CEDR Transnational Road Research Programme
Call 2013: Safety

funded by the Netherlands, Germany, UK and Ireland

European Sight Distances in perspective – EUSight

Scenario Report
Deliverable No D3.1
May 2015

Arcadis, Netherlands

SWOV, Netherlands

TRL, UK

TNO, Netherlands

Prof. Weber, Germany

Hochschule Darmstadt, University of applied sciences
CEDR Call 2013: Safety
EUSight
European Sight Distances in perspective

Scenario report

Due date of deliverable: 31.10.2014
Actual submission date: 5.2.2015
Revised final submission: 31.5.2015

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

Author(s) this deliverable:
Arjan Stuiver (TNO)
Jeroen Hogema (TNO)
Patrick Broeren (Arcadis)
Govert Schermers (SWOV)
John Barrell (TRL)
Roland Weber

PEB Project Manager: Gerald Uitenbogerd

Version: 1.0
Table of contents

Executive summary ............................................................................................................. 5
List of definitions ............................................................................................................... 6
1 Introduction ....................................................................................................................... 7
   Choices ................................................................................................................................. 8
2 Structuring parameters .................................................................................................... 9
   2.1 Situations ......................................................................................................................... 10
      2.1.1 Horizontal curves ...................................................................................................... 10
      2.1.2 Vertical crest curves .................................................................................................. 15
      2.1.3 Vertical sag curves .................................................................................................... 19
      2.1.4 Combinations of horizontal and vertical curves ....................................................... 21
   2.2 Relation among parameters ......................................................................................... 22
      2.2.1 Horizontal sight distance .......................................................................................... 23
      2.2.2 Vertical sight distance .............................................................................................. 23
      2.2.3 Perception-Reaction time ......................................................................................... 24
      2.2.4 Brake time ................................................................................................................. 24
3 Parameters ......................................................................................................................... 25
   3.1 Lane width ....................................................................................................................... 25
   3.2 Shoulder, verge and side slope ..................................................................................... 26
   3.3 Lateral position driver .................................................................................................... 28
   3.4 Object ............................................................................................................................... 29
   3.5 Driver eye height ............................................................................................................ 31
   3.6 Brake performance ......................................................................................................... 32
   3.7 Road friction ................................................................................................................... 33
      3.7.1 Road surface .............................................................................................................. 33
      3.7.2 Road condition .......................................................................................................... 34
   3.8 Situational complexity .................................................................................................. 36
      3.8.1 Traffic conditions ...................................................................................................... 36
      3.8.2 Constructions ............................................................................................................. 37
      3.8.3 Road configuration ..................................................................................................... 38
   3.9 Gradient .......................................................................................................................... 39
   3.10 Tyre ............................................................................................................................... 39
4 Conclusions ....................................................................................................................... 40
5 Acknowledgement ............................................................................................................. 41
6 References ......................................................................................................................... 42

List of figures

Figure 1: Horizontal curves .................................................................................................. 10
Figure 2: Horizontal curve with guardrail ................................................................江 ................................. 13
Figure 3: Horizontal curve in tunnel (inner lane) ................................................................. 14
Figure 4: Horizontal curve in tunnel (outer lane) ................................................................. 14
Figure 5: Horizontal curve on a highway ............................................................................. 15
Figure 6: Vertical crest curve on a highway ........................................................................ 15
Figure 7: Vertical crest curve on a highway ........................................................................ 16
Figure 8: Stationary car on a crest curve ............................................................................. 18
Figure 9: Stationary car on a crest vertical curve ............................................................... 18
Figure 10: Vertical sag curve schema, e.g. tunnel ............................................................... 20
Figure 11: Vertical sag curve in a tunnel ............................................................................. 20
Figure 12: Combination of horizontal and vertical sag curve ............................................. 21
Figure 13: Relations among SD and SSD parameters; parameters with white background are under direct influence of road design; parameters with grey background are not .................................................................22
Figure 14: Schematic representation of a cross section .........................................................27
Figure 15: Summary of range of parameters .................................................................41
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 of divided highways or motorway situations, 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 obstacles 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 3 of the EUSight project. Using the results of the literature review carried out in WP2, a qualitative framework is defined, covering the most important parameters. This framework takes into account all relations between the parameters as well as the different internal and external conditions related to SDD. The framework will be used in the parameter study (WP4) and in the selection of representative parameter values (WP6) to determine the prevalent conditions for SSD and SD. Since there are too many different combinations of conditions possible, we identify best case, worst case and guideline cases for consideration (instead of defining scenarios).
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 reduce speed or to stop while approaching an intersection; 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) among EU Member States. This research considers stopping sight distance from different (related) approaches: human factors ('the driver'), road characteristics, vehicle characteristics and environmental conditions (like wet, snow, ice, dark). Since SSD is related to many different aspects, multiple approaches and methodologies are needed to determine state-of-the-art parameter values.

For determination of the final recommendations for representative values for SSD parameters it is necessary to study the parameters and their relation with each other. This report describes the result of Work Package 3 of the EUSight project. It builds on the literature review that was conducted in WP2 (Van Petegem et al., 2014). In WP3 the parameters and relationships between these parameters are defined.

To develop a well-founded new European guideline for SSD, it is necessary to establish a (possibly situation-dependent) value for each parameter involved. Ultimately this comes down to a trade-off between traffic safety and costs:

- using (too) conservative choices for all parameters can yield an over-dimensional design, where costs become excessive in relation to safety;
- using (too) liberal choice for all parameters can yield an under dimensioned design, where the workload for drivers is temporarily too high, thus leading to unsafe situations.

This deliverable will present a structure that has been developed to show how the various SSD parameters are linked. For each SSD parameter, a range of possible value was identified, ranging from worst case to best case situations. Additionally, the most common values currently used in guidelines have been identified from WP2 (Van Petegem et al., 2014). The (qualitative) relationships are discussed between (1) each parameter on the one hand, and (2) driver behaviour, workload, costs, and safety on the other.

The resulting structure and parameter overview will serve as the starting point for WP4, that deals with quantitative distributions of parameter values on the road.
Choices

The project is restricted to divided highways or motorway situations only. Further, when considering multiple-lane curves, only the inner (most critical) lane will be considered.

Speed is of influence on SSD, both through perception reaction distance and through brake distance. With higher design speed, SSD increases (more than linearly). A basic question is which characteristic of speed to use in the SSD calculations. In line with the most common approach in existing guidelines (Van Petegem et al., 2014), the design speed will be used in this project.
2 Structuring parameters

The parameters related to SSD can be structured according to a few principles. Firstly, we discern different situations: a distinction can be made between parameters related to stopping sight distance and available sight distance.

Situations: This refers to the spatial road situations in which the design has to offer enough sight distance (horizontal curve, vertical crest curve or vertical sag curve). The road designer has limited influence on whether a road has to make a curve to left, a curve to the right, a crest curve or a sag curve. These are a starting point of the project (building a road in a curve). The characteristics or aspects of the curve (including design speed) are for a large part under control of the road designer.

For every situation a further division can be made in:

Sight Distance (SD): These are parameters related to how far away the driver can see as potential hazard. Parameters of relevance are obstacle height and width, curve radius and lane width, eye height and eye position.

Stopping Sight Distance (SSD): the distance required for the driver to bring the vehicle to standstill. This depends on two separate factors:

- Perception reaction time (PRT): PRT is the time it takes for the driver to perceive an obstacle and to initiate an appropriate action to deal with its presence. PRT depends on how fast the obstacle is recognised and how much time the driver needs to initiate the brake after identifying the obstacle as hazardous. The driver will need some time to see the obstacle directly after the first moment the obstacle is visible. After that the driver will need some time to process the information and react (by lifting the foot off the accelerator and depressing the brake). Given the PRT and the (design) speed the total distance PRT contributes to the SSD can be calculated.

- Braking time (BT): This relates to the time needed to bring the vehicle to a total standstill after initiating the brake. This depends mainly on road and vehicle characteristics. Maximum deceleration can be calculated from road aspects, such as type of road surface, road surface condition, gradient and type and of vehicle aspects (condition of tyres on the vehicles, vehicle braking performance and state).

In the following sections this structuring by PRT and BT is used to explain further the aspects relevant in the different situations, ordered by SD and SSD. In Section 3 the relation between the parameters are described in more detail for each parameter.
2.1 Situations

We discern three major situations: horizontal curves, crest vertical curves and sag vertical curves. In this section these situations are explained further and illustrated.

2.1.1 Horizontal curves

Horizontal curves (left/right) with restricted view in the shoulder of the inner arc (guardrail, barrier, wall, vegetation, etc.). The inner lane (in relation to the direction of the curve), is where the view is restricted, and is always normative.

Sight distance in horizontal curves can be limited by objects in the verge of the road or the median (for a left hand bend when driving on the right). Potential objects limiting sight distance are:

- vehicle restraint systems (guardrail or crash barrier),
- walls of a tunnel,
- vegetation (trees and bushes),
- noise barriers,
- steep slopes.

The severity of the sight limitation depends on the distance to the inner marking of the lane and the height of the obstacle. This principle is illustrated in Figure 1.

![Figure 1: Horizontal curves](image)

**Sight distance**

The horizontal curve radius, lane width, obstacle height and width, shoulder width, lateral position of the driver and lateral position of the obstacle are all relevant for sight distance in the horizontal curve situation. Restriction of view is caused by objects on the edge of the carriageway/road (e.g. guardrail, wall or trees), around which the driver cannot see. A larger curve radius means a larger sight distance, since the road will be more like a straight road and the objects will restrict the view less. Road elements adjacent to the lane (shoulder, verge and side slope) are of relevance here. Curve radius, guard rail and walls are to a certain degree under the control of the road
designer. A major design issue is how quickly vegetation grows and what the maintenance regime should be.

*Stopping sight distance*

Perception time is influenced by the visibility of the obstacle, which is depending on lighting conditions that may change in different weather conditions or time of day, but also depends on obstacle characteristics, such as colour, size, luminosity and contrast with the environment. Other aspects such as complexity of the infrastructure, the traffic situation, signing, junction complexity and advertising along the road influence the complexity of the driving task, the amount of distraction and potential overload from the environment. The sum of the complexity of the driving task, distraction and overload determines the amount of time a driver needs to identify an obstacle. Reaction time can be augmented by some types of Advanced Driver Assistance Systems (ADAS), for example Volkswagen’s City Emergence Brake detects obstacles on the road and brakes automatically or Mercedes’s Night Vision which makes it easier to detect and classify obstacles in darkness or poor weather.

Braking time in the horizontal curve situation is determined by road surface, road condition, tyres and their condition and (design) speed. A horizontal curve with a significant gradient becomes a combination of horizontal and vertical curve. For these combinations see section 2.1.4. The available longitudinal friction (for braking) is influenced by the lateral friction that is used to steer the vehicle along the road (without skidding). Driver assistance systems can influence the braking time, e.g. by pre-tensioning the brake, assisting to maximum brake force in case of an emergency, Anti-lock Braking Systems (ABS), etc.

*Driving behaviour*

Obviously, smaller curve radii result in a larger required steering wheel angle for a given speed and a given vehicle. If speed remains constant, smaller curve radii yield higher lateral accelerations. In curves with a small radius, drivers reduce their speed: the smaller the curve radius, the lower the speed (Van Winsum & Godthelp, 1996). Failure of drivers to perceive curve radius and to appropriately adjust their speed may have safety consequences. Horizontal curves with low radii lead to road safety problems: the related risk rates increase significantly for radii < 200 m (Raff, 1953). Campbell et al. (2012) observed that speed selection by drivers on horizontal curves depends on several factors, such as vehicle, driver and road. As an example they mention previous research that showed how drivers with larger engines and/or greater acceleration capacity approach curves differently from other drivers (e.g. Bald, 1987). Middle-aged and experienced drivers judge perceived speed less accurately than younger and inexperienced drivers in curves (Milosevic & Milic, 1990). A review of vehicle speed distributions and speed variation shows that the pattern of speeds in curves is highly dependent on the level of curvature, an effect that was even stronger for curves with radii under 250m (Mintsis, 1998). Campbell et al. further noted that while curvature may not be the only factor determining speed in curves (Andjus & Maletin, 1998), it may be the most important factor (Bird & Hashim, 2005).
In Transportation Research Circular 414, the factors that are stated to determine crash frequency in horizontal curves include higher traffic volume, sharper curvature, greater central angle, lack of a transition curve, a narrower roadway, more hazardous roadway conditions, less stopping distance, steep grade, long distance since last curve, lower road friction and lack of proper signs and delineation (Transportation Research Board, 1993).

Speed reduction as curve radii become smaller does not yield constant lateral acceleration. Many studies have shown that as speed increases, lower lateral acceleration peak levels are realized (e.g., Felipe & Navin, 1998; Reymond et al., 2001).

One of the first studies on speed behaviour in curves including sight distance is Taragin’s study (1954) in which he reports several findings. Speed on the inside lane was found to be similar to speed on the outside lane, regardless of sight distance on the outside lane being about 20% greater; for a given minimum sight distance, vehicle speeds were higher on the inside lane; for sight distances smaller than 112m few drivers exceeded the speed corresponding to safe stopping sight distance; drivers of free-moving vehicles do not change their speed appreciably after entering a horizontal curve, adjustment in speed that is made because of curvature or sight distance is made on the approach to the curve; curvature had 3 times more of an effect on operating speed than minimum sight distance.

McLean (1979) did a review of several studies and found that for curves with design speeds greater than 90 km/h, the 85th percentile speeds tended to be less than the design speed, while for curves of lower standard the 85th percentile speed tended to be in excess of the design speed.

Krebs et al. (1977) investigated various radii with corresponding different sight distances. The radii and sight distances were subdivided into groups. Especially in curves with small radii (R < 400 m) the accident rate is much higher than in other curves if the sight distance is shorter than 99 m. With increasing sight distance the difference between the curves get smaller.

Most studies discussed above focussed on characteristics of curves as such. In addition to this, the succession of adjacent curves or the transition of a straight section to a curve should be considered. Drivers tend to enter curves too fast when the curve follows a long section of straight road as the driver has built up speed on the straight section (Dietze, et al., 2005). “Horizontal alignment sequences should reduce operating speed variations along a route. A sharp (i.e. lower radius) curve after a long tangent or after a sequence of significantly more gentle (i.e. higher radius) curves may increase accident risk. The transition to sharper curves should therefore be carried out by a progressive reduction of radii along sequential curves, following the respective regulations on radius sequences” (ERSO, 2006).

It should be noted that some of the above sources investigated single carriageway situations. Behavioural and safety effects may differ between single and dual carriageway situations.
Visualisation

Figure 2 shows a stationary car in a distance of 40 m at SSD in a horizontal curve in a connecter ramp in an interchange. The eye height of the driver is 1.10m (passenger car). The design speed of the interchange is 50 km/h. In this situation the guardrail, with a height of 0.80m, is close to the driving lane and restricts the visibility of downstream traffic. Both braking lights of the car are visible, the design meets the SSD requirements.

![Horizontal curve with guardrail](image)

**Figure 2: Horizontal curve with guardrail**

Figure 3 shows the field of view of driver in the inner lane in a horizontal curve in a tunnel (design speed 100 km/h, SSD 160m). In this case, there is just enough sight distance available to see one braking light in the horizontal curve. Because of the larger distance to the tunnel wall, the SSD on the outer lane is not normative for the design (Figure 4). Figure 5 shows a real world example of a situation with restricted sight distance in horizontal curves.
Figure 3: Horizontal curve in tunnel (inner lane)

Figure 4: Horizontal curve in tunnel (outer lane)
2.1.2 Vertical crest curves

For vertical crest curves, the view can be restricted by the top of a crest. This is illustrated in Figure 6. For this situation, a passenger vehicle is the normative vehicle, since it has the lowest driver eye height of the standard design vehicle. Figure 7 shows a real world example of limited sight distance on a vertical crest curve.
Sight distance

The vertical curve radius (see Figure 8), the curve tangent length, driver eye height (H1) and obstacle height (H2) are relevant for sight distance in the vertical curve situation. Restriction of view is caused by the crest of the road itself, behind which the driver cannot see. A larger curve radius means a larger sight distance, since the road will be more like a straight road and the crest will restrict the view less. Curve radius is under the control of the road designer, at least to some degree (the characteristics of the terrain and the project budget also influence the choice of the crest curve radius; the road designer can not choose the curve radius freely).

Stopping sight distance

Perception reaction time in the vertical crest situation is similar to the horizontal situation. Perception time may be influenced by infrastructural complexity when the driver is on a crest, for example because he or she is crossing a bridge or approaching a merge/diverge situation with manoeuvring traffic and additional signing to distract away from concentrating on the ahead view.

Braking time in the vertical curve situation is not only determined by road surface, road condition, tyres and their condition and (design) speed, but also by the gradient of the road. Again, driver assistance systems can influence the braking time, e.g. by pre-tensioning the brake, assisting to maximum brake force in case of an emergency, Anti-lock Braking Systems (ABS), etc.

Perception time in the crest situation is affected by driver eye height, diameter of the crest, length of the tangents, gradients and obstacle height. Reaction time is similar to
the horizontal situation determined by infrastructure complexity, an obstacle’s visibility and the availability of ADAS in the vehicle.

Driver behaviour
A study by Fambro et al. (2000) indicates that drivers tended to drive faster on crest curves than the design speed. Average speed and the 85th percentile were both significantly above the design speeds of the crest vertical curves. They also observed that the lower the design speed the larger the difference between the 85th percentile speed and the design speed. The mean reductions in speed in the crest situations tended to increase as available sight distance was decreased (compared to the control situation). Design speed was already adopted for the crest vertical curve, which means drivers tend to drive faster than the road designer intended but not necessarily faster than on normal roads.

McLean (1979) describes classic research done by Lefeve and Los, who relate driver speed to normal operating speed, e.g. do drivers slow down when there is not a lower design speed than normal. Lefeve found that drivers slow down a little (8km/h) on vertical curves with a maximum grade of 4%, although McLean suggests the difference might have occurred because of the used data collection method. Los carried out a similar experiment and found no relation between speed and sight distance on crest vertical curves, which means drivers do not change their speed. In other words, research results are not conclusive on this aspect of driver behaviour.

Figure 8 shows a mainline carriageway. A stationary vehicle is near the top of a crest vertical curve, positioned at a distance 160m. The eye height is 1.10m (driver of a passenger car) and the obstacle height is 0.50m (breaking light; in this example the braking lights are used as an obstacle to check, i.e. not the third braking light). The crest diameter is 8000m combined with tangent length of 125m and a grade of 4.5%. In this situation the crest vertical curve is on a straight horizontal road section with equal available sight distance for the left and right lane: the crest curve offers sufficient sight distance to see the braking lights of the stationary vehicle. Based on these parameters, the car in a distance of 160m is clearly visible.
Figure 8: Stationary car on a crest curve

Figure 9 shows a stationary car at a distance of 40m on a crest vertical curve with a diameter of 1000m and a tangent length of 85m in a connector ramp. The stationary car is positioned in the center of the lane. The design speed is 50 km/h, where the required SSD is only 40m. In this example, the car at a distance of 40m is clearly visible.

Figure 9: Stationary car on a crest vertical curve
2.1.3 Vertical sag curves

Sight distance

In tunnels, the sight distance in sag curves may be restricted by the roof of the tunnel (Figure 10 and Figure 11). Outside tunnels, other elements above the road may be restrictive, e.g. a gantry with signs, overpasses, bridges, etc. In such situations the roof (and objects attached to the roof, like signposting and ventilation) can obstruct the sight on downstream traffic. In this case, the truck is used as the normative vehicle: because of the higher driving position (eye height 2.50m) of a truck driver, compared to a driver of passenger car (eye height 1.10m). A larger curve radius means a larger sight distance, since the road will be more like a straight road and the roof or construction will restrict the view less. Curve radius is (only to a certain degree) under the control of the road designer.

Stopping sight distance

Perception reaction time in the vertical sag situation is similar to the vertical crest situation. Perception time may be influenced by infrastructural complexity (aggravated by the transition from light to dark) when the driver is in a sag situation because he or she is entering a tunnel, approaching an interchange with large gantry signs or an overhead bridge for example.

Braking time in the vertical sag situation is similar to the vertical crest situation and depends on road surface, road condition, tyres and their condition, (design) speed, and the gradient of the road. Again, driver assistance systems may influence the braking time.

Driver behaviour

Yoshizawa et al. (2012) found that in sags drivers tend to approach leading vehicles near the sag (decrease of distance between own car and predecessor) and to increase the gap after the sag (lead car accelerates away). This has a negative effect on traffic flow. With larger gradients this effect was found to be more severe.
Figure 10: Vertical sag curve schema, e.g. tunnel

Figure 11: Vertical sag curve in a tunnel

Figure 11 illustrates that the roof a tunnel can restrict the sight distance. (Since this picture was taken from a visualization, not from a SSD calculation, the curve, tangent length, etc are not specified).
2.1.4 Combinations of horizontal and vertical curves

The sight distance can also be limited in situations with a combination of a horizontal and a vertical curve. Figure 12 shows an example.

![Figure 12: Combination of horizontal and vertical sag curve](image)

For combinations of horizontal and vertical curves, the available sight distance should be calculated simultaneously: the available sight distance is not equal to the minimum of the horizontal and vertical alignment.

**Driver behaviour**

According to the driver perception hypothesis, horizontal curves appear sharper or flatter when overlapping with crest or sag vertical curves, respectively (Bella, 2014). Bella studied driver speed behaviour on combined curves and tested the perception hypothesis in a driving simulator. Quoting from their paper: speeds on the tangent-curve transition of crest and sag combinations were compared to those on the tangent-curve transition of horizontal curves with the same radii but on a flat grade (reference curves). For the crest combinations the results of the statistical analyses were fully consistent with the perception hypothesis. On the sag combinations, the driver’s speed behaviour did not differ in any statistically significant way from that on the reference curves, thereby not supporting the perception hypothesis. The effects of the combined curves on the driver’s speed behaviour did not change as a function of the level of the radius (Bella, 2014).

Hassan et al. (2002) did report that a horizontal curve radius will be perceived incorrectly if the curve overlaps with a crest or sag vertical curve. In particular, that the coincidence of a horizontal and a crest vertical curve may, under certain conditions, lead to significant limitation of the available sight distance and prevent the
prompt perception of the curve. Accordingly, the coincidence of a horizontal and a sag vertical curve may create a false impression of the degree of curvature (i.e. the horizontal curve may seem to have a higher radius than the actual) and may contribute to increased accident rates (Smith, 1993; IHT, 1990).

2.2 Relation among parameters

Structuring the parameters according to the ideas in the previous sections gives a relationship as is depicted in Figure 13. This section describes how these parameters influence each other; mainly how the low-level parameters (lane width, horizontal curve radius, etc.) influence the higher level parameters (horizontal SD, vertical SD, reaction time and braking time). For a detailed view on how the driver behaviour is influenced by low-level parameters and their impact on costs and safety, see section 3.

Figure 13: Relations among SD and SSD parameters; parameters with white background are under direct influence of road design; parameters with grey background are not
2.2.1 Horizontal sight distance

Larger sight distance means that an obstacle can be detected sooner by an approaching driver. The following parameters determine how soon the obstacle is visible in a horizontal situation:

- Lane width: wider lanes make the obstacle visible sooner.
- Shoulder and verge width: similar to lane width, a larger gap between the obstacle and the edge of the lane make the obstacle visible sooner.
- Obstacle size: A wider obstacle gives a larger horizontal SD. The obstacle will protrude further into the lane or the subtended visual angle will be larger. Therefore, the obstacle will be visible sooner.
- Lateral position of the obstacle in the lane: The further the obstacle is away from the edge of the inner side of the lane (side of restricted view) the sooner the obstacle will be visible.
- Lateral position of the driver: The further the driver is away from the edge of the curve (side of restricted view) the sooner the obstacle will be visible.
- Horizontal curve radius: in curves with a larger radius obstacles are visible sooner.
- Tangent length: in curves with shorter tangent, obstacles are earlier visible.

2.2.2 Vertical sight distance

Similar to horizontal sight distance, vertical sight distance increases if the obstacle becomes visible sooner. The following parameters determine how soon the obstacle is visible in a vertical situation:

- Driver eye height: In the case of crest vertical curves, an increased driver eye height makes an obstacle visible sooner. In a sag/hollow situation (with a view restriction by a roof of a tunnel for example) larger driver eye height makes the obstacle visible later, since the roof earlier obscures the visibility of the obstacle.
- Vertical curve radius: The larger the curve radius the less the effect the curve has on sight restrictions, the earlier the obstacle becomes visible.
- Obstacle height: The higher the obstacle, the earlier it will be visible. This is only important in the crest situation. In the sag situation, obstacle height is not relevant.
- Tangent length: The longer the tangents the less the effect the curve has on sight restrictions, the earlier the obstacle becomes visible.
- Roof/Construction height: in the case of a sag situation the height of the roof or construction that is blocking the view is also relevant. The lower this is the later the obstacle becomes visible.
2.2.3 Perception-Reaction time

Perception-Reaction time is an intrinsic property of the driver, but still influenced by situational factors. If the obstacle is difficult to discern between other objects, due to low contrast or complex traffic situations for example, it can take longer for the driver to recognize the obstacle. Longer reaction time means a larger SSD. The following parameters influence reaction time:

- Situation complexity: the more complex the situation, the higher driver workload because the driving task is more complex (relatively more navigation and maneuvering on complex environments).
- Obstacle visibility: If it is more difficult to see the obstacle, drivers will need more time to recognize the obstacle.
- ADAS: Warning systems and sight enhancing systems (night vision) can help decrease reaction time by helping the driver detect and recognize the obstacle faster.

2.2.4 Brake time

Once the driver has activated the brake, SSD is mainly determined by how effective braking is. Braking time is influenced by:

- Road surface type: The type of road surface determines how much friction the road has. More friction gives a shorter braking time, which results in a shorter SSD. See section 3 for more details on the effect of road surface on friction.
- Road surface condition: road surfaces have different friction coefficients under different circumstances. The same holds as for surface type, less friction means a larger braking time and therefore larger SSD. See section 3 for more details on the effect of road surface condition on friction. For example, older asphalt (and new asphalt) has lower coefficients of friction.
- Weather conditions: the water layer depth is influenced by the evenness and the macro texture of the surface. The braking time (distance) increases with the water layer depth.
- The braking time (distance) increases with the water layer depth. Note that a wet road surface is normative; ice and snow are not.
- Tyre type and condition: The type of tyre used and the condition it is in determines, next to road surface type and condition, for a large part the maximum deceleration possible. Tyres with more friction will decrease braking time and SSD.
- Gradient: the gradient of the road influences braking time. It is easier braking uphill than downhill. Larger/positive gradients (uphill) decrease braking time and SSD, negative gradients (downhill) increase braking time and SSD.
- Percentage brake use: Drivers choose their deceleration rate based on the available distance for the braking manoeuvre. When there is no need for severe
braking, they will not use maximum braking capabilities. Even in emergency situations, drivers tend to use the brake suboptimally, typically not braking at maximum from the onset but gradually increasing the braking power during braking. Any time the driver uses the brake under its full capacity increases braking time and therefore SSD. Brake condition also influences braking time. Not all vehicles are fitted with good quality disc brakes (or air brakes in the case of brakes HGVs). Some models still use a mix of disc and drum brakes. Models with only drum brakes are becoming very rare.

- ADAS: ADAS can help increase percentage brake use by pre-tensioning the brake, assisting from hard braking to full braking or taking braking over entirely in case of emergencies.

3 Parameters

In this section a detailed description is given of the relationship of each parameter to driving behaviour and a qualitative risk analysis with respect to traffic safety and costs. A best and worst case situation is given to be able to determine values for these parameters in the next phase of the project.

3.1 Lane width

Relation to SD and SSD

Lane width is relevant for the horizontal curve situation. Lane width influences both the position of the vehicle in the lane and the view on the obstacle (e.g. braking light) in a horizontal curve. For lane width we always look at the lane on the inside of the curve. A wider lane makes the obstacle visible earlier, which increases available sight distance. The lateral position of the driver (see section 3.2) can also influence the effect lane width may have. If the driver drives on the edge of the lane (on the inside of the curve) the additional lane width is not used and has therefore no impact.

Driving behaviour

As motorway lane widths are reduced below 3.50 m, there are two consistent effects on driving behaviour (see for instance the literature review by Hogema & Brouwer, 2001): driving speed is reduced, and lateral control performance improves (standard deviation of lateral position decreases).

Risk and Costs

Wider lanes are safer from a SD and SDD perspective (since obstacles are potentially visible earlier, depending on lateral position of the driver). In a more general sense, wider lanes are often assumed to be safer simply because there is more margin for lateral control variation. However, since drivers tend to driver faster on wider lanes,
the overall effect of lane width on traffic safety is not straightforward, and in fact various studies indicate that narrower lanes are safer than wider lanes (e.g., Noland, 2013; Manuel, 2014).

Wider lanes are more costly to build. Lane width choice depends on the choice of design speed. This latter choice is a higher level choice. The road designer has to provide sufficient SD for the given lane width. Lane width is often defined by standards, but as exception or departure from standards it can be a design consideration.

**Worst case, current guidelines, best case**

As a ‘worst’ (narrowest) case, one might choose the lane width equal to the vehicle width, but this is of course a rather academic choice.

The ‘best’ (widest) case is a 3.75m wide lane (this being the widest lane width in current guidelines of EU countries; see PIRAC, 2001).

A specific guideline case for lane width is not defined since lane width typically varies as a function of design speed (PIARC, 2001).

### 3.2 Shoulder, verge and side slope

A schematic diagram of a cross section, showing the shoulder, verge and side slope with respect to the lane, is shown in Figure 14.

- The *shoulder* is the part of the roadway between the carriageway and the ditch or the (cutting or embankment) slope, which gives the carriageway lateral support.

- The *verge* is the area located between the outer edge of the shoulder and the batter hinge point, used for the purpose of providing drainage, safety barriers and rounding.

- The (side) *slope* (or batter): this is the uniform side slope of a cutting (upward) or an embankment (downward).
Relation to SD and SSD

The shoulder or verge can contain objects that obstruct the view (for example a wall, a tree or a guardrail) and the edge of the inner lane on the side of the shoulder. A larger shoulder or verge width means a larger sight distance.

Driving behaviour

Research results have shown that accident risk decreases when shoulder width increases. Results for two-lane roads indicated that increasing shoulder width beyond 2.5 m may not be justified in terms of road safety benefit (Ogden, 1997). (Note that this research focused on all accidents, not specifically SSD related accidents). However, there is increasing concern that narrow shoulders used as emergency lanes increases the risk of a vehicle being hit by vehicles in the nearside lane.

As already described under lateral position, Ben-Bassat and Shinar (2011) found that shoulder width had a significant effect on actual speed, on lane position and on perceived safe driving speed, but only when a guardrail was present. When a guardrail was absent, the width of the shoulder had little effect on driving behaviour. The results also demonstrated that roadway geometry can be used to reduce driving speeds, but that it can have a negative effect on maintaining a stable lane position in sharp curves. Controlling shoulder width and placing guardrails seems to be a safer approach to speed and lane position control than changing road geometry design.

Risk and Costs

These elements are (to some extent) under the control of the road designer. Larger obstacle/edge distance is in general more expensive.

The road designer has two choices to meet the requirements for SSD:

- Large curve radius in combination with small obstacle distance
- Small curve radius in combination with large obstacle distance

Project characteristics determine which combination has the lowest costs. The second combination has the disadvantage that the driving speed is reduced (for curves radii smaller than approximately 750m).
Worst case, current guidelines, best case

These are not applicable: the obstacle distance (in relation with curve radius) has to offer sufficient sight distance: is a result of road design process.

3.3 Lateral position driver

Relation to SD and SSD

Lateral position is relevant for the horizontal curve situation on motorways. As written in Section 3.1 above, we assume the driver is on the inside lane of the curve, since sight distance is smallest in this position. If a driver gets closer towards the edge of the road (inner side of the curve) sight distance gets smaller. There is a difference in lateral position for left and right curves because the driver does not sit in the middle of the vehicle. Since the current report is restricted to motorway situations:

- in right-side driving countries, sight distance is larger in curves to the right, and
- in left-driving countries in curves to the left.

(On roads with an opposing lane, the width of the opposing lane adds to the obstacle/edge distance and increases sight distance as long as there is no traffic blocking the view).

Driving behaviour

A basic assumption is that drivers keep their vehicle in the middle of their lane. Research shows that there are some effects of other road design parameters that show otherwise. First of all, regarding curve driving, various authors report that drivers tend to 'cut' curves. See for instance Felipe and Navin (1998), Coutton-Jean et al. (2009), and Bella (2013).

Ben-Bassat and Shinar (2011) looked at effects of shoulder width and guardrail presence on driving behaviour. In terms of lateral position, they found that narrower road shoulders resulted in driving further away from the road edge. Adding a guardrail caused participants to shift away from it. Further, Ben-Bassat and Shinar reported a significant interaction between shoulder width and guardrail existence, indicating that the existence of a guardrail amplifies the effects of the shoulder width.

Ben-Bassat and Shinar (2011) also found that shoulder width had a significant effect on actual speed, on lane position and on perceived safe driving speed, but only when a guardrail was present. When a guardrail was absent, the width of the shoulder had little effect on driving behaviour. The results also demonstrated that roadway geometry can be used to reduce driving speeds, but that it can have a negative effect on maintaining a stable lane position in sharp curves. Controlling shoulder width and placing guardrails seems to be a safer approach to speed and lane position control than changing road geometry.
In a driving simulator study Bella (2013) found that the presence of trees along the road represents a factor that increases the severity of run-off-road accidents, drivers do not change their behaviour when barriers are not present. Concerning the effects of the beginning of the barrier, they found a main effect for roadside configuration on lateral position but not on speed. Such an ‘away from the barrier’ effect was also found in a driving simulator study by Antonson et al. (2013).

In line with the Ben-Bassat and Shinar results, Van der Horst and De Ridder (2007) found that removing an emergency lane caused drivers to choose a lateral position further away from the edge of the road.

**Risk and Costs**

The road designer has influence on the lateral position of the driver by changing lane width, placing guardrails, shoulder width, etc. The designer therefore needs to be aware of the collective or individual impacts of these aspects on driver position. For example, if narrow shoulders and guardrail are in place – there may be need for wider lanes. Therefore a risk/cost analysis cannot be made for this parameter. If the guidelines advice a position further away from the sight restricting object this will result in lower costs (but higher risk).

*Worst case, current guidelines, best case*

Worst case: the driver chooses to drive on the inner edge of the inside lane.

For left driving countries, right curves are worst case; for right driving countries, left curves are worst case.

Best case: the driver drives on the outer edge of the inner lane.

Guideline case: In D2.1 (Van Petegem et al., 2014), most current SSD guidelines in Europe specified the middle of the lane as the observation point (e.g Netherlands used 1.25m (ROA) and 2.25m for a right curve). There is a difference in definition between countries however. Denmark and France use fixed distances to the edge marking regardless of lane width (1.5 m and 2.0 m, respectively).

### 3.4 Object

There are two general types of objects that will be considered for SSD: car brake lights and a ‘box’. A ‘box’ is a hypothetical rectangular box with a given width, height and visibility. This parameter is not under the control of the road designer but is defined in guidelines.

**Brake lights**

When focussing on brake lights of a stopped vehicle as the visual cue for SSD, the next question is: which brake light(s). The most conservative choice would be all two or three brake lights of a car. In the review of current guidelines (Van Petegem et al.,
2014), the first brake light that becomes visible was the common approach. The brake light of an overthrown motorcyclist can be used as a worst-case condition.

**Box**

In the literature review (Van Petegem et al., 2014), a height of 0.5 m height has been identified as a traditional value for the ‘box’. This can be considered as the worst-case situation. Smaller dimensions are considered to be irrelevant from a safety perspective because drivers will not initiate an emergency brake manoeuvre: a vehicle can drive over them without colliding, or they do not have sufficient mass to cause severe damage.

Visibility of the ‘box’ depends on the lighting (daylight/darkness) conditions, luminance, contrast and reflectiveness of the object. Weather may influence these parameters.

On main roads with a high traffic load the brake light is most relevant for SSD. The configuration of the brake lights is relevant for all three situations (horizontal and vertical crest/sag), since configuration changes both width and height of object.

**Driving behaviour**

A braking vehicle (for instance in a queue) is a common situation in urban motorways (in peak periods). An object on the road (for instance dropped load of a truck), is rare. Mental processing time depends on factors mentioned above such as visibility. Reaction time decreases with greater signal intensity (brightness, contrast, size, loudness, etc.), whether the object is in the centre field of vision and better visibility conditions. In general, novel input slows response, as does low signal probability, uncertainty (signal location, time or form), and surprise. This means that often occurring things, such as brake lights, may be detected faster than rare occurring objects, such as truck load or ‘boxes’ on the road.

The time necessary to decide which response to make (brake, steer, do nothing) if any at all also depends on familiarity with the stimulus. Response gets slower when multiple choices are possible and when there are multiple possible signals. Conversely, practice decreases the required time to make that choice.

**Risks and costs**

The effect on costs depends strongly on the dimensions of the object or configuration of brake lights: a box of 0.50m height results in the same minimum vertical curve as a brake light on 0.50m height. For dimensioning horizontal curves, the position of the object is determining the minimum horizontal curve and distance to sight restricting objects. In this respect, the visibility of one or all braking lights has a significant influence on road design geometrics.
Worst case, current guidelines, best case

Worst case: a 0.50m box. Best case: first brake light that becomes visible. Current guidelines typically use the 0.50m box.

3.5 Driver eye height

Relation to SD and SSD

Driver eye height is relevant for the two vertical situations. In the vertical crest situation a lower driver eye height means a smaller sight distance. This is the reason to choose the car, which has lower driver eye height than a truck, as normative vehicle. For the vertical sag situation the reverse holds. Larger driver eye height means a smaller sight distance. It becomes more difficult to see further into the tunnel when you are in a truck versus when you are in car. This is why the truck is chosen as reference vehicle for the vertical sag situation.

This parameter is not under the control of the road designer, but defined by the guidelines. The guidelines should give the designer several options to choose from.

For crest curves, the appropriate worst case would be a low car driver eye height (e.g. the 5th percentile); a best case for a car would then be the 95th percentile.

Similar, for sags curves, and thus trucks are the design vehicle; the best case and worst case would be the 5th and 95th percentile, respectively.

Driving behaviour

Rudin-Brown (2004) investigated the effect of eye height on driving speed. The hypothesis was that at a higher eye position, drivers would be less able to judge speed accurately due to reduced optical flow. In her driving simulator experiment, participants were instructed to drive, without reference to a speedometer, at a highway driving speed at which they felt comfortable and safe. As expected, drivers seated at a high eye height drove faster than when they were seated at a low eye height.

Risk and Costs

For crest curves, choosing a lower driver eye height will improve safety at the expense of a more space consuming design.

Similar, for sag curves, a higher (truck) driver eye height will improve safety at the expense of a more space consuming design.

Worst case, current guidelines, best case

For the crest situation, most guidelines that were reviewed in WP2 (Van Petegem, 2014) specified a 1.00 to 1.10 m eye height above the road surface. For sag
situations, when specified, a value of 2.0 to 2.5 m was given. As best and worst case values, the 5th and 95th percentiles of eye height distributions can be used.

### 3.6 Brake performance

**Relation to SD and SSD**

(A)DAS systems can have a large influence on brake performance, effectively by influence reaction time, perception time or braking distance, depending on which ADAS type is used. This parameter is not under the control of the road designer, therefore guidelines will dictate whether no ADAS or else which ADAS is assumed to be standard.

There are several developments that have potentially a large impact on SSD. In terms of driver assistance systems, ABS and Braking Assist Systems (BAS) are standard in new vehicles today but the percentage of old cars without these systems within the fleet remains significant; 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. However, for the foreseeable future, SSD criteria will have to be based on a vehicle fleet containing vehicles without such systems.

**Driving behaviour**

Elvik and colleagues (2009) described the difficulties in studying the effects of ADAS on driver behaviour. For example, the effect of ABS on accident rate is not straightforward. Although many of the studies they report, show small but significant lower accident rates for cars with ABS, if confounding factors are taken into account (for example year, weight etc.) not all these effects are found or even opposite effects are found (e.g. increase in rear-end collision). Some of these effects are explained by behaviour adaptation of the driver, i.e. with ABS they drive faster than without, which increases risk.

Drivers do not use maximum braking capabilities during the entire braking maneuver. They usually increase braking force during the braking maneuver. Deceleration rate is a function of TTC (time to collision). Brake assist systems can decrease stopping distance by assisting the driver in emergency situations by applying maximum brake power earlier.

**Risk and Costs**

If the deceleration rate is based on (A)DAS systems, this would result in shorter SSD and thus less expensive road design (for instance smaller vertical curve radii). Not all
vehicles are equipped with ABS yet: this means that some vehicles will not have enough SSD if roads are designed for vehicles with ABS.

Worst case, current guidelines, best case

Worst case: no ABS (as on vintage cars). As a best case situation (realistic for the current fleet), ABS is reasonable to assume. Currently, no ADAS is used for the guidelines.

3.7 Road friction

3.7.1 Road surface

Relation to SSD

Road surface is relevant for SSD in all situations (horizontal and both vertical situations). The relationship of road surface type works through friction. Different surfaces have different friction coefficients. One way of classifying road surfaces is by surface type. On a high level, the following distinction can be made between concrete, porous asphalt and dense asphalt. The road designer has (to some extent) influence on what type of road surface is used and can therefore control this factor. In most projects, the road surface type is chosen for other reasons (maintenance, construction costs), but still within the designer’s choice.

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 likelihood of aquaplaning (Tromp, 1994). However, porous asphalt also has some disadvantages:

- On dry surfaces, the friction coefficient 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/s² for new porous asphalt, 7 m/s² for old porous asphalt, and 8 m/s² for dense asphalt. Note that this is maximum possible deceleration. These deceleration rates are significantly higher than those incorporated in the current guidelines.

- 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 drainage. Thus, porous asphalt needs more cleaning to maintain its positive qualities (Tromp, 1994).

Originally, porous asphalt was developed in The Netherlands mainly to improve traffic safety. However, after applying it to large parts of the road network, different studies revealed that porous asphalt was not safer. Van der Zwan (2011) concluded that
drivers take advantage of porous asphalt by driving faster during rainfall than they would on dense asphalt concrete.

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.

Driving behaviour

When spray is absent (on open asphalt road sections) driving speeds increase: there is no visual clue of friction or a possible unsafe situation. Reduction of speed during rainy conditions is not proportional to the reduction of friction, see section on road surface condition.

Risk and Costs

Braking performance on a wet road surface is the worst case condition related to SSD. In these conditions, the open asphalt construction has the highest coefficient of friction. On the other hand, the brake distance on a concrete service is the longest and therefore the most dangerous combination. Because deceleration rates in most EU guidelines SSD definitions are below the maximum deceleration rates on the worst case combination, the guidelines are on ‘the safe side’. It is not desirable to distinguish different coefficients of friction for open asphalt, closed asphalt and concrete in design guidelines: the coefficient of friction in the guideline must be lower than the worst case combination of construction type and conditions (rain).

Because stopping sight distance is ordinarily not a deciding factor in the road surface construction choice, the costs of the different road surface types are not relevant in this perspective.

3.7.2 Road condition

Relation to SSD

Road surface condition influences braking time and is therefore relevant for SSD in all situations. This parameter is not under the control of the road designer.

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 characterized 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 values for SSD parameters later on in the project.

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). They show the results of these experimental investigations on the combined effects of water depth and speed. The friction coefficient only becomes greater if the driver slows down or if the thickness of the water layer decreases.

Driving behaviour

Kilpeläinen & Summala (2007) state that drivers are not valid estimators of accident risk and do not always adjust their driving behaviour sufficiently. This is especially true for road conditions in wintertime, as drivers tend to underestimate greatly the slipperiness of a road they are driving on. Slipperiness can be argued to be the most significant of weather-related risks. Even when the road is very slippery (friction < 0.20), drivers on average still drive at speeds somewhat higher than the speed limit and consider it safe (Heinijoki, 1994 from Kilpeläinen & Summala, 2007). It seems that drivers do perceive the weather-related risks and adjust their driving behaviour accordingly to some extent, but not enough. Thus, an accident prevention strategy relying on drivers’ compensatory on-road driving behaviour is not likely to be successful (Kilpeläinen & Summala, 2007).

Research has shown that motorists do adjust their road behaviour during showers. They overtake less, drive slower, and increase their following distance (Hogema, 1996; Agarwal et al., 2005). However, the risk of a crash during rain is still greater than during dry weather. The changes in driving behaviour are, apparently, insufficient to compensate for the greater risk during bad weather (Thoma, 1993). Rain can lead to dynamic aquaplaning. A layer of water on the road surface can cause the vehicle to lose contact with the road surface and to skid. The chance of aquaplaning depends on the skid resistance of the road, the degree of drainage and also on the vehicle's speed and tyre tread depths (Ellinghaus, 1983; Terpstra, 1995; Van Ganse, 1981). When it has been dry for a long time, a drizzle can lead to viscous aquaplaning resulting from water mixing with oil and dust deposits on the road surface that produces a thin liquid film on the road surface that is extremely slippery. When the rain gets heavier, the chance of viscous aquaplaning lessens because the road surface is swept clean (Terpstra, 1995; Eisenberg, 2003) (source: SWOV factsheet influence of weather).

In relation to the maintenance condition of the road surface: drivers do not take into account the maintenance condition of the road (there is no, or little) visible clue. Road authorities can reduce maximum speed because of a bad road condition. However, drivers do often not decrease their speed on these sections (in The Netherlands).
Risk and Costs
Road design has to offer safe driving conditions for the normative, i.e. wet conditions. SSD has to be based on these conditions.

Worst case, current guidelines, best case
Current guidelines are based on the normative wet conditions. Therefore, even though snow/ice/frozen is the absolute worst-case condition, this is out of scope for the guidelines. These are considered non-standard conditions. Their frequency is low and driving behaviour differs significantly from standard conditions, making them very difficult to compare. Taking into account these conditions would lead to an unbalanced road design, where construction costs are very high in relation to the benefits for road safety.

Combining road surface and road condition:
- Worst case in rain is a concrete surface.
- Best case in rain conditions is open asphalt; under dry conditions it is closed asphalt.
- The typical guideline case uses closed asphalt.

3.8 Situational complexity
Situational complexity is composed of three elements:
- the traffic condition
- constructions: a tunnel or a bridge (in contrast to an open road); this also covers overpasses/underpasses, gantries, etc.
- the road configuration

3.8.1 Traffic conditions
Relation to SSD
The normative situation for calculating SSD is a situation where there is a stationary object on the road ahead; no moving vehicles are assumed between the driver and the object. The traffic volume of the road determines in which periods this can be the case: on busy roads, these conditions can occur mostly only outside peak periods. Achieving the design speed of the road in peak periods is less likely due to increased traffic volumes. At the same time, the chances of stationary objects are smaller outside peak periods: a stationary vehicle as a result of congestion is more likely in
peak periods. Outside peak periods, a stationary object on the road is the result of an accident or incident (dropped load).

3.8.2 Constructions

Relation to SD and SSD

Tunnels or bridges have higher construction costs than open roads. Due to a cost-safety trade-off, emergency lanes may be narrower or absent in tunnels. In horizontal curves, the tunnel walls will block the line of sight and thus determine the sight distance. During rain the tunnel road surface might be dry or moist but will not have water layers as on open roads. Smaller vertical curves lead to shorter (cheaper) tunnels, which is a reason for a road designer to want small vertical curves.

Driving behaviour

Driving inside a tunnel may cause anxiety because tunnels are dark, narrow and monotonous (PIARC, 2008). In terms of operational driving behaviour, some studies find a reduction in driving speed whereas others show a change in lateral positioning (Martens & Kaptein, 1997). Although the number of drivers who feel uncomfortable when entering a tunnel is small (Admundsen, 1992), the effect of this group on traffic flow should not be underestimated (Martens & Kaptein, 1997). Tunnel fear causes discontinuity in the traffic flow, and can lead to crashes because the motorist will have less attention for the driving task (SWOV, 2011).

It has been stated that drivers become more alert in the changed environment of the tunnel, which has been used as the rationale for a reduced driver perception-reaction time (Bassan, 2015). It should be noted that the reduced perception-reaction time in tunnels seems to be an assumption rather than an observed change in driving behaviour.

Risk and Costs

The higher construction and operation costs of tunnels might call for different SSD parameters compared to open roads.

Worst case, current guidelines, best case

For tunnels, the worst case condition would be a narrow, long and deep tunnel, whereas the best case would be a wide, shallow, short and straight tunnel.

In D2.1 (Van Petegem, 2014), PRT differences between drivers who are aware or unaware of an impending braking event were discussed, showing shorter PRTs for aware drivers. Bassan (2015) showed that in SSD guidelines, typically the ‘aware’ values of PRT are used for tunnel situations.
3.8.3 Road configuration

Relation to SSD

Complexity of the road configuration is one of the parameters that is assumed to influence reaction time of the driver. For example, a complex system of merge and diverge areas and ramps. With situational complexity we mean the complexity as far as it influences perception and reaction time. Lane width and other infrastructural properties are not part of this parameter. Complex infrastructure may influence drivers reaction time, but may also change the vigilance or alertness of the driver thus decreasing reaction time.

Driving behaviour

Patten et al. (2006) studied the effect of road and traffic environment complexity by using the Peripheral Detection Task (PDT). An environment with higher complexity was found to be related to longer PDT reaction times, i.e., higher workload. However, it is not clear how this relates to brake reaction times when confronted with a SSD scenario.

Road configuration complexity may lead to additional workload for the driver. In Germany a behaviour based approach called orientation visibility (OV) or orientation sight distance has been introduced (Lippold et al., 2007). The orientation sight distance relates sight distances to driver workload and driver stress. The relation was measured by looking at driving and viewing behaviour such as braking retardation, gaze at the road and time spent on secondary tasks. Shorter SDs resulted in extra demand placed on drivers. The effect of this approach on recommendations on SD is investigated in the research by Lippold et al. Orientation sight distance is recommended 30% above SSD.

Risk and Costs

Taking longer reaction times in complex network lay-outs into account, this would result in larger SSD, thus is more expansive road design.

Worst case, current guidelines, best case

The best case consists of a road with low complexity, such as a long distance motorway, with little or no navigation choices, few exits/entries or weaving sections, and no potentially distracting elements in the surroundings.

A worst case condition is a road with high complexity, like a motorway near a city, with many entries/exits as well as elements in the surroundings that might attract the driver's attention. The road designer has limited influence on the complexity of the infrastructure.

Road complexity is not incorporated in the current guidelines.
3.9 Gradient

Relation to SSD

The gradient of the road, i.e. how steep is the road, influences braking distance. On uphill roads braking distances are decreased relative to the gradient, resulting in smaller SSD. On downhill roads braking distances increases relative to the gradient, resulting in larger SSD. This parameter is (to a certain degree) under the control of the road designer, local aspects will dictate a minimum and a maximum.

Driving behaviour

Drivers have a limited ability to compensate for the negative effect that an increase in slope has on vehicle acceleration (Ros et al., 2013). Paraphrasing from the paper from Ros and colleagues: In general, the lower part of the uphill section (i.e., first 500-1000 m downstream of the bottom of the sag) is the main bottleneck. Drivers tend to reduce speed and tend to keep longer headways than expected given their speed. These two changes in car-following behaviour have a negative effect on the capacity of the uphill section. These changes seem to be unintentional and are caused by a limitation in vehicle acceleration. Drivers fail to accelerate sufficiently even though they generally perceive the change in gradient. Drivers are generally able to re-accelerate after the first 500-1000 m of the uphill section and recover their desired speed.

Risk and Costs

No information on these points was available or found during WP3.

Worst case, current guidelines, best case

The best case is a gentle up or downgradient; worst case is a steep up or down gradient. The gradient can (in a limited extent) be influenced by the road designer. In the guidelines, gradient is treated as a parameter.

3.10 Tyre

Relation to SSD

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). Tyre grip is relevant for all situations and is not under the control of the road designer. 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 (A through F) are listed in the WP2 report.

Driving behaviour

Winter tyres increase friction in winter conditions. The effect of this is somewhat diminished because drivers driving on these type of tyres adapt their speed somewhat since they have more grip. However the ‘winter-effect’ is not under the control of the designer and therefor not of relevance for the development of the SSD-Model.

Worst case, current guidelines, best case

Best case: a new type B tyre, i.e. with maximum thread depth. As the worst case condition an A type tyre with the legal minimum tread depth of 1.6 mm is used. Depth is not a factor mentioned in the guidelines.

4 Conclusions

The range of the parameters from Chapter 3 (Worst case, current guidelines, best case) are summarised in Figure 15. Qualitatively, the best case solutions are the safest and the most expensive, whereas the worst case solutions are the cheapest yet least safe.
### Figure 15: Summary of range of parameters

The resulting structure and parameter overview will serve as the starting point for the parameter study (WP4), that deals with quantitative distributions of parameter values on the road.

#### 5 Acknowledgement

The research presented in this 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 the Netherlands, UK, Germany and Ireland.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best case</th>
<th>Guideline</th>
<th>Worst case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane width</td>
<td>3.75 m wide</td>
<td>x</td>
<td>vehicle width</td>
</tr>
<tr>
<td>Lateral position driver</td>
<td>far</td>
<td></td>
<td>close</td>
</tr>
<tr>
<td>Object</td>
<td>1st visible brake light</td>
<td>0.5m box on the road / 1st visible brake light</td>
<td>0.5m box on the road</td>
</tr>
<tr>
<td>Driver eye height, truck</td>
<td>5th percentile</td>
<td>2.0 to 2.5 m</td>
<td>95th percentile</td>
</tr>
<tr>
<td>Driver eye height, car</td>
<td>95th percentile</td>
<td>1.0 to 1.1 m</td>
<td>5th percentile</td>
</tr>
<tr>
<td>(A)DAS</td>
<td>ABS</td>
<td>no (A)DAS</td>
<td>None</td>
</tr>
<tr>
<td>Road surface and condition</td>
<td>open asphalt (rain); closed asphalt (dry)</td>
<td>closed asphalt, wet</td>
<td>concrete, wet</td>
</tr>
<tr>
<td>Situational: traffic</td>
<td>low</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Situational: construction</td>
<td>standard</td>
<td></td>
<td>tunnel</td>
</tr>
<tr>
<td>Situational: road configuration</td>
<td>long-distance motorway,</td>
<td>-</td>
<td>near city motorway,</td>
</tr>
<tr>
<td>Gradient</td>
<td>gentle up/down</td>
<td>-</td>
<td>steep up/down</td>
</tr>
<tr>
<td>Tyres</td>
<td>Typ A, new</td>
<td>-</td>
<td>Type B, 1.6 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Safe</th>
<th>Unsafe</th>
</tr>
</thead>
<tbody>
<tr>
<td>High cost</td>
<td>Low cost</td>
</tr>
</tbody>
</table>

The resulting structure and parameter overview will serve as the starting point for the parameter study (WP4), that deals with quantitative distributions of parameter values on the road.

#### 5 Acknowledgement

The research presented in this 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 the Netherlands, UK, Germany and Ireland.
6 References


Bella, F. (2013). Driver perception of roadside configurations on two-lane rural roads: Effects on speed and lateral placement. Accident Analysis and Prevention, 50, 251–262


Yoshizawa, R., Shiomi, Y., Uno, N., Iida, K., & Yamaguchi, M. (2012). Analysis of car-following behavior on sag and curve sections at intercity expressways with