estimates of PRT values from various studies (Table 5.2 : Perception Reaction time studies reported by Layton and Dixon (2012).

The original table from Layton and Dixon also listed Sivak et al. (1982) as a source for 85th and 95th percentiles. Since this article did in fact not report on these percentiles, this reference was removed fromTable 5.2.

Study	85th Percentile [s]	95th Percentile [s]
Gazis et al. (1960)	1.48	1.75
Wortman & Matthias (1983)	1.80	2.35
Chang et al. (1985)	1.90	2.50

Table 5.2 : Perception Reaction time studies reported by Layton and Dixon (2012).

Maycock and colleagues (1995) showed that the 90th percentile of drivers in a simulator respond within 1.5 s to a road side hazard. This is averaged over 4 hazard types. The 90th percentile varied from 0.67 to 1.99 s, again showing that the criticality of the event influenced PRT. (Note that these were all *aware* drivers, being exposed to several hazards in one simulator run.

In summary, there is reason to believe that a requirement for designing with PRT values of 2 to 2.5 seconds might be conservative. Many of the studies reveal 85th percentile values of below 2 seconds and mean values as low as 1,25s. Considering that in many of these studies drivers were subjected to conditions involving more complex driving situations, PRT values measured were lower than the general 2s value adopted in most guidelines for calculating SSD.

Braking Reaction Times

Young and Stanton (2007) studied the relationship between braking reaction time (BRT), movement time (MT) and Perception Reaction time (PRT) among drivers with different levels of awareness (aware, partially aware, unaware) and drivers from different age groups (young, mid-age, older). As can be seen fromTable 5.3, large differences are found between different scenarios (different implementations in studies) and also between aware and unaware drivers.

As Table 5.3 shows, reaction times are typically longer when the driver is surprised. An exception is the study by Dingus et al. (1998), who found a fastest PRT (0.65 s) in a surprising event and a slower PRT (1.3 s) for a fully anticipated event. This may be due to the nature of the events involved in their study (a barrel fired into the driver's path versus stopping at an intersection for traffic lights). Once again in line with criticality of the event influencing the BRT.

The Van der Hulst et al. (1999) study shows relatively long reaction times. This can be attributed to the nature of the event that they used: Van der Hulst et al. had a lead vehicle with relatively low deceleration (like releasing the gas pedal, not causing the need for rapid reactions). Thus, these reaction times are not to be considered as normative for the current study.

	BRT [ms]	MT [ms]	PRT [ms]
Aware	4200 (1)	180 (2)	1300 (5)
	360 (2)		1290 (3)
			550 (4)
Partially Aware	390 (2)	175 (2)	1100 (5)
			632 (4)
Unaware	6300 (1)	170 (2)	1360 (3)
	420 (2)		739 (4)
			650 (5)
Young	350 (2)		2330 (6)
Mid-Age	390 (2)		
Older	430 (2)		2450 (6)

Table 5.3 : Summary of mean driver response times from the literature review for driver factors (Young & Stanton, 2007).

Notes:
1. Van der Hulst et al. (1999); slow deceleration condition.
2. Warshawsky-Livne and Shinar (2002).
3. Sohn and Stepleman (1998); 85th percentile non-US data.
4. Schweitzer et al. (1995); 50 mph (80 kph) with 12 m gap condition.
5. Dingus et al. (1998).
6. Warnes et al. (1993); no warning or distraction condition.

BRT = Brake Reaction Time; MT = movement time; PRT = Perception Reaction Time.

Field studies on perception (brake) reaction time

Durth and Bernhard (2000) published the results of a field study on Perception Reaction Times. On a crest curve drivers were confronted with cardboard boxes on the road for which they had to come to a full stop. They were initially uninformed about the scenario. The braking task therefore came as a surprise. Results show that all drivers were able to stop in time within a PRT of 2.0 seconds. The 95th percentile was below 1.8 seconds, but as the researchers point out, these were drivers that participated in an experiment and may therefore have been more alert than ‘normal drivers’. Their results showed faster reaction times when the initial speed was higher, in line with the urgency effect mentioned above.

Attention and eyes on the road

Using the 100-car study data to test the effects of distraction and eyes-on/off-the-road, Dozza (2012) found evidence for the slowing down of reaction times when drivers perform other tasks in the car. Attending to secondary tasks and eyes-off-road significantly slowed down response times in real-traffic (by 16% and 29%, respectively). In addition, different incident types, and related evasive manoeuvres, elicit different response times. Also, during night driving, response times were faster on lighted roads than on unlit roads. Finally, truck drivers were found to respond faster than car drivers; however, Dozza (2012) concluded that a more sophisticated analysis of the possible confounders is needed to further explore this conclusion.

5.1.2 Driver eye height

Driver eye height determines for a large part the sight of the driver on the road, especially in situations with a crest in the road and sight obstacles alongside the road. Driver eye height depends on the model of passenger cars, the length and the posture of the driver. Drivers will take different postures in the car (to maximise comfort), which is highly accommodated for in modern cars that allow longitudinal positioning, vertical positioning, backrest and headrest adjustments. This may all vary the actual driver eye height. Chapter 0 gives an overview of the design guidelines for European countries for driver eye height figures.

Driver eye height had on average decreased slightly over time with changing designs of vehicles (Layton & Dixon, 2012). However in recent years the variation in driver eye height has also increased, with the rise of the number of large vehicles (i.e. SUV's) and cars with higher seat height (designed for an easier entry/exit into the car) (Layton & Dixon, 2012).

Actual driver eye height may differ from the design driver eye height that is stated in national guidelines. Capaldo (2012), for example, took experimental measures to compare actual (Italian) driver eye height with the standards of the Italian government. By examination of pictures, taking measures from scale sketches and measuring in a fleet from 2004 to 2011, Capaldo was able to establish that the average driver eye height was 125cm, and the 15th percentile value of the data distribution was 117cm. The 15th percentile value is relevant since this represents the lowest driver eye height value (giving a longer SSD) and therefore should be used to determine SSD rather than the 85 or 95th percentiles values representing the highest value (and resulting in a shorter SSD). Both values were higher than the value indicated by Italian standards (110 cm).

Differences between European countries can be assessed from the CAESAR database. Table 5.4 shows the mean eye height above seat level of the Dutch and the Italian populations, which are representative for the extremes of the populations within the EC. The difference in means between both countries is about 3.5 cm.

Population	**n**	**Mean (cm)**	**S.D. (cm)**
Dutch, male	563	82.7	4.0
Dutch, female	668	77.6	3.6
Italian, male	412	79.1	3.4
Italian, female	387	74.3	2.9

Table 5.4 : Eye height data from the CAESAR database (eye height seat level; Robinette et al., 2002).

Trucks

Driver eye height for trucks is normally not of concern because they are significantly higher than passenger cars, which may even compensate for longer braking 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. – (Layton and Dixon, 2012).

No studies were found on changes in the average eye height for truck drivers. Bassan (2012) presented SSD calculations for trucks, buses and cars. He used an eye height of 2.4 m for trucks and 1.8 m for small trucks, however, without showing empirical data.

5.1.3 Visual acuity and eye movement time

Visual acuity is the ability to resolve the details of an object. It is dependent on the physical composition of the eye and is one of the limiting factors for detecting objects on the road. Together with the required movement time to move the eye to a certain position, this constitutes how much time drivers physically need to discern an object or event. Humans have a clear field of vision of about 10° in which they are able to see clear enough to detect objects and interpret its meaning for the current situation. The time to shift to a new position (0.15-0.33s) combined with the time to focus on the object (0.1 – 0.3s) means a driver needs 0.5s to focus on an object. A full cycle, scanning from left to right, takes therefore 1.0s. This increases with glare (3.0s) and when changing from bright to dim conditions (6s) (Layton & Dixon, 2012).

5.1.4 Traffic conditions and driver expectancy

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 manoeuvres 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 manoeuvring 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 manoeuvres ranging from stopping, to speed, path or direction change within the traffic stream.

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* (Layton and Dixon, 2012).

In this project the focus is on stopping sight distance, if traffic conditions, local activities and driver expectancy play a very important role this will be noted. A few important aspects will be explicitly described here.

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.*

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. 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. (Layton and Dixon, 2012).

The simulator study by Van der Hulst, Meijman, and Rothengatter (1999) showed a difference between drivers that expect an event and those that do not. The fastest BRT (3.6s) was in the condition where the driver was expecting the lead vehicle to decelerate and the speed of the lead vehicle deceleration was fast. This compares to 6.3s when deceleration was slow and unexpected. The reason for the relatively longer BRT results in this study is due to the relatively slow rate of deceleration compared to the braking scenarios that other researchers have investigated. Although the 'slowly braking lead car scenario' with the resulting relatively long reaction times are of little relevance for the current project, the results are in line with the general finding of faster reactions for expecting drivers.

Young and Stanton report a study by Schweitzer (1995), who found that *'greater awareness of the driver leads to a reduction in mean (and maximum) TBT* (PRT)*. Moreover, TBT increases in line with the size of the gap between vehicles. On the basis of their data, the worst case scenario should assume a TBT of 1.5s in a car-following task.'*

This finding is similar to the results of Warshawsky-Livne and Shinar (2000) who also found that BRT increases with uncertainty from a minimum of 0.36s to a maximum of 0.42s, although MT actually decreases slightly.

Complexity differs for different road types and driver states. Table 5.5 from Layton and Dixon gives insight into the different Perception Reaction Times for different complexities and driver states (Layton & Dixon, 2012; Sivak ,1982). Interesting to note is the PRT on an urban arterial with an alert driver and complex traffic situation is the same as that of a rural freeway with a fatigued driver and low task complexity. This again illustrates that task complexity has a major impact on the PRT, as does fatigue.

Road Type	Driver 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

Table 5.5 : Perception Reaction Times Considering Complexity and Driver State (Layton & Dixon, 2012; Sivak ,1982).

Orientation sight distance/orientation visibility and driver workload

Lippold, Schulz, Krüger, Scheuchenpflug, & Piechulla (2007) developed what they called an orientation visibility or orientation sight distance model. They used an interdisciplinary approach, blending transport engineering and traffic psychology. The empirical foundation of their work was a combination of real-life test drivers with an instrumented vehicle and driving simulator studies. Participants drove a test vehicle over a fixed route, with and without a visual-manual secondary task. The secondary task rationale was that drivers would engage the secondary task only after having obtained sufficient preview of the upcoming route section. During runs, driving behaviour as well as gaze patterns were logged.

Results of the real-life tests showed an influence of available visibility, shorter visibility (due to road lay-out, not due to e.g. fog) being associated with more concentrated looking at the road and reducing speed and are associated by the authors with higher workloads or driver stress. Such effects start to manifest themselves at visibility ranges below 200 m. In runs with secondary tasks, the task was ignored completely at visibilities below 150 m.

Based on their findings, Lippold et al. (2007) recommended orientation sight distances for four different design classes. These orientation sight distances typically extend beyond the SSD criteria being used in the German design guidelines.

5.1.5 Elderly drivers

Perception Reaction Times

The Perception Reaction Times for elderly drivers have not been found to be significantly longer than the average for younger drivers. 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 (Staplin et al.,1997) - (Layton & Dixon, 2012).

Warshawsky-Livne and Shinar (2002) also considered the effects of age on reaction times in a driving simulator, with younger drivers (aged less than 25 years) demonstrating the fastest BRT (0.35s), ages 26–49 years were slightly slower (0.39s), while those over 50 years were slowest (0.43s). Warnes et al. (1993) found elderly drivers were slightly (although non-significantly) slower than controls (2.45s vs. 2.33s) when not given a warning, the elderly drivers were however significantly faster than the control group when there was a warning and a distraction task (2.61s vs. 3.89s).

Visual acuity, contrast sensitivity, illumination

For drivers over 65, the average static visual acuity has dropped to 20/70 (Holland, 2001). 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 related to crash involvement is 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. Horswill et al., (2008) 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.

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 (Staplin et al., 1997).

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. – (Layton and Dixon, 2012).

Note: A standard, normal eye has 20/20 vision (ie. the letter being read does not need magnification at 20ft/6m). If vision is said to be 20/70 then the eyesight of the subject has deteriorated by some 30% compared to a standard eye.

5.1.6 Driver deceleration behaviour

Van der Horst (1990) conducted a study in an instrumented vehicle, where participants approached a stationary obstacle (a mock-up resembling a stopped vehicle). Participants were instructed to brake “at the latest moment you think you are able to stop in front of the object”. The initial approach speeds varied from 30 to 70 km/h. The surface where braking was performed was (dry) asphalt. The maximum deceleration level that was reached during braking was around 6.5 m/s^2 for an initial speed of 30 km/h, up to 7.5 m/s^2 when driving 70 km/h. The results suggested that drivers followed a “constant minimum Time-To-Collision” strategy more than a “constant deceleration” strategy. Given the experimental setting, the deceleration values found by Van der Horst should be considered as a upper limit of driving performance, not of values that are suitable for SSD criteria.

The field trial of Durth and Bernhard (2000), involving a surprise braking situation, also showed that drivers braked harder when the initial speed was higher, in line with the urgency effect mentioned above. The levels ranged from about 3 m/s^2 at 70 km/h to 7.5 m/s^2 at 100 km/h. For SSD calculations, they recommended the use of a constant level of 4.5 m/s^2.

Kusano and Gabler (2011) also investigated deceleration and time to collision (TTC) in crash-iminent situations. Their data were collected by Event Data Recorders (EDRs), using cases from a database with real-world cases of actual collisions. They reported an average braking deceleration of 0.52 g's (5.1 m/s^2). It should be noted that all these manoeuvres ended in a collision, meaning that the braking was too little or too late. Lower values of TTC at the initiation of braking corresponded to stronger deceleration, which is again in line with the ‘urgency’ effect. The average maximum deceleration is lower than the values reported by Van der Horst (1990). This may be due to the methodology applied by Kusano and Gabler. Drivers who applied stronger braking might have avoided the collision, thus not ending up in the EDR data.

Fambro et al. (2000) measured driver braking distances and decelerations to both unexpected and anticipated stops:

Differences were noted in individual driver performance in terms of maximum deceleration. ... Overall, drivers generated maximum decelerations from 6.9 to 9.1 m/s^2. The equivalent constant deceleration also varied among drivers. Based on the 90-km/h data, 90 percent of all drivers without ABS chose equivalent constant decelerations of at least 3.4 m/s^2 under wet conditions, and 90 percent of all drivers with ABS chose equivalent constant deceleration of at least 4.7 m/s^2 on dry pavements. – (Fambro et al., 2000). Their results show that drivers typically realise decelerations that are below the levels that are possible given the pavement's coefficient of friction: the average maximum deceleration was about 75 percent of that level.

5.2 Factors related to vehicles

In the context of SSD, the vehicle factors are essentially those that determine the braking capabilities of the vehicle:

- brake coefficients,
- tyre changes,
- fleet difference between countries (deceleration rates),
- effect of ABS and other brake system developments.

5.2.1 Minimum braking requirements

The ECE regulation (UN, 2014) describes the brake tests and minimal requirements for the type approval of the braking systems of passenger cars. It describes among others the cold and hot brake performance, including detailed procedures for how to conduct the tests. Note that these tests are technical tests, not involving driving behaviour.

The minimal requirements of the cold and hot brake tests are:
- Cold test with engine disconnected: deceleration > 6.43 m/s^2
- Cold test with engine connected: deceleration > 5.76 m/s^2
- Hot test with engine disconnected: deceleration > 4.82 m/s^2

These deceleration values are the so-called mean fully developed deceleration (mfdd) between 80% and 10% of the test speed. The test speed is prescribed to be 100 km/h for the disconnected test and 80% of the vehicle’s maximum speed for the connected test.

5.2.2 Effects of brake system developments

Barrios, Aparicio, Dündar, and Schoinas (2008) listed the following safety systems related to brake systems.

- Control
- Anti-Lock Braking System (ABS)
- Cornering Brake Control
- Sensotronic Brake Control
- Electronic Brake Force Distribution
- Cross by Wire Brakes
- Electro Mechanical Brake
- Electro Hydraulic Braking
- Electro-Hydraulic parking brake
- Electronic Parking brake
- Assisted

- Brake Assist (BAS)
- Predictive Assist Braking
- Dynamic Brake Control
- Hydraulic Brake Boost

Fambro et al. (2000) measured driver braking distances and decelerations to both unexpected and anticipated stops. *Vehicle speeds, braking distances, and deceleration profiles were determined for each braking manoeuvre. The research results show that ABS result in shorter braking distances by as much as 30m at 90km/ h. These differences were most noticeable on wet pavements where ABS resulted in better control and shorter braking distances. – (Fambro et al., 2000).*

Similar, Fambro, Fitzpatrick, and Koppa (1997) reported an experimental study (expected braking), showing shorter stopping distances and larger deceleration under influence of ABS.

However, Burton et al. (2004) reported several studies that showed an increase of braking distance on loose surfaces (such as gravel or snow; ABS still offering the benefit of improved vehicle control). Forkenbrock, Flick, and Garrott (1999) confirmed that for most maneuvers, on most surfaces, ABS yielded shorter braking distances and that loose gravel was an exception.

ABS is highly common on new vehicles. Looking at the 50 best sold vehicle types in the Netherlands, the percentage of newly sold vehicles with ABS has risen from around 10% in 1995 to 50% in 2000 and to almost 100% in 2005 (BOVAG/RAI, 2013). Due to a commitment by the European Car Manufactorers Association all new cars have to be equiped with ABS since mid of 2004. Since 2009 all new cars have to be equiped with BAS.

The effects of these newer systems on driving behaviour (especially deceleration behaviour) is not well documented. There is a potential for ‘better’ braking behaviour when those are implemented. Still, for the current vehicle fleet, the SSD considerations will have to be based on vehicles not equipped with such systems.

5.2.3 Effects of tyres

Van Zyl, De Roo, Dittrich, Jansen, and De Graaf (2014) performed a quick scan to the potential of high-quality tyres on safety, noise and CO_2 emissions.

In the context of road surface and tyre interactions, dry grip and wet grip are distinguished (where ‘grip’ and ‘friction coefficient’ are the same concept). The wet grip performance and dry grip performance are determined by different tyre characteristics. In terms of safety effects, the focus is entirely on the wet grip level.

Wet grip for a given tyre is defined relative to the wet grip of a reference tyre, which is tested under the same conditions. In the analyses of Van Zyl et al. (2014), the calculations were done for a wet grip level of the reference tyre of 0.6 (this is in the required range defined by the standard).

The resulting grip levels (coefficients of friction) for different tyre labels are listed inTable 5.6. As a reference a grip level for non-labelled tyres is set at the legal requirement for passenger car braking performance according to ECE R13H & ECE R13 (defined for dry roads) `

Tyre label	C1 – passenger cars	C2 – vans & light trucks	C3 - trucks
A	>0.92	>0.84	0.75
B	0.84 – 0.92	0.75 – 0.83	0.66 – 0.74
C	0.75 – 0.83	0.66 – 0.74	0.57 – 0.65
E	0.66 – 0.74	0.57 – 0.65	0.39 – 0.47
F	0.6 – 0.65	0.53 – 0.56	0.35 – 0.38
Legal limit (dry)	>0.52	>0.5	>0.5

Table 5.6 : Wet grip levels (or coefficients of friction) for different tyre labels and vehicle categories (source: Van Zyl et al., 2014)

Table 5.6 : Wet grip levels (or coefficients of friction) for different tyre labels and vehicle categories (source: Van Zyl et al., 2014) gives the calculated braking distances for the respective tyre labels as a function of a number of initial speeds and given the calculated coefficients of friction.

	Braking distance [m]			
Tyre label	50 km/h	80 km/h	100 km/h	130 km/h
A	10.4	26.6	41.5	70.1
B	11.5	29.4	45.9	77.6
C	12.9	32.9	51.4	86.9
E	14.6	37.4	58.5	98.8
F	16.1	41.2	64.3	108.7
Legal limit	18.5	47.5	74.2	125.4

Table 5.7 : Calculated braking distance for different tyre label as a function of initial speed.

In 2003 the Motor Industry Research Association (MIRA) investigated the effects of tread depth on stopping distances by means of real wet brake test (RoSPA, 2005). The tests were carried out on a test track, where 5 different tread depths were tested (Figure 5.1).

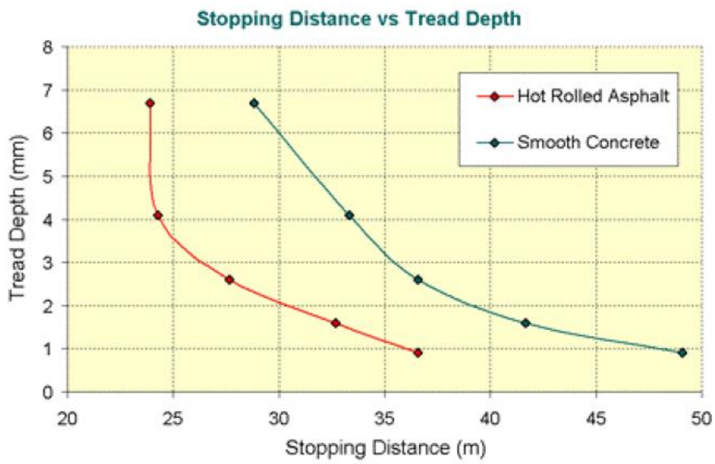


Figure 5.1 : Stopping distance vs treads depth on wet roads (source: RoSPA, 2005).

The stopping distance is different for the two road surfaces due to their different water retention properties. Further, the graph clearly indicates that the stopping distances increases dramatically at tread depths below 3 mm. Comparing the results of the maximum tread depth of 6.7 mm to the legal minimum tread depth of 1.6 mm, the stopping distance is increased by 36.8% on the hot rolled asphalt and 44.6% on the smooth concrete .

5.2.4 Brake light systems

In some countries the tail light or the brake light of a leading vehicle is defined to be the relevant element to be perceived and reacted upon. (see also Section 5.3.5). In the USA 600mm is applied as the height of a passenger cars' tail light (this compared to a standard object of 150mm)(Layton and Dixon, 2012). It is not only the height of the tail lights but with the introduction of the third tail light there is now also the matter of the tail light configuration. Including the presence of a third brake light, Sivak et al. (1982) found no effects of a high-mounted brake light system on BRT in their field study (exposing un-alerted drivers to brake signals). In contrast, Theeuwes and Alferdinck (1995) found in a lab study that reaction time measures (speed and accuracy) improved for a high-placed centre high-mounted stop lamp. They mentioned that the absolute differences were small but reliable, indicating that this effect is systematic and occurs for all subjects.

Various other brake light systems have been reported in the literature.

- Results from Wierwille at al. (2006) showed that adding an visual "imminent warning signals" to brake lights can help reduce BRT.
- Isler and Starkey (2010) evaluated g-force controlled activation of the rear hazard lights (the rear indicators flashed), in addition to the standard brake lights. They found that responses to the braking manoeuvres of the leading vehicles when the hazard

lights were activated by the warning system were 0.34. s (19%) faster compared to the standard brake lights.
- Stanton et al. (2011) assessed the effectiveness of a Graded Deceleration Display (GDD) that is designed to replace the rear centre high mounted stop lamp on automobiles.*" Results entailed that the graded system produced more accurate behavioural responses during deceleration, fewer collisions, and a safer following distance than the binary system."*

5.3 Factors related to the road

5.3.1 Friction

As already explained in section 5.2.3, a distinction is made between wet and dry friction (or grip) levels. For SSD, the wet grip level is the relevant condition. Two main determinants for the friction are (1) the road surface (expressed as texture or surface type), and (2) the depth of the water film.

5.3.2 Texture

Two different texture scales are distinguished, i.e. a macro scale and a micro. The extremes of micro texture and macro texture (rough versus smooth) are illustrated in Figure 5.2. The texture at macro scale is required to remove on a wet road surface, especially at higher vehicle speeds, the water from the contact area between the tyre and the road surface. The macro texture is determined by the size of the aggregate particles on the road surface. The micro texture is determined by the roughness and angularity of the surface of the aggregate particles. The micro texture ensures the removal of the last traces of water from those locations where high contact pressures between the aggregate and the tyre are present.

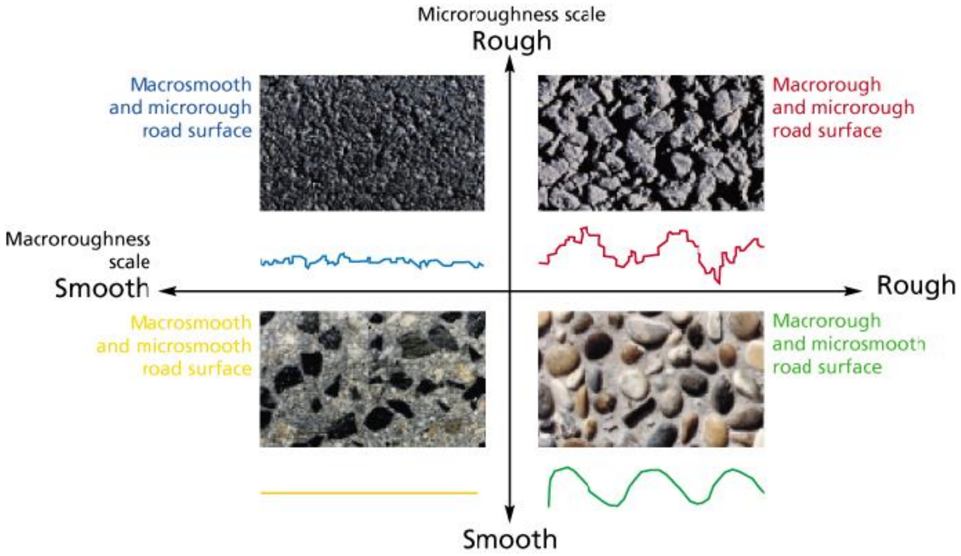


Figure 5.2 : Extremes of texture likely to be encountered on roads: microroughness and macroroughness (Source: Kane & Scharnigg, 2009).

For road surfaces with rough macro textures the wet friction coefficient is almost independent of speed, but the level of friction coefficient is very much dependend on the micro texture, see Figure 5.3. The wet friction coefficient of road surfaces with smooth macro textures are very influenced by speed and also by the micro texture (rough vs smooth).

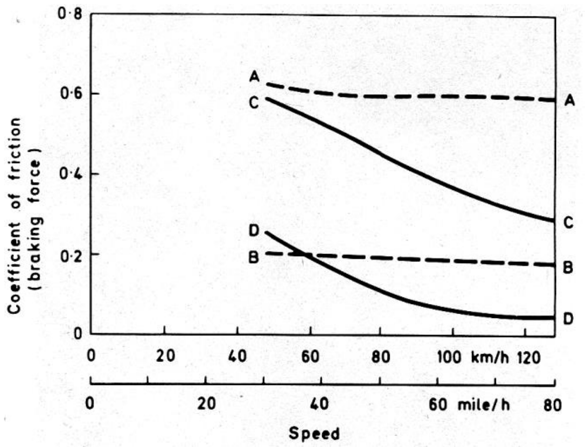


Figure 5.3 : Wet road skid resistance measured with smooth tyre on four surfaces representing the extremes of micro and macrotexture as shown in Figure 5.2 (Source: Sabey et al., 1970). A: rough micro and macro; B: rough macro smooth micro; C: smooth micro rough macro; D: smooth micro and macro.

The skid resistance (wet road friction coefficient) is dependent on the macro-texture depth, see Figure 5.4. The figure shows how the friction coefficient (given as the Friction Number: Fn = wet road friction coefficient * 100) noticeably decreases with the macro-texture depth (SMTD: sensor measured texture depth) at a test speed of 100 km/h (Fn100) whereas the skid resistance remains relatively constant with macro-texture when tested at 20 km/h (Fn20).

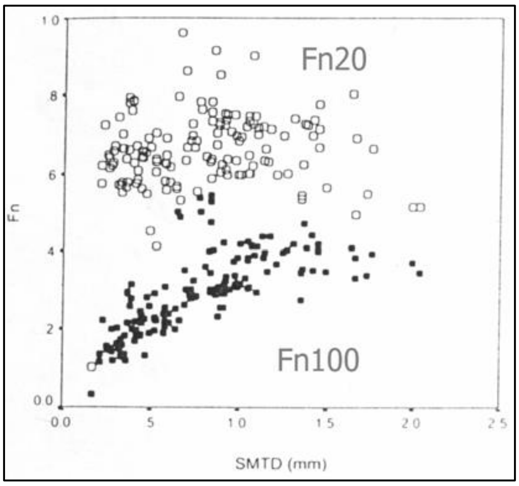


Figure 5.4: Friction number as a function of texture depth (SMTD) and tread depth and speed (Fn20, Fn100: Friction Number at 20km/h and 100km/h) (for a smooth tyre on a wet road)(Ref: Viner, Roe, Parry, & Sinhal, 2000).

5.3.3 Road surface type

Another way of classifying road surfaces is by surface type. On a high level, the following distinction can be made:

- Concrete
- Asphalt
  - Porous (or open) asphalt
  - Dense asphalt.

On asphalt, drainage of water is improved compared with a concrete surface (Elvik et al., 2009). Porous asphalt has even better drainage properties, reducing the splash and spray as well the likelyhood of aquaplaning (Tromp, 1994). However, porous asphalt also has some disadvantages:

- On dry surfaces, the friction on porous asphalt is less than on dense asphalt. This holds especially for newly applied porous asphalt. Tromp (1994) mentioned maximum decelerations (locked wheels) of 6 m/s^2 for new porous asphalt, 7 m/s^2 for old porous asphalt, and 8 m/s^2 for dense asphalt.
- In winter conditions, porous asphalt freezes sooner than dense asphalt (Elvik et al., 2009).
- The open structure can become blocked by dirt, which reduces the draining. Thus, porous asphalt needs more cleaning to maintain its favourable effects (Tromp, 1994).

Sandberg et al. (2011) made an overview of developments in Thin Asphalt Layers (TAL). Their main conclusion was that the application of TAL is certainly worthwhile, combining sufficient skid resistance, low noise levels and relatively low rolling resistance because of the favourable surface texture. In various studies, skid resistance of TAL was reported to be higher than of dense asphalt.

5.3.4 Water film thickness

On a dry road surface the influence of the speed of the wheel (vehicle) on the friction coefficient in general is limited. The effect of the thickness of the water layer on the wet road friction coefficient or skid resistance is small at low speeds but quite pronounced at higher speeds. Two studies, in France and the UK confirm this conclusion (cited in Kane & Scharnigg, 2009) show the results of these experimental investigations on the combined effects of water depth and speed (Figure 5.5 andFigure 5.6). The friction coefficient only becomes greater if the driver slows down or if the thickness of the water layer decreases.

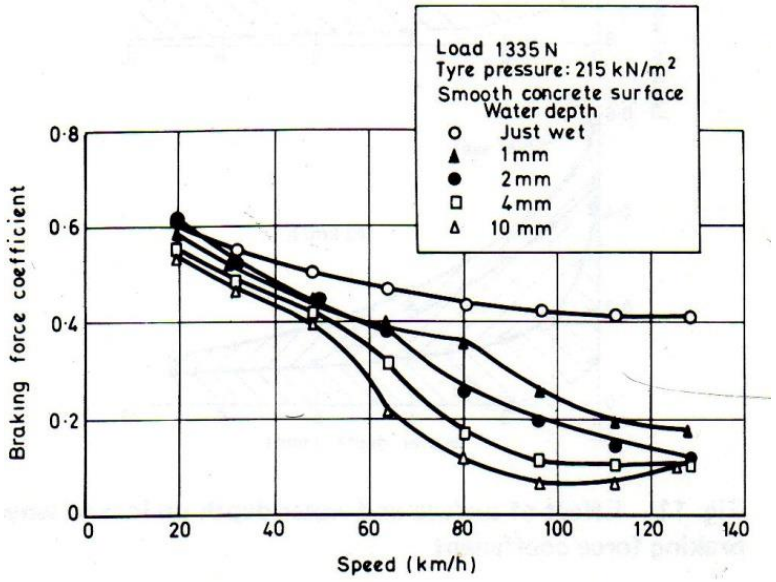


Figure 5.5 : Effect of water depth on the braking force with a radial ply tyre (source: Kane & Scharnigg, 2009 / Sabey at al., 1970)

On a dry road surface the influence of the speed of the wheel (vehicle) on the friction coefficient in general is limited. However, on a wet road surface the friction coefficient strongly decreases with increasing vehicle speed and increasing thickness of the water layer (seeFigure 5.6).

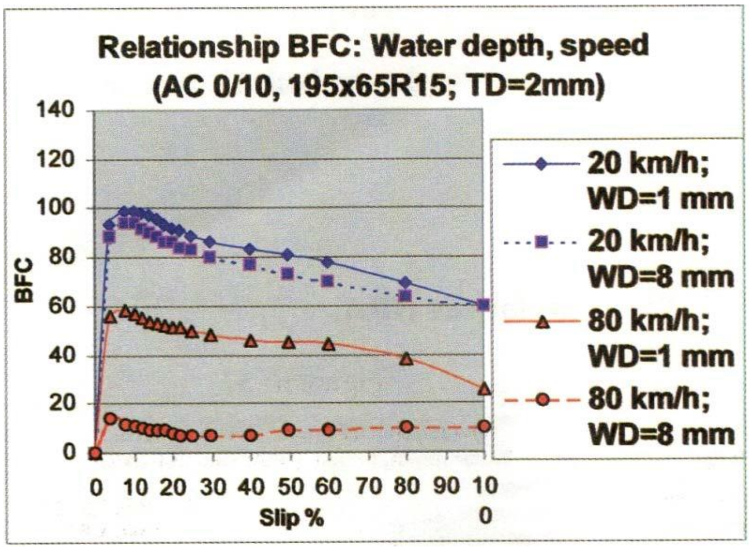


Figure 5.6: Comparison of the locked-wheel BFC (Brake Friction Coefficient) versus slip ratio relationships for a tyre with 2 mm tread depth (WD) on asphalt concrete, at two speeds and two water depths (WD=1 mm and WD=8 mm) (source: Kane & Scharnigg, 2009 / Gothié, 2001)

Jahromi et al. (2011) conducted a study to quantify the effect of pavement surface temperature on the frictional properties of the pavement–tyre interface. To accomplish this, tests were carried out on seven different wearing surfaces under different climatic conditions were analysed. Results showed that at low speed, pavement friction tends to decrease with increased pavement temperature, and at high speed, the effect is reverted and pavement friction tends to increase with increasing pavement temperature.

5.3.5 Obstacles

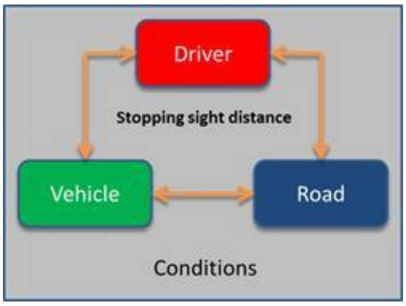
Implicit in the SSD definition of equation (1) is that the driver brakes in response to detecting an obstacle. However, there is little clarity on what actually constitutes an obstacle or an object that may be a hazard for approaching drivers. It could be argued that a large pothole constitutes a major threat but in providing adequate SSD such a situation could hardly be accommodated. It has been general practice to define an object on the road as an object 150mm high. This seems to have been a pragmatic rather than researched choice.

The object height that has been used for stopping sight distance has been 150 mm since 1965. (…) This arbitrary value recognized the hazard an object of that height or larger would represent, since 30% of the compact and subcompact vehicles could not clear a 150 mm object. (…) Under some circumstances the height of the tail-light at 450 mm to 600 mm was recognized as a more appropriate (Layton & Dixon, 2012)

This quote shows the use of a rather artificial “standardised” obstacle has been common practice in road design guidelines for many years. Another approach is to investigate what kind of obstacles traffic really has to deal with, which may vary depending on the geographical location being studied. In addition to object size, there are other visibility factors that determine if an object is visible, e.g. luminance contrast, colour contrast, ambient luminance levels (Fambro et al., 1997). Fambro et al. (1997) reported on several studies that investigated detection and recognition distances of various objects, such as a bale of hay, a dog or a tyre casing. Obviously, the detection distances vary with daylight versus night time, and with vehicle light configurations.

Fambro et al. (1997) argue that small, non-reflective objects are often beyond most driver's visual capabilities at distances greater than 100-130 m. Such objects, if they turn out to be an obstacle, "almost never result in injuries to vehicle occupants". They propose to use obstacles that represent a realistic hazard to drivers, e.g. cattle, deer, other traffic etc.

5.4 Discussion



The initially developed figure suggests that the blocks are more or less independent within any given set of conditions. However, the conditions have a relationship individually and collectively with the blocks. The analyses of reports on the different aspects makes clear that the blocks should partially overlap, as many factors are so strongly interacting. Just to give some examples:

- Eye height is partially determined by vehicle height.
- ABS reduces braking distance, especially on wet pavement (but not on snow)
- There is an interaction between tyre tread and surface type on braking distance

This literature study started with the intention to focus on recent articles and reports. This revealed that much of the recent Human Factors meta studies are based on research that is in many cases decades old.

5.4.1 Drivers

Many studies are available on PRT. Obviously, there are differences in PRT between and within drivers. Hence, PRT is characterised by a distribution rather than by a constant value. For SSD, the common approach is to use a percentiles of the PRT distribution. The 85th percentiles that have been reported range from 1.4 to 1.9 s; 90th or even 99th percentiles may range from 1.8 to 2.5 s. But *which* percentile should be used for SSD calculations does not follow from the literature review. Ultimately, this is a trade-off between safety and comfort on the one hand and cost/space and adaptation to landscape on the other.
Many studies confirm the influence on PRT of driver alertness (aware, partially aware, unaware) and of the urgency involved in the event on PRT. Effects of driver age do not have that strong an influence on PRT. Thus, there is no strong case for accommodating the aging society with an extra PRT margin in SSD criteria.

Since drivers will be distracted, current standards on the PRT are on the conservative side. At the same time, the occurrence of distractions in the car only seem to increase with the introduction of more and more in-car technology. Therefore, care must be taken to decrease standards for Perception Reaction times.

No single study can reproduce the full complexity of human behaviour and its sensitivity to environmental variables. Moreover, studies cannot be quantitatively combined because no mathematical formalism can capture the subtle effects of methodology and variable interaction or incorporate general knowledge from the basic science literature on RT, perception and cognition. For the time being, RT estimation remains part science and part intuition. (Green, 2000).

Compared to PRT, the amount of information on braking behaviour is not so abundant. Reported values are often in the range of 3.4 to 5 m/s^2, although in some circumstances higher levels are reached.

5.4.2 Vehicles

There are several developments that have potentially a large impact on SSD. In terms of driver assistance systems, ABS and BAS is standard in new vehicles today but the percentage of old cars without these systems within the fleed is relevant; the other systems like Predictive Assist Braking are typically optional or still under development. The effects of these newer systems on driving behaviour (especially deceleration behaviour) is not well documented. There is a potential for 'better' braking behaviour when those are implemented: brake assist and similar systems can help improve the response time of the vehicle and of the brake performance of the driver-vehicle system. It can be expected that more of these systems will become available over the coming years. Still, for the years to come, SSD criteria have to be based on a vehicle fleet containing vehicles *without* such systems.

Some tests have been conducted with rear light or brake light configuration, possibly reducing PRT (even for distracted drivers).

In terms of eye height, the overall effect is unclear from what the literature has revealed. On the one hand, cars are getting lower; on the other hand, there is an increase of larger vehicle types (SUV types).

5.4.3 Road

The classical road condition used in SSD calculations is a wet surface. As a consequence, the road friction should be considered as a function of speed and of water depth, because for a wet surface the friction is speed dependent. Further, at higher speeds, the friction coefficient is a function of the tyre tread depth. The existing surface types (concrete / dense asphalt / porous asphalt) are characterised by different micro and macro structures and by different water draining characteristics, accumulating to different friction coefficients in rain. These characteristics should be taken into account when choosing SSD parameters later on in the project.

5.5 Points for discussion and clarification in WPs 3-6

- Several guidelines state wet road conditions to be leading on the SSD. What are effects of glare of wet road surfaces on the perception time?
- What are the effects of rain on perception time? And how would this compare to the findings in 5.1.1 ?
- What should be used to define an object for SSD calculation and what are the physical properties of such object?
- What is the influence of vehicle technology on SSD requirements and do we account for the 15th percentile, mean, 85th or 95th percentile values of physical and performance characteristics the vehicle population? (i.e. do we accommodate for older vehicles with much lower deceleration capability)
- Do we design for the elderly (taking into account smaller people with lower eye height and higher reaction times) ?

6 Review of guidelines, country factsheets

6.1 Introduction

This chapter reviews in separate factsheets the design guidelines on sight distance requirements for motorways with a minimum configuration of 2x2 lanes, as discussed in the design guidelines of the following European countries: Austria; Denmark; France; Germany; Ireland; The Netherlands; Switzerland; United Kingdom. These countries represent a broad range of different operating environments in Europe. Also the European Agreement on Main International Traffic Arteries was studied (AGR) (*EUROPEAN AGREEMENT ON MAIN INTERNATIONAL TRAFFIC ARTERIES (AGR)*, 2008).The AGR however was not as complete as the country design guidelines and was consequently left out of the comparisons. With sight distance is meant the unobstructed visibility that is needed to be able to safely and comfortably perform the driving task and to avoid conflicts or collisions with objects or other road users.

The following topics on sight distance have been considered during the review of the design guidelines; stopping sight distance, orientation visibility or orientation sight distance and decision sight distance. However, other sight distance criteria than the stopping sight distance, relevant for motorways, are rarely discussed in the several design guidelines. Consequently, these factsheets only consider the stopping sight distance from the several design guidelines.

Table 6.1 gives a general explanation of the terms used in the factsheet tables. Only definitions and specifications explicitly presented in the country guidelines are completed in the country factsheets. Definitions and specifications which are not presented in the guidelines itself are left blank in the country factsheets. Equations, figures and tables on the specifications on sight distance characteristics are presented in every country factsheet in separate paragraphs.

Type	Term		
Sight distance types	Sight distance	Definition	A definition of the sight distance
	Stopping sight distance	Definition	A definition of the stopping sight distance
Observation conditions	Observation point	Definition	A definition of the observation point, which is an international term for the point from where the driver is looking
	Observation point position left curve	Specification	A specification of the position of the observation point in the cross section of the road in left turning curves
	Observation point position right curve	Specification	A specification of the position of the observation point in the cross section of the road in right turning curves
	Observed point	Definition	A definition of the observed point, which is an international term for the point or object at which the driver is looking
	Object	Specification	A specification of the object at which the driver is looking
	Observed point height crest curve	Specification	A specification of the height of the observed point for crest curves

	Observed point height sag curve	Specification	A specification of the height of the observed point for sag curves
	Observed point position left curve	Specification	A specification of the position of the observed point in the cross section of the road in left turning curves
	Observed point position right curve	Specification	A specification of the position of the observed point in the cross section of the road in right turning curves
	Driver Eye Height	Definition	Definition of the driver eye height (also observation point height)
	Driver Eye Height flat alignment	Specification	Specification of the driver eye height at flat roads
	Driver Eye Height Crest curve	Specification	Specification of the driver eye height at crest curves
	Driver Eye Height sag curve	Specification	Specification of the driver eye height at sag curves
	Light conditions	Specification	Specifcation of the light conditions
SD braking conditions	Car	Specification	Car specifications like weight and size
	Road Surface	Specification	Specification of road surface conditions
	Air resistance	Specification	Specification of the air resistance
	Deceleration rate	Definition	Definition of the deceleration rate
	Deceleration rate	Specification	Specification of the deceleration rate
	Coefficient of friction	Definition	Definition of the coefficient of friction
	(Resulting) coefficient of friction	Specification	Specification of the (resulting) coefficient of friction
	Tangential or braking coefficient of friction	Specification	Specification of the tangential or braking coefficient of friction
	Radial or side coefficient of friction	Specification	Specification of the radial or side coefficient of friction
Perception and Reaction times	perception reaction time	Definition	Definition of the perception reaction time
	perception reaction time	Specification	Specification of the perception reaction time
	Braking distance	Definition	Definition of the braking distance
	Braking distance	Specification	Specification of the braking distance
Alignment Conditions	General design principles	Design principle	General design principles found in the guidelines related to the partition of the guidelines on the stopping sight distance
	Vertical curves	Design principle	Design principles of the design of vertical curves related to the stopping sight distance
	Horizontal curves	Design principle	Design principles of the design of horizontal curves related to the stopping sight distance

Table 6.1 Parameter reviewed in the guidelines

6.1.1 Disclaimer

The values reflected in the fact sheets were obtained from the country guidelines and in most cases checked and verified by experts in those countries. However, in a number of cases (Switzerland, Ireland, Denmark) these have not been verified. Although every attempt has been made to provide correct information from the country guidelines and standards, the authors apologise for possible omissions or inaccuracies.

6.2 Factsheet Denmark

This factsheet describes in brief the definitions, specifications and design principles on the stopping sight distance, as dealt with in the Danish design guidelines on motorways; Håndbog - Tracéring I Åbent Land – Anlæg Og Planæegning (Vejregler, 2012b) and "Håndbog - Grundlag for udforming af trafikarea - Anlæg Og Planæegningl" (Vejregler, 2012a).

6.2.1 Definitions, specifications and design principles

Type	Term		Definition
Sight distance types	Sight distance	Definition	The longest continuous visible stretch a motorist/cyclist has over the road from eye height above the ground.
	Stopping sight distance	Definition	-
Observation conditions	Observation point	Definition	
	Observation point position left curve	Specification	1.5m from the edge marking on the inner lane, as shown in Figure 6.1
	Observation point position right curve	Specification	1.5m from the edge marking on the inner lane, as shown in Figure 6.2
	Observed point	Definition	-
	Object	Specification	-
	Observed point height crest curve	Specification	0.5m
	Observed point height sag curve	Specification	0.5m
	Observed point position left curve	Specification	1.5m from the edge marking on the inner lane, as shown in Figure 6.1
	Observed point position right curve	Specification	1.5m from the edge marking on the inner lane, as shown in Figure 6.2
	Driver Eye Height	Definition	-
	Driver Eye Height Horizontal alignment	Specification	1.0m
	Driver Eye Height Crest curve	Specification	1.0m

	Driver Eye Height sag curve	Specification	2.5m
	Light conditions	Specification	-
SD braking conditions	Car	Specification	
	Road Surface	Specification	
	Air resistance	Specification	
	Deceleration rate	Definition	
	Deceleration rate	Specification	A specification of the deceleration rate is given by equation (2)
	Coefficient of friction	Definition	The coefficient of friction is a measure of the resistance between wheel and road surface and forms together with the side friction the foundation for calculation of the tangential or braking coefficient of friction μ_{br}
	(Resulting) coefficient of friction	Specification	The resulting coefficient of friction μ_{res} has a fixed value of 0.377
	Tangential or braking coefficient of friction	Specification	The tangential or braking coefficient of friction μ_{br} can be determined by equation (4) and is presented in Table 6.3 as a function of speed.
	Radial or side coefficient of friction	Specification	The radial or side coefficient of friction μ_r is presented in Table 6.3 as a function of the design speed
Percecption and Reaction times	perception reaction time	Definition	The reaction time is the time that elapses from the moment that a driver perceives a clear danger to the moment that the driver initiates a manoeuvre (braking) Note that perception time is not mentioned as a separate element and is included in the reaction time
	perception reaction time	Specification	2s
	Braking distance	Definition	-
	Braking distance	Specification	-
Alignment Conditions	General design principles	Design principle	The visibility of the alignment is to be determined for vertical and horizontal curves. Vertical elements should be considered when determining sightlines as they can block the sightlines. Tools for CAD programmes can be used to calculate sight lines. If so, vertical elements alongside the road should be incorporated in the CAD drawing. A margin of 20km/h should be used on top of the (planned) speed limit as the design speed when determining or checking the SSD
	Vertical curves	Design principle	The sight distance on crest curves should be checked according to Figure 6.3 and equation (9) The SSD should be checked for sag curves in tunnels
	Horizontal curves	Design principle	The design of the curve and selection of the curve radius is to be based on: stopping sight; driving dynamics; road safety; driving comfort and perspective/aesthetics The sight distance in curves can be checked with equation (8) and Figure 6.2 and Figure 6.1

Table 6.2: Definitions, specifications and design principles- Denmark

6.2.2 SSD parameters, figures and equations

6.2.2.1 Coefficient of friction

The deceleration rate g_d can be calculated by the equation

$$g_d = \mu_{res} \cdot g \qquad (2)$$

where

g_d	Deceleration rate [m/s^2]
g	Gravity acceleration 9.81 m/s^2
μ_{res}	Coefficient of friction 0.377

The sidefriction μ_r is a function of speed and can be determined by the equation

$$\mu_r = 0.28 \cdot e^{-0.0096 \cdot V_d} \qquad (3)$$

where

V_d	Design speed [km/h]
μ_r	Side friction

The coefficient of friction is

$$\mu_{res}{}^2 = \mu_r{}^2 + \mu_{br}{}^2 \qquad (4)$$

where

μ_{br}	Coefficient of braking (or tangential component of the coefficient of friction)

Table 5.3 shows μ_r and μ_{br} as a function of speed.

Dimensionerende hastighed (km/h) V_d	Resulterende friktionskoefficient μ_{res}	Sidefriktions-koefficient μ_r	Bremsefriktions-koefficient μ_{br}
130	0,377	0,08	0,37
120	0,377	0,09	0,37
110	0,377	0,10	0,36
100	0,377	0,11	0,36
90	0,377	0,12	0,36
80	0,377	0,13	0,35
70	0,377	0,14	0,35
60	0,377	0,16	0,34
50	0,377	0,17	0,33
40	0,377	0,19	0,32
30	0,377	0,21	0,31

Table 6.3 coefficients of friction as a function of speed (Vejregler, 2012a)

6.2.2.2 Stopping Sight Distance

The stopping sight distance is determined by

$$L_{stop} = L_{re} + L_{br} \quad (5)$$

where

L_{stop} Stopping sight distance [m]
L_{re} Reaction time distance [m]
L_{br} Braking distance [m]

And

$$L_{re} = \frac{V_d \cdot t_{re}}{3.6} \quad (6)$$

where

V_d Design speed [km/h]
t_{re} Reaction time [s]

$$L_{br} = \frac{V_d{}^2}{2 \cdot g \cdot (\mu + i_t) \cdot 3.6^2} \quad (7)$$

where

V_d Design speed [km/h]
g Gravity acceleration 9.81 m/s^2
μ μ being μ_{res} or μ_{br} depending if the considered road stretch is a curve or a straight
i_t The grade (i_t) is negative when the grade is downward

The braking distance for straight stretches and curves of a grade of 50 ‰, 0‰ and -50‰ is shown in Table 6.4.

	Stopping Sight Distance L_{stop} [m] on a straight			Stopping Sight Distance L_{stop} [m] in a curve		
Design Speed V_d [km/h]	Grade [‰]			Grade [‰]		
	50	0	-50	50	0	-50
130	228	248	275	231	253	281
120	199	217	240	203	221	246
110	173	187	207	176	192	212
100	148	160	176	151	164	182
90	125	134	147	128	139	153
80	103	111	121	107	116	127
70	84	90	98	87	94	103
60	66	71	77	69	75	82
50	51	54	58	53	57	62
40	37	39	41	39	42	45
30	25	26	28	26	28	30

Table 6.4 SSD for straight stretches and horizontal curves as a function of the grade and design speed (Vejregler, 2012a)

6.2.2.3 Horizontal curves

1.1 Horizontal curves need to be checked on stopping sight requirements. It can be checked with equation (8) and Figure 6.1 and Figure 6.2 if the sight distance in the curve meets the requirements for the stopping sight distance.

$$R_h = \frac{L_{sight}^2}{8 \cdot d_{sh}} \tag{8}$$

where

R_h	Horizontal curve radius as measured for the observation point [m]
L_{sight}	Stopping Sight Distance [m]
d_{sh}	Distance from the observation point to sight blocking objects [m]

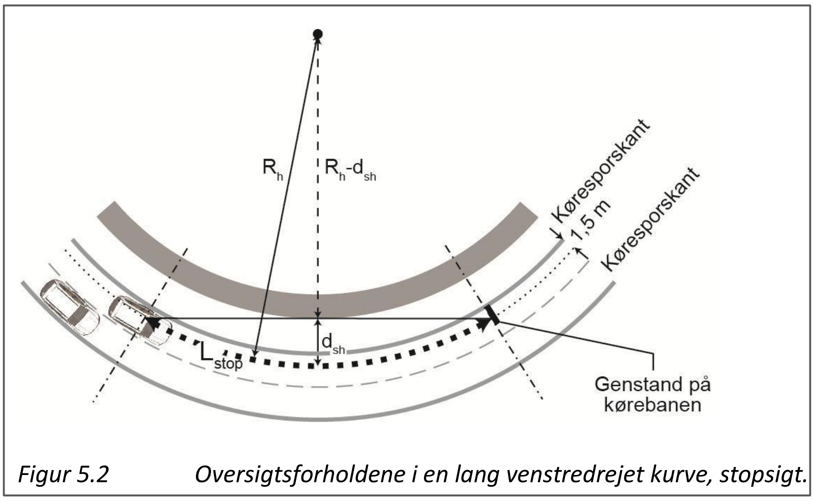


Figure 6.1 Sight distance in horizontal left turn curves (Vejregler, 2012b)

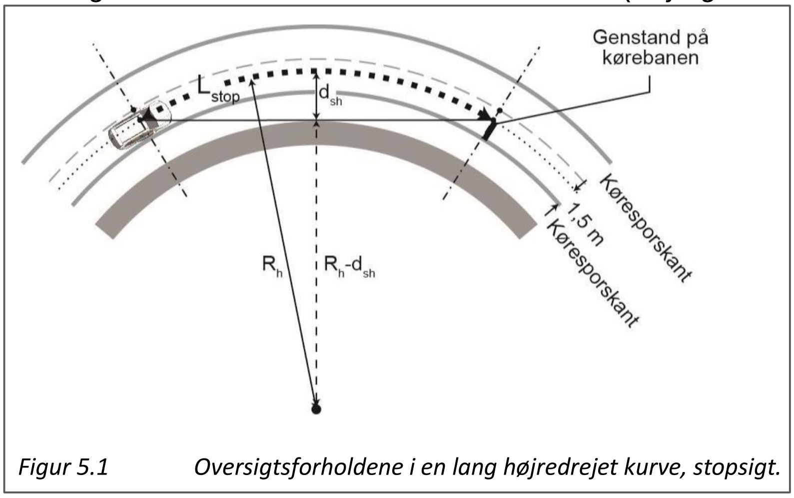


Figure 6.2 Sight distance in horizontal right turn curves (Vejregler, 2012b)

6.2.3 Crest Curves

The sight distance on crest curves should be checked according to Figure 6.3 and equation (9)

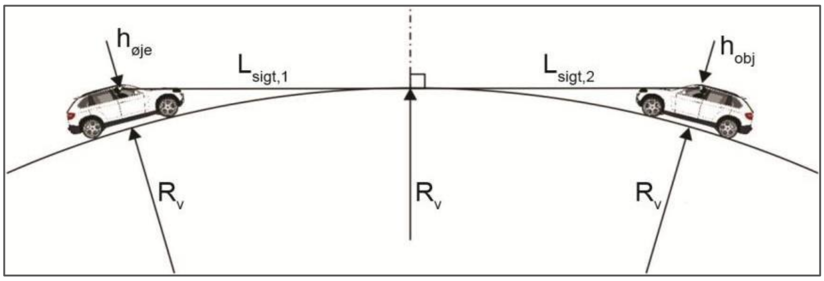


Figure 6.3 Sight distance in crest curves (Vejregler, 2012b)

$$R_v = \frac{L_{sigt}^2}{2 \cdot \left(\sqrt[2]{h_{oje}} + \sqrt[2]{h_{obj}}\right)^2} \tag{9}$$

With

R_v	Crest curve radius [m]
L_{sigt}	Stopping Sight Distance [m]
h_{oje}	Driver eye height (1.0m) [m]
h_{obj}	Observed point / object height (0.5m) [m]

6.2.4 Sag Curves

The sight distance on crest curves should be checked according to Figure 6.4Figure 6.4 and equation (10)

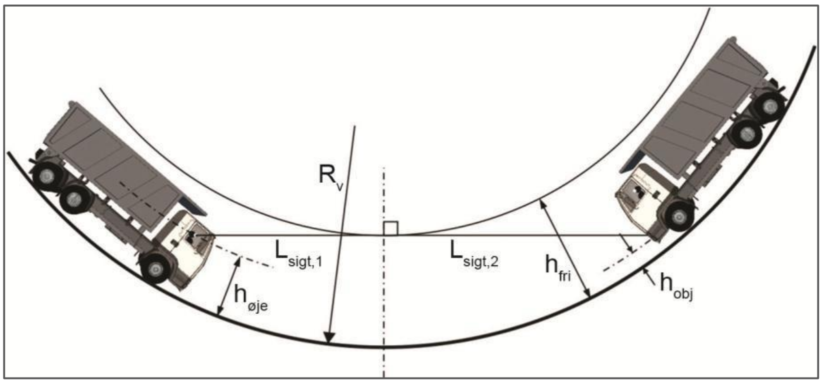


Figure 6.4 Sight distance in sag curves (Vejregler, 2012b)

$$R_v = \frac{L_{sigt}^2}{2 \cdot \left(\sqrt[2]{h_{fri} - h_{oje}} + \sqrt[2]{h_{fri} - h_{obj}}\right)^2} \tag{10}$$

With

R_v	Sag curve radius [m]
L_{sigt}	Stopping Sight Distance [m]
h_{fri}	Free height [m]
h_{oje}	DriverEye height (2.5m) [m]
h_{obj}	Observed point / object height (0.5m) [m]

6.3 *Factsheet France*

This factsheet describes in brief the definitions, specifications and design principles on the stopping sight distance, as dealt with in the French design guidelines on motorways; Instruction sur les Conditions Techniques d'Aménagement des Autoroutes de Liaison (ICTAAL) (Sétra, 2001) and Les échangeurs sur routes de type « Autoroute » : Complément à l'ICTAAL (Sétra, 2013).[1]

6.3.1 Definitions, specifications and design principles

Type	Term		Definition
Sight distance types	Sight distance	Definition	-
	Stopping sight distance	Definition	Theoretical conventional distance required for a vehicle to stop in relation to its speed, calculated as the sum of the braking distance and the distance travelled during the perception reaction time. Notation: d_a
Observation conditions	Observation point	Definition	The eye of the driver of a light vehicle
	Observation point position left curve	Specification	2.0m from the right sight of the driving lane (right and left turns are not separately specified)
	Observation point position right curve	Specification	2.0m from the right sight of the driving lane (right and left turns are not separately specified)
	Observed point	Definition	
	Object	Specification	Where the observed point concerns a vehicle, the observed point is the most effortlessly perceived of the two rear lights
	Observed point height crest curve	Specification	Rear braking light vehicle: 0.6 m above the ground
	Observed point height sag curve	Specification	-
	Observed point position left curve	Specification	1.0m to 2.5m from the right side of the lane in question (right and left turns are not separately specified)
	Observed point position right curve	Specification	1.0m to 2.5m from the right side of the lane in question (right and left turns are not separately specified)
	Driver Eye Height	Definition	-
	Driver Eye Height Horizontal alignment	Specification	-
	Driver Eye Height Crest curve	Specification	1.0m above the ground
	Driver Eye Height sag curve	Specification	-
	Light conditions	Specification	-
SD braking conditions	Car	Specification	Conventional conditions of tyres
	Road Surface	Specification	wet

[1] An English version of ICTAAL 2001 is used

	Air resistance	Specification	
	Deceleration rate	Definition	-
	Deceleration rate	Specification	$\gamma_{(v)}$ is presented as: the mean deceleration as a fraction of g. $\gamma_{(v)}$ is actually the tangential or braking component of the coefficient of friction
	Coefficient of friction	Definition	-
	Resulting coefficient of friction	Specification	-
	Tangential or braking coefficient of friction	Specification	The tangential coefficient of friction (see deceleration rate) $\gamma_{(v)}$ is presented in Table 6.5 as a function of the design speed.
	Radial or side coefficient of friction	Specification	-
Perception and Reaction times	perception reaction time	Definition	-
	perception reaction time	Specification	2s
	Braking distance	Definition	The distance travelled during the braking action
	Braking distance	Specification	-
Alignment Conditions	General design principles	Design principle	- Design constraints of the alignment do not necessarily achieve an alignment that complies to the SSD. Incorporating the SSD in early stage of design helps in achieving SSD requirements - Compliance to the SSD may not always be met due to design constraints. - The SSD should always be ensured at approaches to points or areas that present a particular risk of slowing or tailbacks: reduction in the number of lanes, access points, toll plazas, non-standard engineering structures, tunnels, etc. - The interruption of visibility of a given point for less than two seconds can be acceptable. (This type of interruption is usually caused by lateral point obstacles) - Visibility rules should not lead to the implementation of disproportionate measures like excessive clearance distances of curb lanes (offset) or non credible speed limits
	Vertical curves	Design principle	-
	Horizontal curves	Design principle	- Within curves with a radius R<5V (v in km/h and R in meters), the stopping distance is increased by 25% (2013)

6.3.2 SSD parameters, figures and equations

6.3.2.1 Stopping Sight Distance

The SSD is to be determined with the help of equation (11) and or Table 6.5. The determination of the SSD is based on the design speed, a fixed perception reaction time of 2 seconds, mean deceleration and the grade of the road.

$$d_a = \frac{V^2}{2g \times (\gamma_{(v)} + p)} + 2V \qquad (11)$$

Where:

d_a	SSD [m]
V	speed [m/s]
$\gamma_{(v)}$	mean deceleration as a fraction of g and a function of V (Table 6.5)
p	the grade as an algebraic value

The expression for the stopping distance in curves with R<5V is

$$d_a = 1.25 \times \frac{V^2}{2g \times (\gamma_{(v)} + p)} + 2V \quad (12)$$

The sight distances for a level road are presented in Table 6.5 as a function of the speed limit.

	Speed (km/h)	30	50	70	90	110	130
Mean deceleration as a fraction of g	(V)	0.46	0,46	0,44	0,40	0,36	0,32
Total stopping distance on a level section (p=0)	d_a	25	50	85	130	195	280
Total stopping distance in curves with R<5v	d_{ac}	30	55	95	150	230	335
Sight distance on markings	d_{vm}	25	45	60	75	95	110
Reading distance	l_c			125	125	150	180
Distance of non-disturbance	n_p			170	170	170	220
Exit manoeuvering distance	d_{ms}(6.V)		85	120	150	185	220

Table 6.5 SSD parameters as a function of speed (values rounded up to 5m) (Sétra, 2013)

6.4 Factsheet Germany

This factsheet describes in brief the definitions, specifications and design principles on the stopping sight distance, as dealt with in the German design guidelines on motorways; Richtlinien fur die Anlage von Autobahnen (RAA), Ausgabe 2008 (Fgsv, 2008)

6.4.1 Definitions, specifications and design principles

Type	Term		Definition
Sight distance types	Sight distance	Definition	The sight distance is the direct connection between an observation point and an observed point. In case that no visual obstruction exists, the sight distance is determined by the horizontal and vertical alignment as well as the cross section.
	Stopping sight distance	Definition	The sight distance that a car driver needs to be able to stop for a unexpected obstacle on the road during wet road conditions. It consists of the distance travelled during the perception reaction time and the braking distance. Because of the special conditions for motorways safer stopping sight distances are prescribed than the physically possible minimum for reaction times and car dynamic minimal braking distance.
Observation conditions	Observation point	Definition	*(Drivers in a light vehicle[2])*
	Observation point position left curve	Specification	In the middle of the most left lane (3.25/2m up to 3.75/2m)
	Observation point position right curve	Specification	In the middle of the most right lane (3.25/2m up to 3.75/2m)
	Observed point	Definition	The observation point is a light vehicle in front.
	Object	Specification	Stopping lights of a light vehicle
	Observed point height crest curve	Specification	1.0m
	Observed point height sag curve	Specification	1.0m
	Observed point position left curve	Specification	In the middle of the most left lane (3.25/2m up to 3.75/2m)
	Observed point position right curve	Specification	In the middle of the most right lane (3.25/2m up to 3.75/2m)
	Driver Eye Height	Definition	-
	Driver Eye Height Horizontal alignment	Specification	1.0m-
	Driver Eye Height Crest curve	Specification	1.0m
	Driver Eye Height sag curve	Specification	1.0m
	Light conditions	Specification	*(Dark[3])* -
SD braking	Car	Specification	No ABS

[2] Not clearly mentioned in the guideline
[3] Not clearly mentioned in the guideline

	Road Surface	Specification	-
	Air resistance	Specification	-
	Deceleration rate	Definition	-
	Deceleration rate	Specification	3.7 m/s^2 (mean breaking deceleration, set to constant)
	Coefficient of friction	Definition	-
	Resulting coefficient of friction	Specification	The coefficient of friction is presented in Table 6.6 as a function of speed.
	Tangential or braking coefficient of friction	Specification	Open roads: 0.4 in case of 6% crossfall, 0.1 in case of 2,5% crossfall slip roads at junctions: 0.5 in case of 6% crossfall, 0.3 in case of 2,5% crossfall 0.25 for crossfall of minus 2.5%
	Radial or side coefficient of friction	Specification	$0.925*f_T$
Perception and Reaction times	perception reaction time	Definition	-
	perception reaction time	Specification	2s
	Braking distance	Definition	-
	Braking distance	Specification	The breaking distance depends on the design speed and the grade (see Table 6.7)
Alignment Conditions	General design principles	Design principle	The design of the road alignment should -result in a balanced horizontal and vertical alignment -guarantee the traffic safety standards for stopping sight distance -adapt to the topography and landscape as much as possible -consider the reality of the urban environment The Stopping Sight distance is the normative SD criterion for motorways. The SSD also guarantees visibility on driving information and the visibility for orientation. For merging lanes the merging sight distance should be provided. If design standards for curves are or cannot be met, it should be proven that SSD requirements are still guaranteed. If no speed limit is prescribed, an advisory speed limit of 130 km/h is be used for checking the SSD requirements
	Crest curves	Design principle	In a straight crest curves the SSD is guaranteed if the diameter of the crest is designed in compliance to the minimum criteria of vertical curves, see Table 6.8. The diameters for sag curves given in this table ensures that the SSD is given under crossing engineering constructions. Else the sight distance should be checked based on Figure 6.8 and equation (17)
	Horizontal curves	Design principle	In none of the seasons the vegetation may block the visibility for the needed sight distance. Maximum height of vegetation within the sight lines is 0.90 m If there are sight blocking elements in the road verge, it should be checked if the SSD is guaranteed with help of Figure 6.6 and Figure 6.7

6.4.2 SSD parameters, figures and equations

6.4.2.1 Coefficient of friction

The coefficient of friction is presented in Table 6.6 as a function of speed.

V [km/h]	fT SRM1990)	µSKM80	fT, RAA
30	0.51	0.52	0.45
40	0.46	0.47	0.41
50	0.41	0.44	0.38
60	0.36	0.41	0.36
70	0.32	0.39	0.34
80	0.29	0.37	0.32
90	0.25	0.35	0.3
100	0.23	0.33	0.29
120	0.19	0.3	0.27
130	0.18	0.29	0.25

Table 6.6 Coefficient of friction (Fgsv, 2008)

f-r (SRM1980)	[-] = tangential adhesion coefficient, measured using SRM (1980)
µSKM80	[-] = skid resistance value measured using the SKM skid resistance measurement procedure at V = 80 km/h (threshold value in accordance with MB Griff)
fT, RAA	[-] = tangential adhesion coefficient, RAA design principles (fT, RAA = 0.877 .µSKMao)

6.4.2.2 Stopping Sight Distance

The stopping sight distance is determined by

$$S_h = S_1 + S_2 \qquad (13)$$

where

S_h	Stopping sight distance [m]
S_1	Reaction time distance [m]
S_2	Braking distance [m]

And

$$S_1 = \frac{V}{3.6} \cdot t_r \qquad (14)$$

where

V	Design speed [km/h]
t_r	Reaction time [s]

And

$$S_2 = \frac{\left(\frac{V}{3.6}\right)^2}{2 \cdot g \cdot \left(f_t + \frac{s}{100\%}\right)} = \frac{\left(\frac{V}{3.6}\right)^2}{2 \cdot \left(a + g \cdot \frac{s}{100\%}\right)} \qquad (15)$$

where

g	Gravity acceleration 9.81 m/s^2
f_t	Tangential friction coefficient
a	Deceleration rate – constant 3.7 m/s^2 (braking without ABS)
s	The grade [%]

The deceleration rate can be determined by equation (16). However, a constant average deceleration rate is used in the determination of the SSD instead.

$$f_t = \frac{a}{g} \qquad (16)$$

where

f_t	Tangential friction coefficient
a	Deceleration rate (braking without ABS)
g	Gravity acceleration 9.81 m/s²

The SSD as a function of the design speed and grade is presented in Table 6.7

V [km/h]	s [%]										
	−5,0	−4,0	−3,0	−2,0	−1,0	0	1,0	2,0	3,0	4,0	5,0
30	27	27	27	27	26	26	26	26	25	25	25
40	41	41	40	40	39	39	38	38	38	37	37
50	58	57	56	55	55	54	53	53	52	51	51
60	77	75	74	73	72	71	70	69	68	67	66
70	98	96	94	93	91	90	89	87	86	85	84
80	121	119	117	115	113	111	109	108	106	105	103
90	147	144	142	139	137	134	132	130	128	126	125
100	176	172	169	166	163	160	157	155	152	150	148
110	207	202	198	194	191	187	184	181	178	175	173
120	240	235	230	225	221	217	213	209	206	202	199
130	275	269	264	258	253	248	244	240	235	232	228

Table 6.7 The SSD as a function of the grade and design speed (Fgsv, 2008)

6.4.2.3 Horizontal curves

The SSD should be determined for the inner lane of the curve, according to Figure 6.5, in which the ‘augpunkt’ is the observation point and the ZPs the different observed points which should be checked.

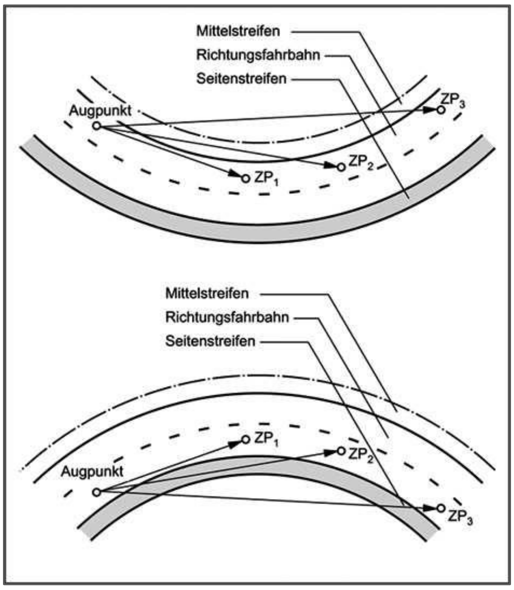


Figure 6.5 Sight distance in horizontal curves (Fgsv, 2008)

Figure 6.6 and Figure 6.7 should be used to determine if the SSD is guaranteed in the curve, taking into consideration possible sight blocking objects (higher than 0.9m) in the road verge.

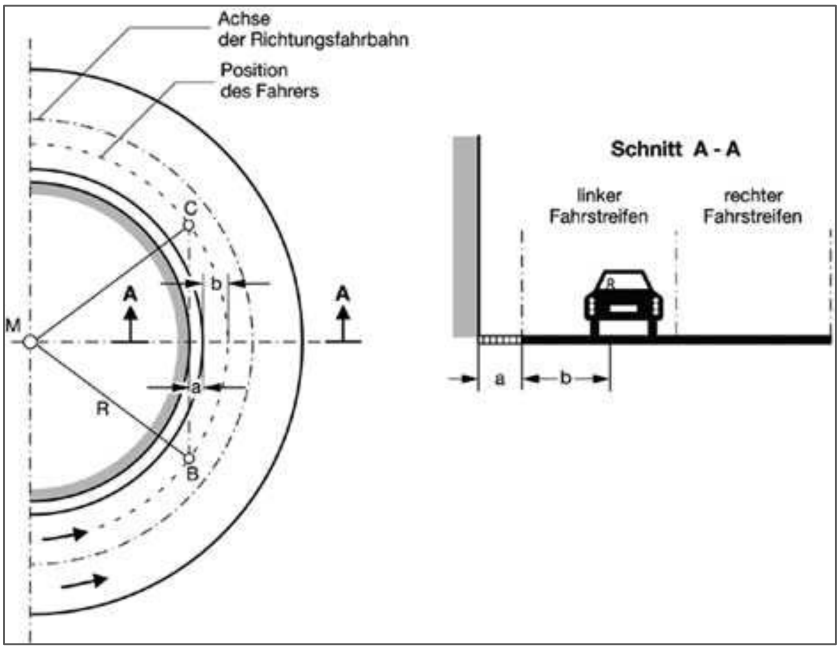


Figure 6.6 Sight distance in horizontal curves - 2 (Fgsv, 2008)

With

B	Observation point
C	Observed point
R	Curve radius
A	Distance from the edge marking to the sight blocking object
b	Distance from the observation point to the edge marking (considered fixed at 1.8m)
S_h	SSD
s	Grade of the road with wet (nasse, up) and dry (trockene, down) conditions

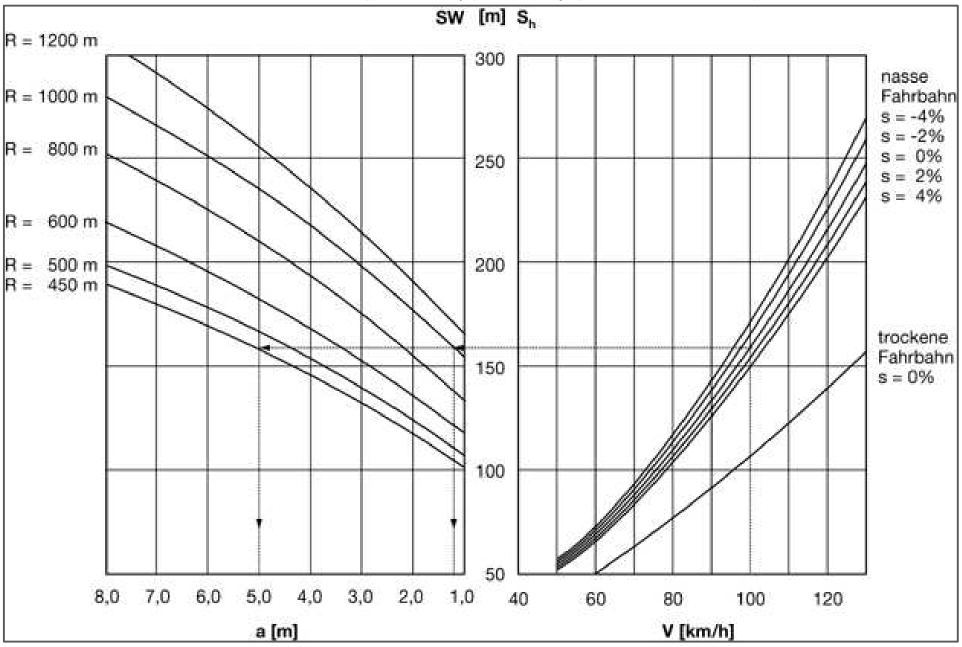


Figure 6.7 Sight distance in horizontal curves - 3 (Fgsv, 2008)

6.4.2.4 Crest curves

The minimum criteria for vertical curves is given by Table 6.8.

Design class	min H_{crest} [m]	min H_{sag} [m]
EKA 1A	13000	8800
EKA 1B	10000	5700
EKA 2	5000	4000
EKA 3	3000	2600

Table 6.8 Minimum vertical curve radius (RAA 2008)

The minimum figures for the vertical crest curves are calculated for an object height of 0.5m. If the curve radius of a straight crest curve does not comply toTable 6.8, the SSD is not guaranteed and should be checked according to Figure 6.8 and equation (17)

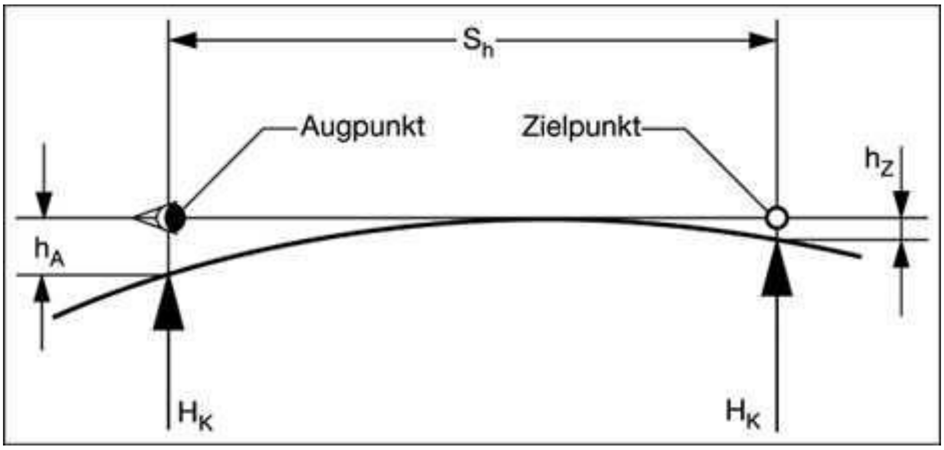


Figure 6.8 Sight distance in crest curves (Fgsv, 2008)

$$min\ H_K = \frac{{S_h}^2}{2\cdot\left(\sqrt[2]{h_A}+\sqrt[2]{h_Z}\right)^2} \qquad (17)$$

With

$min\ H_K$	Minimum curve radius of the crest curve [m]
S_h	Stopping Sight Distance[m]
h_A	Eye height (1.0m) [m]
h_z	Observed height (0.5m) [m]

6.5 Factsheet Ireland

This factsheet describes in brief the definitions, specifications and design principles on the stopping sight distance, as dealt with in the Irish design guidelines on motorways; Design Manual for Roads and Bridges, Volume 6, Section 1, Part 1 Highway Link Design (Nra, 2012) and Guidance on Road Link Design, Volume 6, Section 1, Part 1A (National Roads Authority, 2003).

6.5.1 Definitions, specifications and design principles

Type	Term		Definition
Sight distance types	Sight distance	Definition	-
	Stopping sight distance	Definition	Stopping Sight Distance (SSD) is the theoretical forward sight distance required by a driver in order to stop when faced with an unexpected hazard on the carriageway. It represents the sum of: a) The distance travelled from the time when the driver sees the hazard and realises that it is necessary to stop – the perception distance; b) The distance travelled during the time taken for the driver to apply the brakes – the reaction distance; c) The distance travelled whilst actually slowing down to a stop - the braking distance.
Observation conditions	Observation point	Definition	-
	Observation point position left curve	Specification	-
	Observation point position right curve	Specification	-
	Observed point	Definition	For the lower bound of the visibility envelope, an object height of 0.26m will include the rear tail lights of other vehicles, whilst an upper bound of 2.00m will ensure that a sufficient portion of a vehicle ahead can be seen to identify it as such. A vertical crest curve on a straight alignment designed to provide SSD equivalent to one Design Speed step below Desirable Minimum to the 0.26m object height will automatically provide Desirable SSD to a 1.05m object height (see Section 4.3 (National Roads Authority, 2003)).
	Object	Specification	Rear taillight
	Observed point height crest curve	Specification	0.26 m to 2.00 m above the road surface
	Observed point height sag curve	Specification	0.26 m to 2.00 m above the road surface
	Observed point position left curve	Specification	-
	Observed point position right curve	Specification	-
	Driver Eye Height	Definition	The distribution of eye heights of drivers of private vehicles (TRL, 1979a) shows that drivers eye heights are as much a result of drivers posture as the types of vehicles being driven; 95% of drivers eye heights are above 1.05m, and this value is adopted as the lower extreme of the visibility envelope. The upper bound is assumed to be 2.00m to represent the eye height of a driver of a large vehicle.
	Driver Eye Height Horizontal alignment	Specification	-
	Driver Eye Height Crest curve	Specification	1.05 m to 2.00 m above the road surface
	Driver Eye Height sag curve	Specification	-
	Light conditions	Specification	-

SD braking conditions	Car	Specification	-
	Road Surface	Specification	-
	Air resistance	Specification	-
	Deceleration rate	Definition	The braking distance must be long enough to allow the required degree of friction to develop between the tyres and theroad surface and to avoid excessive discomfort to the driver. Research has shown that the maximum comfortable rate of deceleration is about 0.25g; however, deceleration rates of the order of 0.375g can be achieved in wet conditions on normally textured surfaces without loss of control.
	Deceleration rate	Specification	0,375g
	Coefficient of friction	Definition	-
	Resulting coefficient of friction	Specification	-
	Tangential or braking coefficient of friction	Specification	-
	Radial or side coefficient of friction	Specification	-
Perception and Reaction times	perception reaction time	Definition	The total elapsed time during perception and reaction, under test conditions, is generally in the region of 0.4 – 0.7 seconds. However, drivers may be tired and also subject to a variety of conflicting stimuli such as noise and lights, so that in reality their reaction time will be somewhat more. For safe and comfortable design, a reaction time of 2 seconds has been adopted.
	perception reaction time	Specification	2s
	Braking distance	Definition	-
	Braking distance	Specification	-
Alignment Conditions	General design principles	Design principle	A (desirable) minimum is prescribed for the SSD and horizontal and vertical curvature for different design speeds. If meeting the (desirable) minimum design standards will lead to too much costs or damage to the environment however, designers may choose to design one or more steps below the minimum. Combinations of relaxations are only allowed for few predefined exceptions. Figure 6.9 shows the design standards including the relaxations. - The envelope of visibility is the measurement of the stopping sight distance and is defined by Figure 6.11
	Vertical curves	Design principle	Although the use of permitted vertical curve parameters will normally meet the requirements of visibility, the SSD shall always be checked because the horizontal alignment of the road, presence of crossfall, superelevation or verge treatment and features such as signs and structures adjacent to the carriageway will affect the interaction between vertical curvature and visibility.
	Horizontal curves	Design principle	The radius of the curve and offset of the verge should be checked with Figure 6.10 to ensure that the appropriate SSD is not obstructed by sight blocking objects

6.6.1 SSD parameters, figures and equations

6.6.1.1 Stopping sight distance

The Irish design parameters including the stopping sight distance are presented in Figure 6.9

DESIGN SPEED (km/h)	120	100	85	70	60	50	V^2/R
STOPPING SIGHT DISTANCE m							
Desirable Minimum Stopping Sight Distance	295	215	160	120	90	70	
One Step below Desirable Minimum	215	160	120	90	70	50	
Two Steps below Desirable Minimum	160	120	90	70	50	50	
HORIZONTAL CURVATURE m							
Minimum R+ without elimination of Adverse Camber and Transitions	2880	2040	1440	1020	720	510	5
Minimum R+ with Superelevation of 2.5%	2040	1440	1020	720	510	360	7.07
Minimum R with Superelevation of 3.5%	1440	1020	720	510	360	255*	10
Desirable Minimum R with Superelevation of 5%	1020	720	510	360**	255**	180*	14.14
One Step below Desirable Min R with Superelevation of 7%	720	510	360	255**	180**	127*	20
Two Steps below Desirable Min R with Superelevation of 7%	510	360	255	180**	127**	90*	28.28
Three Steps below Desirable Min R with Superelevation of 7%			180	127**	90**	65*	40
Four Steps below Desirable Min R with Superelevation of 7%			127	90**	65**	44*	56.56
VERTICAL CURVATURE – CREST							
Desirable Minimum Crest K Value	182	100	55	30	17	10	
One Step below Desirable Min Crest K Value	100	55	30	17	10	6.5	
Two Steps below Desirable Min Crest K Value	55	30	17	10	6.5	6.5	
VERTICAL CURVATURE – SAG							
Desirable Minimum Sag K Value	53	37	26	20	13	9	
One Step below Desirable Min Sag K Value	37	26	20	13	9	6.5	
Two Steps below Desirable Min Sag K Value	26	20	13	9	6.5	6.5	
*** Absolute Minimum Vertical Curve Length to be used on Dual Carriageways	240	200	-	-	-	-	
OVERTAKING SIGHT DISTANCES							
Full Overtaking Sight Distance FOSD m.	N/A	580	490	410	345	290	
FOSD Overtaking Crest K Value	N/A	400	285	200	142	100	

Notes

+ Not to be used in the design of single carriageways (see Paragraphs 7.25 to 7.30).

The V2/R values simply represent a convenient means of identifying the relative levels of design parameters, irrespective of Design Speed.

K Value = Desirable Minimum curve length divided by algebraic change of gradient (%). Or Desirable Minimum curve length multiplied by the algebraic change of gradient (%) = K Value See Paragraph 4.5.

* For roads of design speeds 50km/h and less, a maximum superelevation of 3.5% shall apply.

** For roads of design speeds 60 km/h and 70km/h, a maximum superelevation of 5% shall apply.

*** Notwithstanding the minimum vertical curve K values contained in Table 1/3 for dual carriageways the selected K value shall be sufficiently large to ensure compliance with the Absolute Minimum Vertical Curve length indicated.

Table 1/3: Design Speed Related Parameters

Figure 6.9 Design parameters as a function of speed (Nra, 2012)

6.6.1.2 Horizontal curves

It should be checked with Figure 6.10 if any objects block the stopping sight distance. The figure helps checking what offset and radius are in compliance to the desirable minimum SSD or one or two relaxations.

The curve radius is checked for the lane marking (not the edge marking) of the right lane for right hand curves and for the lane marking of the left lane for left hand curves.

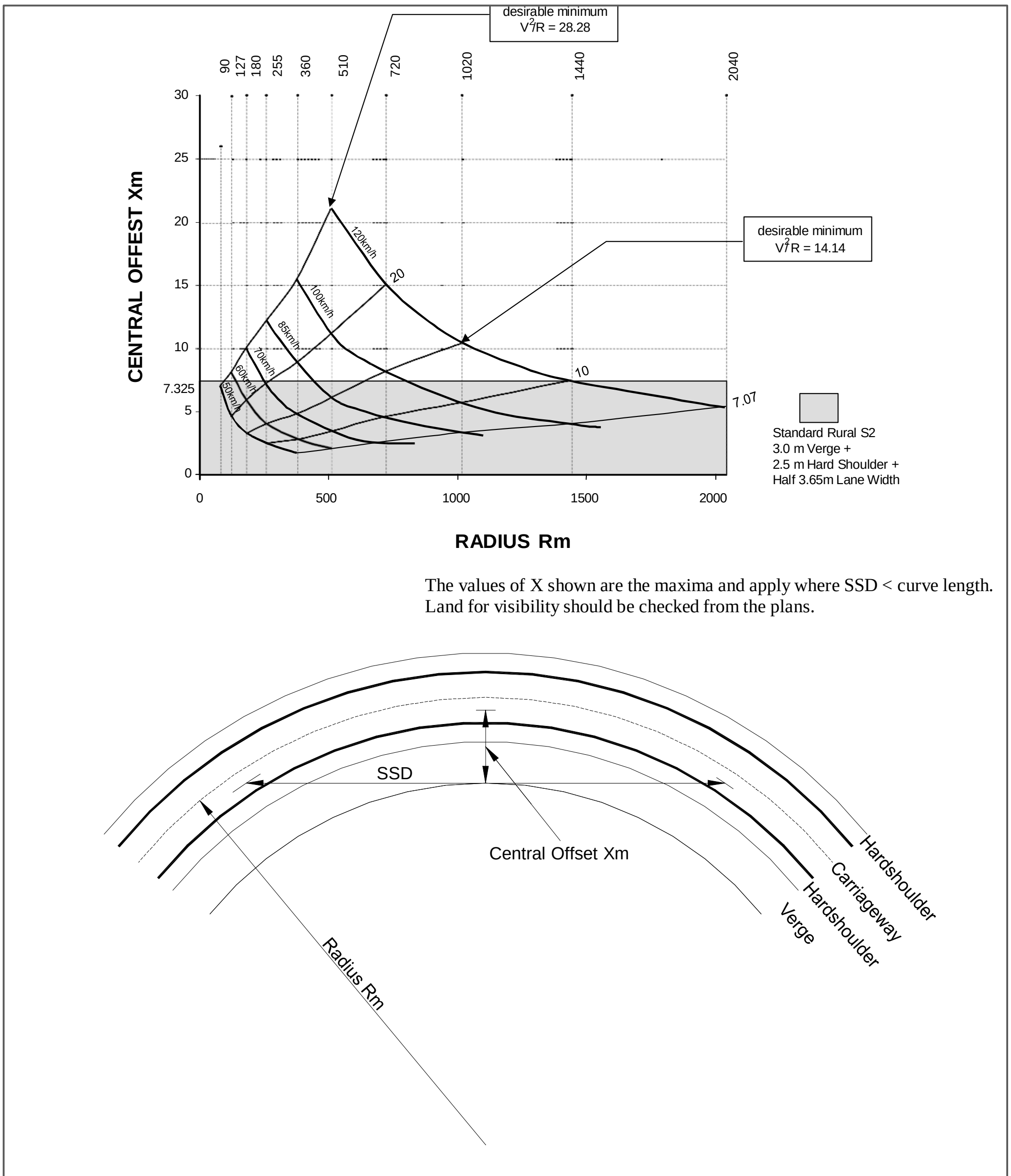


Figure 3/2: Verge Widening for Desirable Minimum Stopping Sight Distance

Figure 6.10 Sight distance in horizontal curves (Nra, 2012)

6.6.1.3 Crest curves

For crest curves the envelope of visibility - is the measurement of the stopping sight distance - should be checked according toFigure 6.11, where the drivers eye height varies between 1.05 and 2.0m and the object height varies between 0.26m and 2.00m.

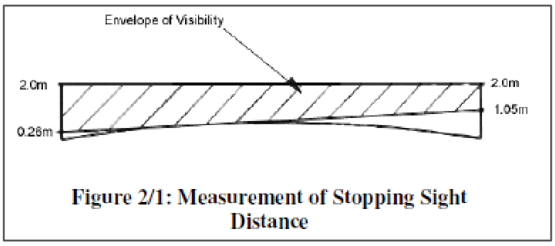


Figure 6.11 Sight distance in crest curves (Nra, 2012)

6.7 Factsheet The Netherlands

This factsheet describes in brief the definitions, specifications and design principles on the stopping sight distance, as dealt with in the Dutch design guidelines on motorways; the Nieuwe Ontwerprichtlijnen Autosnelwegen (Rijkswaterstaat, 2007)

6.7.1 Definitions, specifications and design principles

Type	Term		Definition
Sight distance types	Sight distance	Definition	The distance over which the driver can overlook the road in front of him The distance over which the driver needs to be able to overlook the road in front of him is separately defined as the sight length
	Stopping sight distance	Definition	The sight length on stationary traffic upstream is the distance over which the road user needs to be able to overlook the road to spot a possibly present traffic jam on the carriageway, recogniwe this as such and stop his vehicle on time
Observation conditions	Observation point	Definition	An observation point is the spot of the eye of the driver
	Observation point position left curve	Specification	1.25m outside the left edge marking
	Observation point position right curve	Specification	2.25m outside the right edge marking
	Observed point	Definition	The observed point is the spot where the driver is looking
	Object	Specification	The outer braking light on the inner lane
	Observed point height crest curve	Specification	0.2m (in case of static obstacle) 0.5m (in case of congestion)
	Observed point height sag curve	Specification	-
	Observed point position left curve	Specification	1m outside the edgemarking of the inner lane (not separately specified for left and right curves)
	Observed point position right curve	Specification	1m outside the edgemarking of the inner lane (not separately specified for left and right curves)

	Driver Eye Height	Definition	-
	Driver Eye Height Horizontal alignment	Specification	-
	Driver Eye Height Crest curve	Specification	1.1m
	Driver Eye Height sag curve	Specification	- It is assumed that the design principles for the perspective of the vertical road alignment are normative for sag curves.
	Light conditions	Specification	Daylight
SD braking conditions	Car	Specification	non blocked wheels (86% wheel slip)
	Road Surface	Specification	a wet road surface and some safety factor
	Air resistance	Specification	-
	Deceleration rate	Definition	-
	Deceleration rate	Specification	-
	Coefficient of friction	Definition	-
	(Resulting) coefficient of friction	Specification	-
	Tangential or braking coefficient of friction	Specification	The tangential component of the coefficient of friction is a function of speed presented in Table 6.10
	Radial or side coefficient of friction	Specification	The effect of the reduction of the tangential component of the coefficient of friction by a horizontal curve is assumed negligible
Perception and Reaction times	perception reaction time	Definition	The perception reaction time is the time between perception and action. The perception reaction time differs for individuals and depends strongly on the conditions of the road and surroundings.
	perception reaction time	Specification	The perception reaction time is presented in Table 6.9 as a function of the design speed as it is assumed that the perception reaction time decreases at lower design speeds because of an assumed higher attention level
	Braking distance	Definition	-
	Braking distance	Specification	-
Alignment Conditions	General design principles	Design principle	-
	Crest curves	Design principle	The sight distance is the normative criterium for the dimension of crest curves. Figure 6.13 can be used to check the radius of a crest curve on the sight distance.
	Sag curves	Design principle	It is assumed that the design principles for the perspective of the vertical road alignment are normative for sag curves and not the SSD.
	Horizontal curves	Design principle	Sight blocking elements in the inner curve are called a 'point of interest' in the design of curves. Figure 6.12 can be used to test if the minimal SD is guaranteed.

6.7.2 SSD parameters, figures and equations

6.7.2.1 Stopping sight distance (SSD)

The SSD is to be determined with the help of equation (18) and or Table 6.9. The determination of the SSD is based on the design speed, the perception reaction time, the friction coefficient and the grade of the road.

$$L_{rem} = \left[prt \times \frac{v_0}{3.6}\right] + \left[\left[\frac{v_0}{3.6}\right]^2 \times \left[\frac{1}{2g\left[f_{lg}+\frac{p}{100}\right]}\right]\right] \quad (18)$$

L_{rem}	Total SSD braking distance (including distance traveld in the prt)
prt	perception reaction time [s]
v_0	Design speed [km/h]
g	Gravity acceleration (9.8 m/s^2)
f_{lg}	Average tangential friction coefficient, according to the matching design speed (Table 6.10)
p	Grade, negative at descent [%]

The perception reaction time prt and friction coefficient f_{lg} vary with the different design speeds which can be found in Table 6.9 and Table 6.10.

For a grade of 0%, the total SSD is given in Table 6.9.

Design Speed [km/h]	perception reaction time		braking distance		total sight distance
	[s]	[m]	[s]	[m]	[m]
120	2.5	83	11	177	260
100	2.25	63	8	107	170
80	2	44	6	61	105
50	1.5	20	3	20	60

Table 6.9 Components of the total SSD as a function of speed (Rijkswaterstaat, 2007)

Design Speed [km/h]	50	80	100	120
Friction Coefficient	0.48	0.41	0.36	0.32

Table 6.10 Friction coefficient f_{lg} as function of speed (Rijkswaterstaat, 2007)

6.7.2.2 Horizontal curves

Horizontal curves need to be checked on sight distance requirements. The sight distance in the curve can be determined with the help of Figure 6.12 as presented in the guidelines (NOA).
The curve radius is checked for the lane marking (not the edge marking) of the right lane for right hand curves and for the lane marking of the left lane for left hand curves.

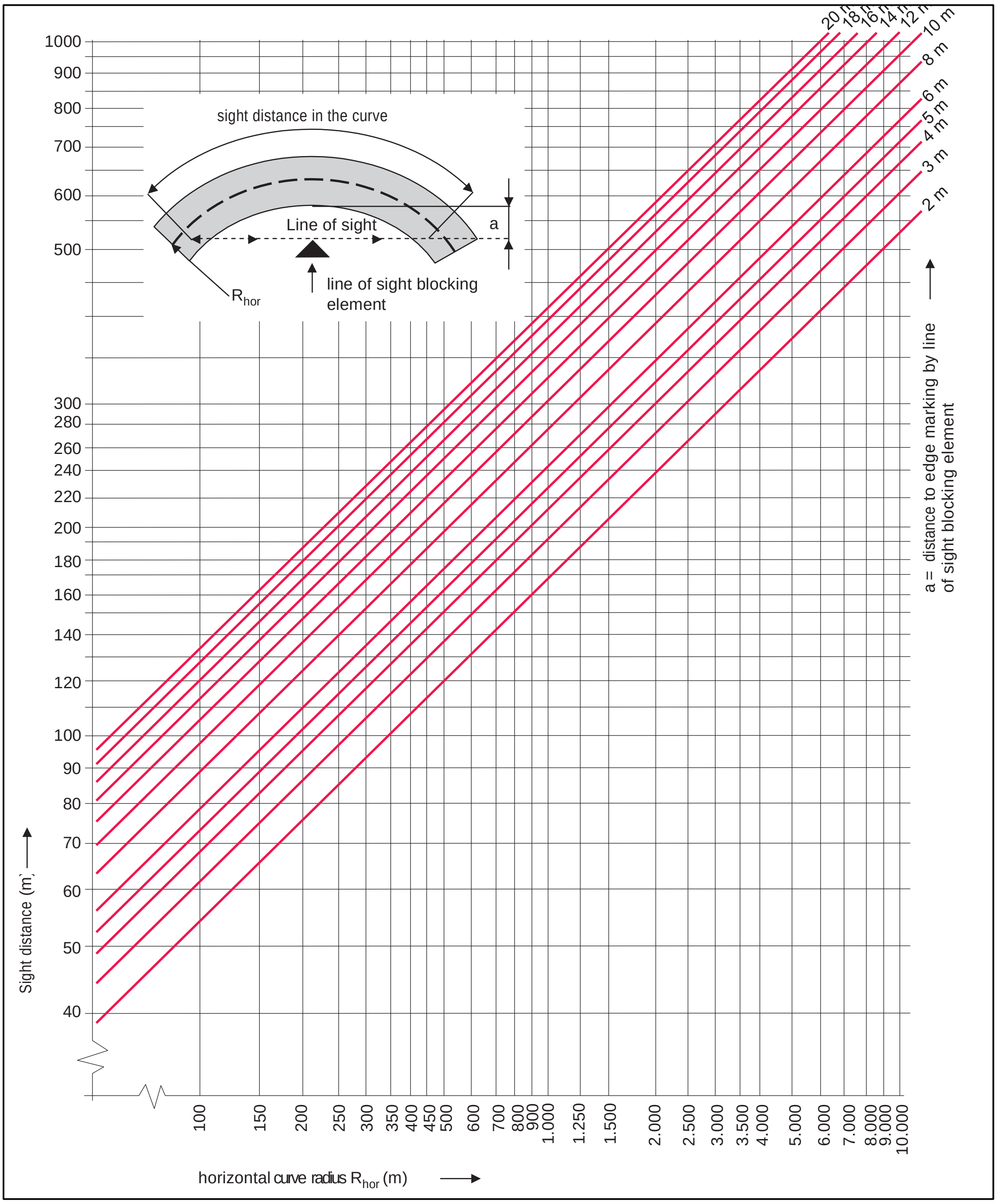
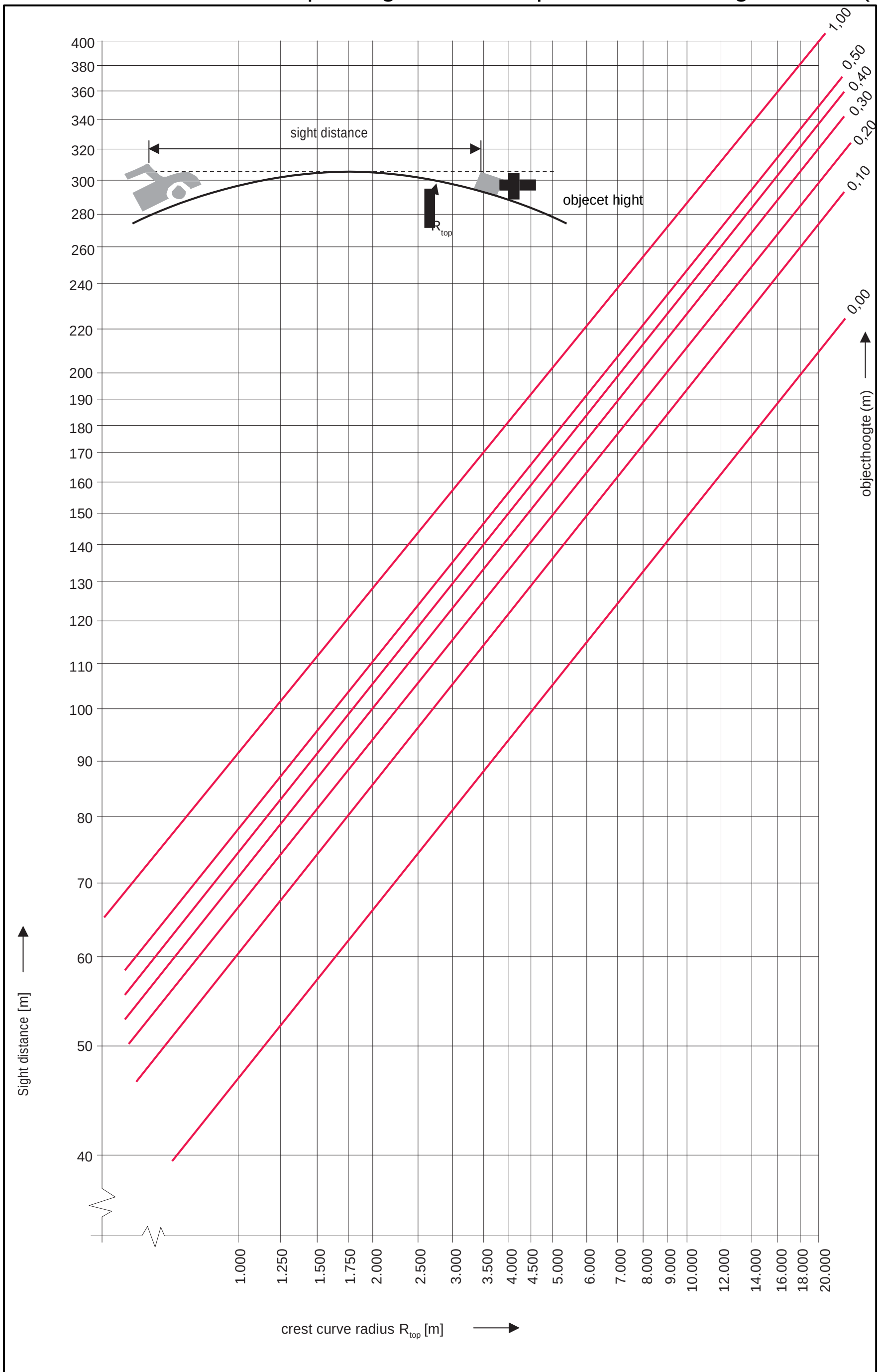


Figure 6.12 Sight distance in horizontal curves (Figure 7-2 from Rijkswaterstaat, 2007)

6.7.2.3 Crest curves

Crest curves need to be checked on sight distance requirements. The sight distance in the curve can be determined with the help of Figure 6.13 as presented in the guidelines (NOA)



Figuur 3-28

Zichtafstanden in verticale bogen (ooghoogte bestuurder = 1,10 meter)

Figure 6.13 Sight distance in crest curves (Figure 3-28 from Rijkswaterstaat, 2007)

6.8 *Factsheet Switzerland*

This factsheet describes in brief the definitions, specifications and design principles on the stopping sight distance, as dealt with in the Swiss design guidelines on motorways; 'Projektierung, Grundlagen : Geschwindigkeit als Projektierungselement - Schweizer Norm SN 640 080b' (Vss, 1991), 'Projektierung, Grundlagen : Sichtweiten - Schweizer Norm SN 640 090b' (Vss, 2001), 'Linienführung : Elemente der horizontalen Linienführung - Schweizer Norm SN 640 100a' (Vss, 1996), 'Linienführung : Elemente der vertikalen Linienführung - Schweizer Norm SN 640 110' (Vss, 1983)

6.8.1 Definitions, specifications and design principles

Type	Term		
Sight distance types	Sight distance	Definition	The free visibility over a road stretch taking into account the alignment, the cross sectional road design and the surroundings of the road. Obstructions of traffic, weather and lighting conditions are ignored in the determination of the sight distance.
	Stopping sight distance	Definition	The minimal distance a car driver needs to be able to see, to be able to stop for an unexpected obstacle. This corresponds to the braking distance.
Observation conditions	Observation point	Definition	-
	Observation point position left curve	Specification	Halfway on the most right lane
	Observation point position right curve	Specification	Halfway on the most left lane
	Observed point	Definition	-
	Object	Specification	-
	Observed point height crest curve	Specification	0.15m
	Observed point height sag curve	Specification	-
	Observed point position left curve	Specification	Halfway on the most right lane
	Observed point position right curve	Specification	Halfway on the most left lane
	Driver Eye Height	Definition	-
	Driver Eye Height Horizontal alignment	Specification	-
	Driver Eye Height Crest curve	Specification	1.0m
	Driver Eye Height sag curve	Specification	2.5m
	Light conditions	Specification	Light conditions are ignored in the consideration of the sight distance
SD braking conditions	Car	Specification	Normal tire profile Car weight 1250 kg
	Road Surface	Specification	Wet and clean

	Air resistance	Specification	The air resistance is based on a coefficient c_w of 0.35 and a sectional area of the car of 2.1m^2 The air resistance can be calculated by equation (21)
	Deceleration rate	Definition	-
	Deceleration rate	Specification	-
	Coefficient of friction	Definition	The coefficient of friction μ is a function of speed and is composed by a radial and a tangential component as shown in equation (19) Figure 6.14
	(Resulting) coefficient of friction	Specification	The coefficient of friction is specified by equation (19)
	Tangential or braking coefficient of friction	Specification	The real tangential component of the coefficient of friction $f_L$is specified by equation (19) The tangential component of the coefficient of friction $f_L$used in the calculation of the SSD is specified as 0.9μ and includes a safety buffer for curves. This f_L is presented in Table 6.11 as a function of speed
	Radial or side coefficient of friction	Specification	The radial component of the coefficient of friction is specified by Figure 6.14
Perception and Reaction times	perception reaction time	Definition	-
	perception reaction time	Specification	2s
	Braking distance	Definition	The braking distance equals the stopping sight distance
	Braking distance	Specification	The braking distance is determined by equation (20) and consists of two parts. The distance travelled during the perception reaction time and the distance travelled during braking
Alignment Conditions	General design principles	Design principle	The SSD should be guaranteed on all roads for safety reasons. When there are valid reasons why the SSD cannot be realised, mitigating measures such as signalling and markings are essential.
	Vertical curves	Design principle	If the normal guidelines on the radius of crest curves cannot be met, the SSD should still be guaranteed. When there are sight blocking elements in a sag curve, it should be proved that the SSD for a truck driver is still guarenteed
	Horizontal curves	Design principle	- A driver adjust his speed to the first visible curve, also when a second curve is visible - The sight distance before a curve needs to be longer than the distance necessary to adjust to a proper speed to take the curve.

6.8.2 SSD parameters, figures and equations

6.8.2.1 Deceleration rate

The deceleration rate is not used in the Swiss guidelines as a separate component. The coefficient of friction is used in determining the SSD.
The coefficient of friction is determined by

$$\mu = \sqrt[2]{{f_L}^2 + {f_R}^2} \tag{19}$$

with

f_L	Tangential component of the Coefficient of friction
f_R	Radial component of the Coefficient of friction
μ	Coefficient of friction

The radial component of the coefficient of friction can be determined by Figure 6.14.

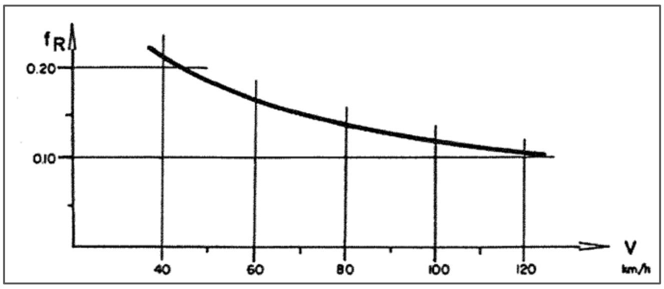


Figure 6.14 Radial component of the coefficient of friction (Vss, 1991)

No determination of the tangential component of the coefficient of friction is presented. The transferable coefficient of friction to the tangential component to braking is assumed to be 0.9 μ and includes a safety buffer for the loss of friction due to curves. The transferable coefficient of friction is presented in Table 6.11 as a function of speed.

	40	60	80	100	120
f_L for Motorways	-	0.49	0.44	0.40	0.36
f_L for other roads	0.48	0.35	0.30	-	-

Table 6.11 The tangential component of the coefficient of friction based on 0.9μ (Vss, 2001) - note that this is not the real f_L from equation (19) but an approximation

6.8.2.2 Stopping Sight Distance

The stopping sight distance is determined by

$$S_A = L_A = \frac{V_p \cdot t}{3.6} + \frac{{V_p}^2}{(3.6)^2 \cdot 2\left[g \cdot \left(f_L \pm \frac{i}{100}\right) + \frac{W_L}{m}\right]} \quad (20)$$

with

$$W_L = 0.0326 \cdot {V_p}^2 \quad (21)$$

and with

V_p	Design speed [km/h]
g	Gravity acceleration 9.81 m/s²
t	Reaction-perception time with t=2 [s]
i	The grade [%]
f_L	Transferable tangential component of the coefficient of friction μ from Table 6.11
W_L	Air-resistance with $[mkg \cdot s^{-2}]$

The SSD for motorways is presented in Figure 6.15 as a function of speed and the grade.

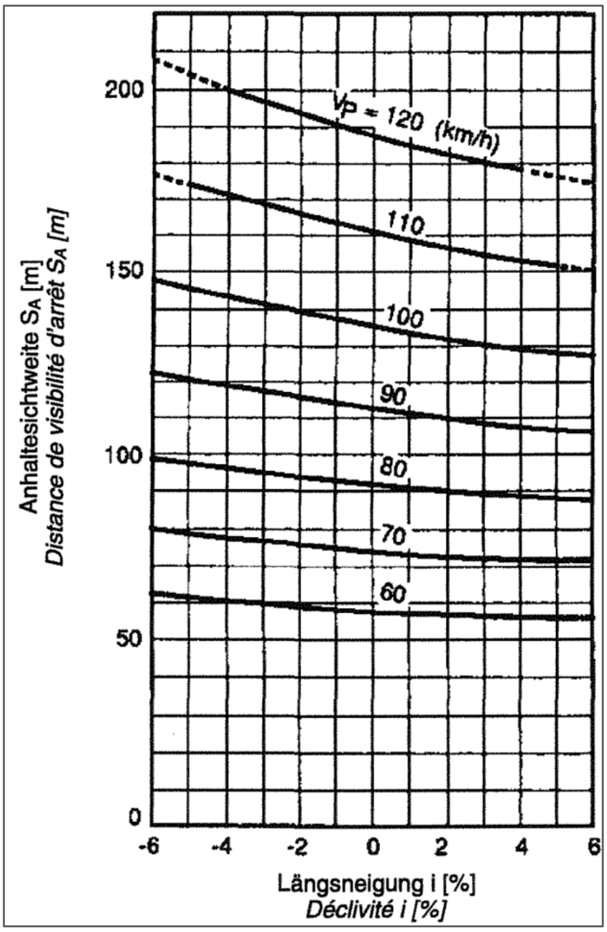


Figure 6.15 Sight distance as a function of speed and the grade (Vss, 2001)

6.8.2.3 Horizontal curves

The SSD should be guaranteed in curves according to Figure 6.16. The SSD should be visually checked.

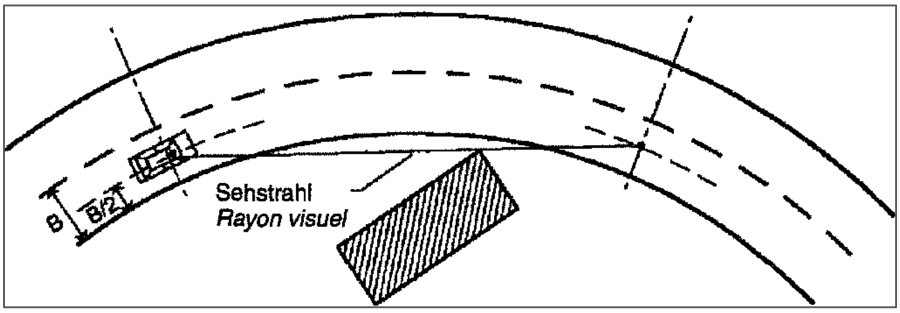


Figure 6.16 Sight distance in horizontal curves (Vss, 2001)

6.8.3 Crest Curves

The SSD in crest curves should be checked according to Figure 6.17.

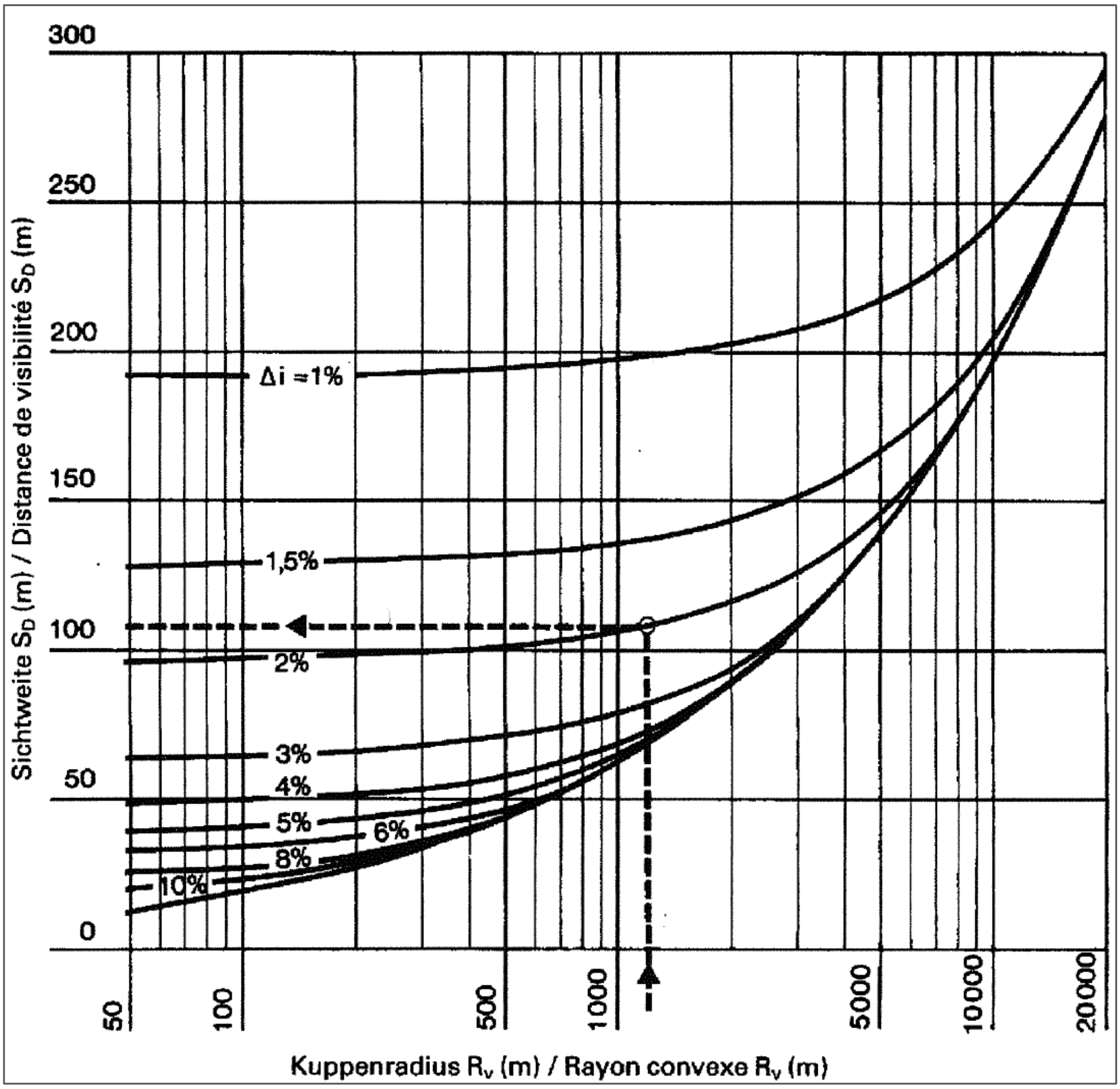


Figure 6.17 Sight distance in crest curves as a function of the curve radius (Vss, 1983)

The sight distance in the crest curve can be determined with help of Figure 6.18 and equations (22) and (23). When the SSD is shorter than the curve length, the SD for the crest curve can be determined with equation (22). When the SSD is longer than the curve length, the SD for the crest curve should be checked with equation (23).

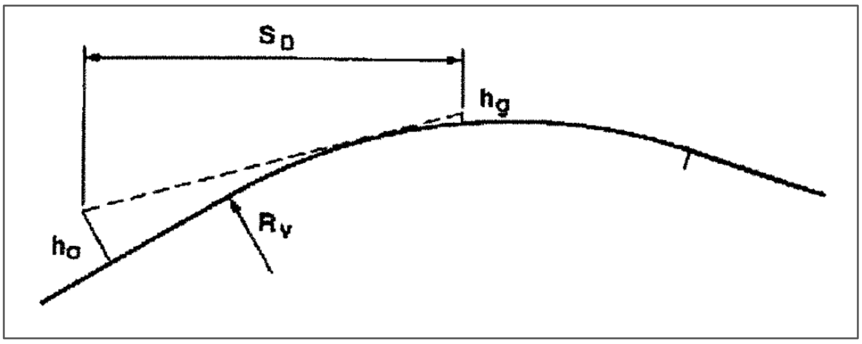


Figure 6.18 Sight distance in crest curves (Vss, 1983)

$$S_D = \sqrt[2]{2R_v}\left(\sqrt[2]{h_o} + \sqrt[2]{h_g}\right) = 1.96\sqrt[2]{R_v} \quad (22)$$

with

S_D	Sight distance
h_o	Eye Height = 1.00m [m]
h_g	Observed Height = 0.15m [m]
R_v	Radius of the crest curve

$$S_D = \frac{h_o + h_g + 2\sqrt[2]{h_o h_g}}{\Delta i} \cdot 100 + \frac{R_v \cdot \Delta i}{200} = \frac{192.5}{\Delta i} + \frac{R_v \cdot \Delta i}{200} \quad (23)$$

With

Δi	Change in grade [%] (see figure x)

and with Figure 6.19displaying Δi

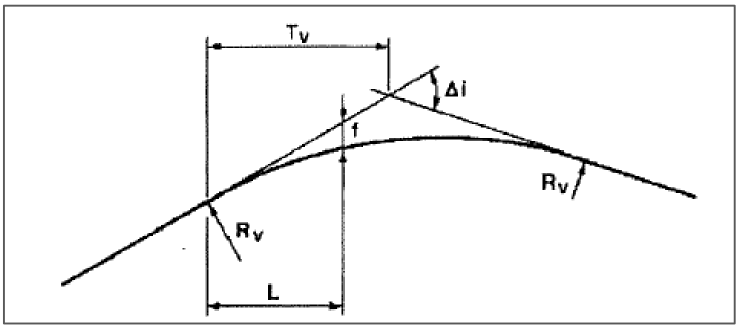


Figure 6.19 Geometrical elements of crest curves (Vss, 1983)

6.8.3.1 Sag Curves

The SSD for trucks should be visually checked when there are sight blocking objects in sag curves.

6.9 Factsheet United Kingdom

This factsheet describes in brief the definitions, specifications and design principles on the stopping sight distance, as dealt with in the design guidelines on motorways from the United Kingdom; Design Manual for Roads and Bridges, Volume 6, Section 1, Part 1 Highway Link Design (Highways Agency, 2002). This section of the Manual is also referenced TD 9/93.

6.9.1 Definitions, specifications and design principles

Type	Term		Definition
Sight distance types	Sight distance	Definition	-
	Stopping sight distance	Definition	-
Observation conditions	Observation point	Definition	-
	Observation point position left curve	Specification	The centre of the inner lane
	Observation point position right curve	Specification	The centre of the inner lane
	Observed point	Definition	-
	Object	Specification	-
	Observed point height crest curve	Specification	0.26m to 2.00m above the road surface
	Observed point height sag curve	Specification	-
	Observed point position left curve	Specification	The centre of the inner lane
	Observed point position right curve	Specification	The centre of the inner lane
	Driver Eye Height	Definition	-
	Driver Eye Height Horizontal alignment	Specification	-
	Driver Eye Height Crest curve	Specification	1.05m to 2.00m above the road surface
	Driver Eye Height sag curve	Specification	-
	Light conditions	Specification	-
SD braking conditions	Car	Specification	-
	Road Surface	Specification	-
	Air resistance	Specification	-
	Deceleration rate	Definition	-
	Deceleration rate	Specification	- 2,45 m/s^2 (6,57 m/s^2 emergency braking)
	Coefficient of friction	Definition	-
	(Resulting) coefficient of friction	Specification	-
	Tangential or braking coefficient of friction	Specification	-

	Radial or side coefficient of friction	Specification	-
Percecption and Reaction times	perception reaction time	Definition	-
	perception reaction time	Specification	- 2s (of which 0,67s reaction time)
	Braking distance	Definition	-
	Braking distance	Specification	-
Alignment Conditions	General design principles	Design principle	- A (desirable) minimum is prescribed for the SSD and horizontal and vertical curvature for different Design Speeds. If meeting the (desirable) minimum design standards will lead to too high costs or damage to the environment however, designers may choose to design one or more steps below the minimum. Combinations of relaxations are only allowed for few predefined exceptions. Table 6.12 shows the design standards including the SSD and SSD relaxations. - The envelope of visibility is the measurement of the stopping sight distance and is defined by Figure 6.21
	Vertical curves	Design principle	Although the use of permitted vertical curve parameters will normally meet the requirements of visibility, the SSD shall always be checked because the horizontal alignment of the road, presence of crossfall, superelevation or verge treatment and features such as signs and structures adjacent to the carriageway will affect the interaction between vertical curvature and visibility.
	Horizontal curves	Design principle	The SSD has to be checked between any two points in the centre of the lane on the inside of the curve for each carriageway Figure 6.20 shows the maximum central offset required for the verge and sight obstructions with varying horizontal curvature, in order to maintain the Design Speed related stopping sight distances

6.9.2 SSD parameters, figures and equations

6.9.2.1 Stopping sight distance

The British design parameters including the stopping sight distance are presented in Table 6.12.

DESIGN SPEED kph	120	100	85	70	60	50	V^2/R
STOPPING SIGHT DISTANCE m							
Desirable Minimum	295	215	160	120	90	70	
One Step below Desirable Minimum	215	160	120	90	70	50	
HORIZONTAL CURVATURE m.							
Minimum R* without elimination of Adverse Camber and Transitions	2880	2040	1440	1020	720	520	5
Minimum R* with Superelevation of 2.5%	2040	1440	1020	720	510	360	7.07
Minimum R* with Superelevation of 3.5%	1440	1020	720	510	360	255	10
Desirable Minimum R with Superelevation of 5%	1020	720	510	360	255	180	14.14
One Step below Desirable Minimum R with Superelevation of 7%	720	510	360	255	180	127	20
Two Steps below Desirable Minimum Radius with Superelevation of 7%	510	360	255	180	127	90	28.28
VERTICAL CURVATURE							
Desirable Minimum* Crest K Value	182	100	55	30	17	10	
One Step below Desirable Min Crest K Value	100	55	30	17	10	6.5	
Absolute Minimum Sag K Value	37	26	20	20	13	9	
OVERTAKING SIGHT DISTANCES							
Full Overtaking Sight Distance FOSD m.	*	580	490	410	345	290	
FOSD Overtaking Crest K Value	*	400	285	200	142	100	

Table 6.12 Design parameters as a function of the design speed (Highways Agency, 2002)

The design speed is different from the speed limit. The relation between the speed limit and design speed is presented in Table 6.13.

SPEED LIMIT		**DESIGN SPEED**
MPH	KPH	KPH
30	48	60B
40	64	70A
50	80	85A
60	96	100A

Table 6.13 The relation between the design speed and the speed limit (Highways Agency, 2002)

6.9.2.2 Horizontal curves

The design should be checked with Figure 6.20 to ensure that there are no objects in the verge that block the stopping sight distance. The Figure helps to check that the offset and radius are in compliance to the desirable minimum SSD, or one or two relaxations of the SSD.

The relation between the curve radius and SSD is checked for the edge marking of the right lane for right hand curves and the edge marking of the left lane for left hand curves.

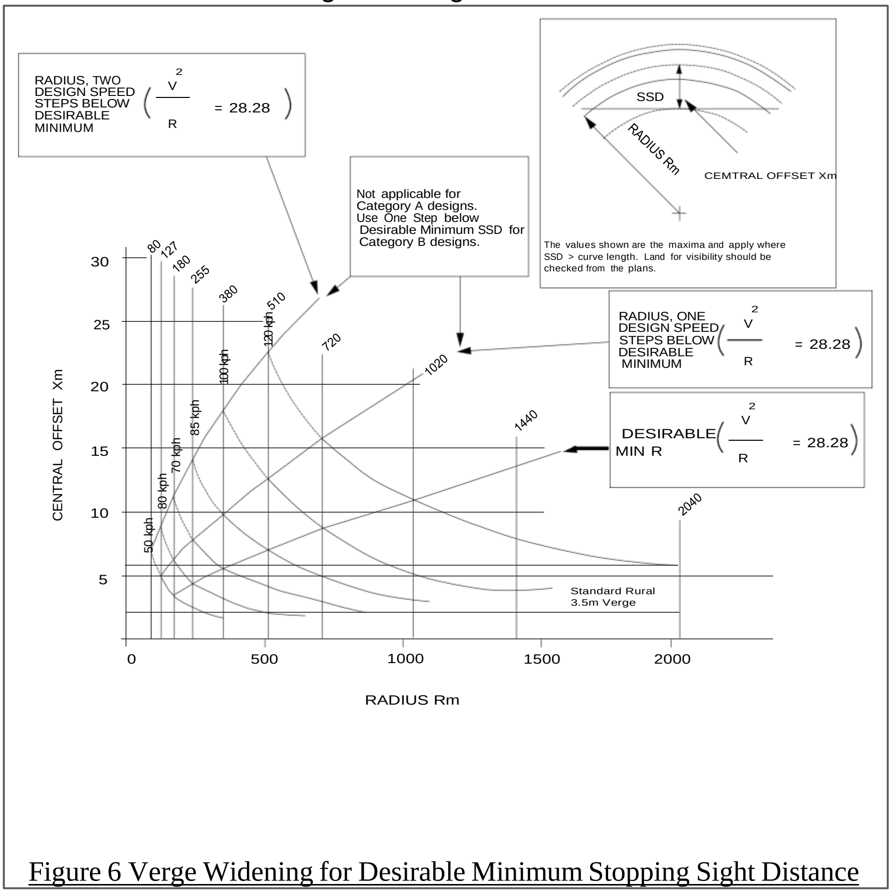


Figure 6.20 Sight distance in horizontal curves (Highways Agency, 2002)

6.9.2.3 Crest curves

For crest curves there should be an unobstructed envelope of visibility as shown inFigure 6.21. The driver's eye height varies between 1.05 and 2.0m and the object height varies between 0.26m and 2.00m. The horizontal distance in this envelope should be the SSD.

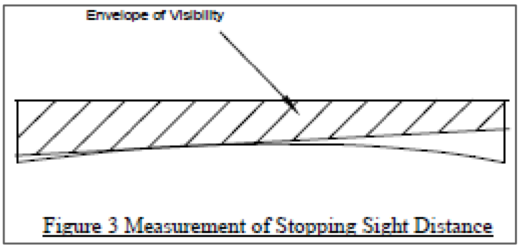


Figure 6.21 Sight distance in crest curves (Highways Agency, 2002)

6.10 Summary of the guideline review

All the design guidelines present the requirements on the SSD for different design speeds, which are generally similar to one another. Safety considerations on the importance of the SSD are often very compact and no information is provided on the quantitative safety effects of the SSD. Furthermore almost none of the design guidelines present references to the SSD requirements.

Most of the guidelines present some of the road, vehicle and or driver characteristics related to the SSD. The amount of detail however varies, with the UK and Ireland being the most minimalistic in this regard by only providing the SSD requirements.

The approach on meeting the SSD requirements also differs between countries. Various countries emphasize for instance taking the SSD requirements into consideration at an early stage in the design of the alignment. This should enable the alignment to meet the SSD requirements better without having to take extensive measures like extensive earth movements to be able to meet the SSD requirements and would minimise damage to the environment. Several guidelines give room for not meeting the SSD requirements when necessary measures would be too disproportionate. The Irish and the UK design guidelines are however the only guidelines which provide (preferred) minimum SSD requirements, with the possibility of two steps of relaxations of these requirements. Relaxations for other design characteristics like curve radii are also possible, but combinations of relaxations are not allowed, as it is not allowed to go below the possible 2 steps of relaxation.

Table 6.14 to Table 6.16 provide a summarised comparison between countries of the SSD requirements, braking coefficients and driver/object height values. From these tables it is evident that there is some amount of variation on SSD characteristics among these countries. But it can also be seen that most of these differences are small.

Country	Perception – Reaction time [s]	Stopping Sight Distance (SSD) [m]								
		50 km/h	60 km/h	70 km/h	80 km/h	90 km/h	100 km/h	110 km/h	120 km/h	130 km/h
Denmark	2	54	71	90	111	134	160	187	217	248
France	2	50		85		130		195		280
Germany	2	54	71	90	111	134	160	187	217	248
Ireland	2	70 50 50	90 70 50	120 90 70	160 120 90		215 160 120		295 215 160	
The Netherlands	Variable by design speed	60 (1.5s)			105 (2s)		170 (2.25s)		260 (2.5s)	
Switzerland	2		62		100		147		208	
United Kingdom (85 km/h instead of 80 km/h)	2	70 50	90 70	120 90	160 120		215 160		295 215	

Table 6.14 Stopping Sight Distance and perception reaction times per country

From Table 6.14 it can be seen that most countries prescribe a fixed perception reaction times of 2 seconds. The Dutch guidelines deviate from other countries by prescribing different PRTs for different design speeds. Looking at the SSDs it can also be seen that the differences between the SSDs for most countries are small, except for Ireland and the UK where the preferred SSD requirements are about one third higher than for the other countries. Overall though there is a consensus about what the SSD requirements are. Taking into account that the oldest guidelines from this selection are the Swiss guidelines which are dated at 1983, it can be concluded that these requirements have not changed much over time.

The design guidelines in Ireland follow for the most part the UK design guidelines. Both countries recommend higher minimum SSDs than other countries. However the Irish and UK guidelines provide road designers with two steps of relaxations of the SSD. One step down resulting in equal SSDs compared to other European countries and two steps down being considerably smaller than the minimum SSDs from other countries. As the guidelines do not provide a background on the SSD design values, the differences cannot be explained based on these guidelines.

Country	tangential or braking coefficient of friction								
	50 km/h	60 km/h	70 km/h	80 km/h	90 km/h	100 km/h	110 km/h	120 km/h	130 km/h
Denmark: straights (up) and horizontal curves (down)	0.377 0.33	0.377 0.34	0.377 0.35	0.377 0.35	0.377 0.36	0.377 0.36	0.377 0.36	0.377 0.37	0.377 0.37
France	0.46		0.44		0.40		0.36		0.32
Germany	0.377	0.377	0.377	0.377	0.377	0.377	0.377	0.377	0.377
Ireland	-	-	-	-	-	-	-	-	-
The Netherlands	0.48			0.41		0.36		0.32	
Switzerland: motorways (up) and other roads (down)		0.49 0.35		0.44 0.30		0.40		0.36	
United Kingdom (85 km/h instead 80 km/h)	-	-	-	-	-	-	-	-	-

Table 6.15 Tangential or braking coefficient of friction per country

There are some differences in the way the different countries account for the tangential or braking coefficient of friction. The Danish and Swiss guidelines take a loss of the tangential component of friction into account due to curves. The Danish differentiate however between straigths and curves, while the Swiss present a conservative approach accounting 90% of the tangential component of friction for all road sections including straights.
The Dutch and the French guidelines both prescribe a tangential component of friction as a function of speed and are very similar. The Dutch guidelines consider the effects of curves on the SSD to be negligible while the German guidelines prescribe a fixed value for all design speeds. The Danish guidelines prescribe the same value for straitghts, referring to German underlying research on the SSD.

The design guidelines from Ireland and the UK only provide the design values on the SSD. They lack information on SSD parameters, which is why no information on the UK and Ireland is provided in Table 6.15 and Table 6.16.

Country	*Driver eye height (observation point height)*			Observed point height (object height)		
	flat	*Crest curve*	*Sag curve*	flat	Crest curve	Sag curve
Denmark	*1.0m*	*1.0m*	*2.5m*	-	0.5m	0.5m
France	-	*1.0m*	-	-	0.6m	-
Germany	-	*1.0m*	-	-	0.5m	-
Ireland	-	*1.05m-2.00m*	-	-	0.26m-2.00m	-
The Netherlands	*1.1m*	*1.1m*	-	0.5m	0.2m 0.5m	-
Switzerland		*1.0m*	*2.5m*		0.15m	
United Kingdom	-	*1.05m-2.00m*	-	-	0.26m-2.00m	-

Table 6.16 Driver eye height and observed eye height per country, differentiated by vertical alignment characteristics

Most countries take the driver eye height into account when checking the SSD in crest curves. No separate driver eye heights are mentioned for flat roads, where the driver eye height can be considered equal to the driver eye height in curves.
Denmark and Switzerland specifically take the driver eye height of truck drivers into account at sag curves where tunnels or other vertical elements can block the view of view of truck drivers. Ireland and the UK also take this situation into account, prescribing a check on the envelope of visibility from a driver eye height of 1.05m to 2.00m.

Further differences can be found in the way that road designers are prescribed to check the SSD for horizontal and vertical curves. Most of the guidelines provide designers with graphs and or formulas to check the SSD in curves. The combinations used formulas and figures can differ however. Some also mention the checking of the alignment as a whole, taking changes in the horizontal and vertical alignment together into consideration. No tools or methods to do so are however considered or prescribed.

7 Conclusion

The main goals of work package 2 were to;

- review the latest insights on sight distance (SD) and identifying important changes in driver, vehicle, and road characteristics related to stopping sight distance,
- review the design guidelines on sight distance and stopping sight distance (SSD) of a selection of EU member states and identifying similarities and differences between those countries on SSD characteristics,

The literature study started with the intention to focus on recent articles and reports. This revealed that much of the recent Human Factors meta studies are founded on often decades old studies.

Many studies are available on PRT. Obviously, there are differences in PRT between and within drivers. Hence, PRT is characterised by a distribution rather than by a constant value. For SSD, the common approach is to use a percentiles of the PRT distribution. But *which* percentile should be used for SSD calculations does not follow from the literature review. Ultimately, this is a trade-off between safety and comfort on the one hand and cost/space travel time and adaptation to landscape on the other. However, there may be reason to believe that a requirement for designing with PRT values of 2 to 2.5 seconds might be conservative. Many of the studies reveal 85th percentile values of below 2 seconds and mean values as low as 1,25s. Considering that in many of these studies drivers were subjected to conditions involving more complex driving situations, PRT values measured were lower than the general 2s value adopted in most guidelines for calculating SSD. However, tests among elderly drivers do not reveal a clear picture although the indication is that the PRT of elderly drivers is generally longer than that of younger drivers. Given the ageing European population, special consideration should be given to elderly drivers before PRT values in design guidelines are reduced.

Compared to PRT, the amount of information on braking behaviour is not so abundant. Reported values are often in the range of 3.4 to 5 m/s^2, although in some circumstances higher levels are reached.

There are several developments that potentially have a large impact on SSD. In terms of driver assistance systems. ABS is standard in new vehicles today; the other systems like Predictive Assist Braking are typically optional or still under development. The effects of these newer systems on driving behaviour (especially deceleration behaviour) is not well documented. There is a potential for ‘better’ braking behaviour when those are implemented: brake assist and similar systems can help improve the response time of the vehicle and of the brake performance of the driver-vehicle system. It can be expected that more of these systems will become available over the coming years. Still, for the years to come, SSD criteria have to be based on a vehicle fleet containing vehicles *without* such systems.

In terms of eye height, the overall effect is unclear from what has been revealed by the literature. On the one hand, cars are getting lower; on the other hand, there is an increase of larger vehicle types (SUV types).

The classical road condition used in SSD calculations is a wet surface. As a consequence, the road friction should be considered as a function of speed and of water depth, because for a wet surface the friction is speed dependent. Further, at higher speeds, the friction coefficient is a function of the tyre tread depth. The existing surface types (concrete / dense asphalt / porous asphalt) are characterised by different micro and macro structures and by different water draining characteristics, accumulating to different friction coefficients in rain.

These characteristics should be taken into account when choosing SSD parameters later on in the project.

Chapter 6 provides an overview on the SSD design requirements for different countries. The SSD requirements are very similar for most countries except the for the UK and Ireland, where the preferred SSD requirements are about one third higher than for the other countries. And while the guidelines differ somewhat for the considered details on driver, vehicle and road characteristics, the differences are most often small when they are considered.

Considering the small differences between the SSD requirements it can be concluded that there is a wide spread consensus on the SSD requirements between the country design guidelines. And as the oldest guidelines of the selection is dated in 1983, it can be concluded that the requirements have not changed much over time.

From both the literature review and the country comparisons it is evident that the criteria used for determining SSD and SD, and consequently SD and SSD themselves, have not changed significantly over time. However, indications are that cars are becoming marginally bigger giving drivers a higher view of the road. At the same time vehicles are becoming smarter and able to decelerate faster than older vehicles. This suggest that SSD and SD will in time become smaller affording designers the opportunity to compromise on horizontal and vertical alignment without negatively affecting safety. However, given the present mix of vehicles and drivers, and given the road surface and weather conditions, it is more appropriate to continue using the same criteria for calculating SSD as has been done in the past. This will ensure that new designs accommodate both older vehicles and drivers whilst providing extra safety margins for new technology and vehicles.

The study has revealed that there is a need to quantify the relevance of current PRT and braking/deceleration rates adopted in EU guidelines. Also important for SSD calculation is a standard definition for the object and the dimensions of the object. There is currently little or no empirical evidence supporting the choice and size of such object. The EUSight project should further investigate the properties of the object and develop a standard definition for use in EU countries. The same applies to developing standard values for PRT and deceleration rates to be used in calculating SSD.

8 Acknowledgement

The research presented in this report/paper/deliverable was carried out as part of the CEDR Transnational Road Research Programme Call 2013. The funding for the research was provided by the national road administrations of Netherlands, Germany and Ireland.

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