

SIGHT DISTANCES AT UNSIGNALIZED INTERSECTIONS: A COMPARISON OF GUIDELINES AND REQUIREMENTS FOR HUMAN DRIVERS AND AUTONOMOUS VEHICLES

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Abstract:

Many traffic accidents are caused by unforeseen and unexpected events in a site that was hidden from the driver's eyes. Road design parameters determining required visibility are based on relationships formulated decades ago. It is worth reviewing them from time to time in the light of technological developments. In this paper, sight distances for stopping and crossing situations are studied in relation to the assumed visual abilities of autonomous vehicles. Current sight distance requirements at unsignalized intersections are based among others on speeds on the major road and on accepted gaps by human drivers entering or crossing from the minor road. Since these requirements vary from country to country, regulations and sight terms of a few selected countries are compared in this study. From the comparison it is remarkable that although the two concepts, i.e. gap acceptance on the minor road and stopping on the major road have different backgrounds, but their outcome in terms of required sight distances are similar. Both distances are depending on speed on the major road: gap sight distances show a linear, while stopping sight distances a parabolic function. In general, European SSD values are quite similar to each other. However, the US and Australian guidelines based on gap acceptance criteria recommend higher sight distances. Human capabilities and limitations are considered in sight field requirements. Autonomous vehicles survey their environment with sensors which are different from the human vision in terms of identifying objects, estimating distances or speeds of other vehicles. This paper compares current sight field requirements based on conventional vehicles and those required for autonomous vehicles. Visibility requirements were defined by three vision indicators: distance, angle of view and resolution abilities of autonomous cars and human drivers. These indicators were calculated separately for autonomous vehicles and human drivers for various speeds on the main road and for intersections with 90° and 60° angles. It was shown that the required sight distances are 10 to 40 meters shorter for autonomous vehicles than for conventional ones.

Keywords: intersection, sight distance, autonomous vehicle, speed; gap acceptance

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1. Introduction

There is a huge amount of literature concerning autonomous vehicles (AV's); these sources are dealing mostly with issues of the vehicles and their communication. However, the infrastructure has received little attention so far.

Recently, Farah et al. (2018) presented a state of the art on this topic while considering both the digital and the physical infrastructure. Based on the state of the art, and a brainstorming workshop involving experts from different disciplines in the Netherlands, a detailed mind map was presented and recommendations for future research directions were suggested. They concluded that a considerable research effort exists with respect to the digital infrastructure, while for the physical infrastructure it is scarce.

Lytrivis et al. (2018) gave a good overview on advances in road infrastructure, both physical and digital, for mixed vehicle traffic flows. In Germany, an advisory committee for the Federal Minister of Transport and Digital Infrastructure (see the responsibilities of the minister) produced a paper on "Automated driving: Challenges for the future transport policy". This paper devotes two pages out of forty to the infrastructure (Eisenkopf et al., 2017).

A lot of rules and parameters of road design guidelines (e.g. curvature, superelevation and sight distances) are based either on vehicle dynamics and/or on human capabilities (e.g. reaction time). Autonomous vehicles are coming soon to our roads. Even though they will coexist with conventional ones for a longer period, thinking about potential savings in road space, required sight distances etc. has started. Autonomous vehicles collect a lot of information helping them to prepare decisions in different situations. These cars survey their environment with sensors which are different from the human vision in terms of identifying objects, estimating distances or speed of other vehicles. An autonomous vehicle (AV) has to drive safely without any external information, based exclusively on self-collected data. Therefore, in this paper connected vehicles (CV) and roadside units (RSU) are not considered.

Vehicles with different levels of automation can travel on the same road infrastructure with parameters (e.g. speed, headway) which are different from those of conventional cars. It is important to investigate these differences for two reasons. Firstly, the way of using the road depends on vehicle specifications, e.g. a faster vehicle needs shorter passing sight

distance or a weaker sensor to measure distance requires a lower speed to ensure safety. Secondly, the geometrical parameters used in road design are based on human and physical relationships supplemented with safety factors. The goal is to define minimum requirements for AV's which are required to use the infrastructure without CV systems or RSUs. The impact of AV's on road and intersection capacity is outside the scope of this paper. See e.g. (Lu, Tettamanti, et al. 2019).

This paper compares current visibility requirements at priority intersections, based on conventional human driven vehicles and those required for autonomous vehicles. Furthermore, some recommendations are drawn to update design rules concerning visibility requirements.

2. Visibility requirements at unsignalized intersections

Approaching intersections drivers have to collect information about the traffic regulation, position of other vehicles and have to decide quickly about entering the intersection or not. Visibility criteria are defined similarly in various international sources. Required sight distances usually depend on the traffic management, location of intersection, speeds on the major and minor roads and maneuver (behavior of drivers). Although design guidelines define criteria for visibility, there are still a lot of intersections where these criteria are not met. For example, a study in Japan showed that most of the 1629 urban intersections studied have poor visibility. It was found that the accident rate was high when visibility was poor (Nomura et al. 2021). Another study of 22 intersections in built-up rural area along a provincial road in Poland concluded that the main reason for the insufficient visibility at many intersections is the fact that the geometrical parameters of roads and their surroundings were shaped in the past when the traffic conditions were completely different (Brycht, 2020).

Specified areas along intersection approach legs and across their included corners should be clear of obstructions that might block a driver's view of potentially conflicting vehicles. These specified areas are known as clear sight triangles. The dimensions of the legs of the sight triangles depend on the design speeds of the intersecting roadways and the type of traffic control used at the intersection. (AASHTO, 2018).

Roundabouts have specific visibility requirements (Highways England 2020/2), (Salwan, et al. 2021). This paper concentrates on T or X-type intersections, roundabouts are not considered here. Furthermore, in darkness, the presence or absence of public lighting and its performance makes visibility issues more complicated (Bhagavathula et al. 2019). However, in this paper lighting is not considered.

Visibility requirements should relate to all types of road users. Most studies are related to cars, but there are examples about visibility problems and conflicts with pedestrians. With the intention of verifying how car-centered designs perform for non-motorized users, a 3D procedure that evaluates the visibility of pedestrians and other users was presented and applied to specific cases by González-Gómez and Castro (2019). In the absence of proper visibilities, interactions between vehicles and pedestrians may be dangerous (Thakur, Subhadit, 2019). In this paper cars, electric scooters and pedestrians will be also considered.

According to an international survey by Harwood et al. (1998), there are four different cases of sight triangles for intersections with no control, approach with YIELD control, STOP-controlled approach and drivers turning left or right onto the major road from a STOP-controlled approach. However, most of the guidelines or standards define just two cases of triangles for YIELD and STOP-controlled intersections such as the German one by FGSV (2012), the UK guideline (Highways England, 2020) and the Hungarian one by HRS (2004). The available visibilities will determine the use of YIELD and STOP-signs at these locations (Duda, 2019).

In Fig. 1. S_d is the conflicting vehicle distance and d_e is the decision point distance. These distances vary depending on the type of sight distance in question.

Although the principles are similar, road design guidelines in different countries define different terms and rules for required sight distances and sight fields. In the next paragraphs we give an overview on minor, major road and crossing sight terms, provide a comparison of several guidelines.

2.1. Minor road sight terms

2.1.1. Approach Sight Triangles (AASHTO, 2018)

Each quadrant of an intersection should contain a triangular area free of obstructions. The length of the legs of this triangular area, along both intersecting

roadways, should be such that the drivers can see any potentially conflicting vehicles in sufficient time to slow or stop before colliding within the intersection. The provision of a clear sight triangle for vehicles without the right-of-way also permits the drivers of vehicles with the right-of-way to slow, stop, or avoid other vehicles, if needed.

Although desirable at higher volume intersections, approach sight triangles are not needed for intersection approaches controlled by stop signs or traffic signals. In that case, the need for approaching vehicles to stop at the intersection is determined by the traffic control devices. However, departure sight triangles are required (see later).

2.1.2. Approach Sight Distance (Austroads, 2017)

The Australian guidelines define the Approach Sight Distance (ASD) as the minimum level of sight distance which must be available on the minor road approaches to all intersections to ensure that drivers are aware of the presence of an intersection. It is different from the Stopping sight distance (SSD) in the object height used in its calculation. ASD is measured from a driver's eye height (1.1 m) to 0.0 m, which ensures that a driver is able to see any line marking and curbing at the intersection whereas SSD is measured from 1.1 m to 0.2 m (a nominal object height). ASD is also desirable on the major road approaches so that drivers can see the pavement and markings within the intersection and should be achieved where practicable.

2.2. Major road sight terms

2.2.1. Stopping sight distance (EUSight)

Stopping sight distance (SSD) is provided continuously along each roadway so that drivers have a view of the roadway ahead that is sufficient to allow drivers to stop. The provision of stopping sight distance at all locations, including intersection approaches (both on major and minor roads), is fundamental to intersection operation.

Part of the CEDR Transnational Road Research Programme Call 2013: Safety, was the research project European Sight Distances in perspective – EUSight. The objective of the research project was 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 European countries (Weber et al., 2016).

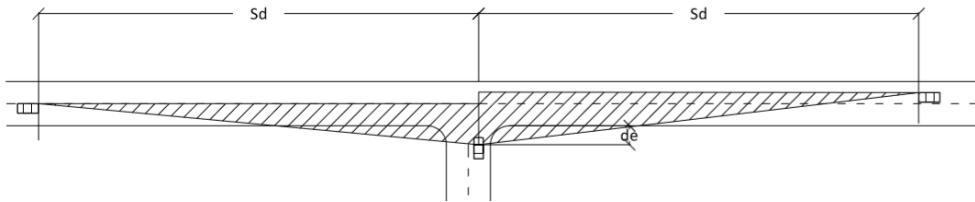


Fig. 1. Intersection Sight Triangles

SSD is affected by both the horizontal and vertical alignment. Within curves, the cross section and the roadside space might also have an impact. 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 with a specific speed to be able to stop before reaching the obstacle/hazard. SSD depends on:

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

A basic SSD formula (Fambro, Fitzpatrick, Koppa, 1997) is given as (1):

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

where:

V – the design speed (km/h),

t_{RT} – the reaction time (s),

a – the average deceleration rate (m/s^2).

Weber et al. (2016) compared between countries the various input parameters of the SSD requirements, braking coefficients and driver/object height values. From the research it was evident that there is some amount of variation on SSD characteristics among these countries. Most countries prescribe a fixed perception reaction times (PRT) of 2 seconds. Overall, though there is a consensus about what the SSD requirements are.

2.2.2. Safe Intersection Sight Distance (Austroads, 2017)

Safe Intersection Sight Distance (SISD) is the minimum distance which should be provided on the major road at any intersection. SISD provides sufficient distance for a driver of a vehicle on the major road to observe a vehicle on a minor road approach moving into a collision situation (e.g. in the worst case, stalling across the traffic lanes) and to decelerate to

a stop before reaching the collision point. The calculation of SISD is very similar to that of SSD, except that SISD includes a longer observation time (3s).

2.3. Crossing sight terms

2.3.1. Time gap

Gap is the distance between two vehicles expressed in time. In traffic engineering, it is usually measured from the front of the first vehicle to the front of the next vehicle (gross headway). For visibility and safety studies the 85-percentile gap should be used, which is accepted by 85% of the users. According to Brilon et al. (1997) ‘The critical gap represents the minimum time period in the priority stream that a minor road user is ready to accept for crossing or entering the major stream’. For estimating the critical gaps, statistical models or procedures are required. There exist many different models for estimating critical gaps.

2.3.2. Departure Sight Triangles (AASHTO, 2018)

According to the AASHTO Green Book, departure sight triangle provides sight distance sufficient for a stopped driver on a minor-road approach to depart from the intersection and enter or cross the major road. Departure sight triangles should be provided in each quadrant of the intersection approach controlled by stop or yield signs.

The AASHTO (2018) Green Book gives critical gaps for passenger cars depending on the maneuver type (right turn, left turn, crossing) and on the vehicle type (passenger car, single-unit truck, combination truck). Australian sources define the time gap depending on speed between 5.4 and 9.0 seconds (Cox et al., 2015). Time gaps for certain maneuvers are given by AASHTO in tables like Table 1. Left turn can be considered as a worst case.

In a STOP-controlled intersection, the position of driver's eyes is assumed to be three meters from the nearest edge of intersection according to the AASHTO (2018) handbook. In case of 50 km/h

speed (which is the ordinary speed limit in built-up areas) the required visibility distance is 105 meters in both directions.

Table 1. Time gap for certain maneuvers from the minor road (AASHTO, 2018)

Design vehicle	Time gap (s)	
	crossing and right turn	left turn
Passenger car	6.5	7.5
Single unit truck	8.5	9.5
Combination truck	10.5	11.5

In a YIELD controlled situation, the driver's position (decision point) is assumed to be located further away from the intersection and the necessary sight distance is larger. In both cases, the visibility distance was defined as the function of speed (V).

For STOP-controlled intersections, safe intersection sight distance is determined from the size of acceptable gap that a driver requires to enter the roadway and design speed of major road.

$$SD = 0.278 * V_m * t_c \quad (2)$$

where:

SD – required intersection sight distance along a major road (m),

V_m – design speed of major road (km/h),

t_c – time gap that drivers will accept to enter major road (s).

2.3.3. Minimum Gap Sight Distance (Austroads, 2017)

According to the Australian guidelines, Minimum Gap Sight Distance (MGSD) is based on distances corresponding to the critical acceptance gap that drivers are prepared to accept when undertaking a crossing or turning maneuver at intersections. Typical traffic movements are: (translated to right-hand traffic) right-hand turn, crossing, left-hand turn from major road, left-hand turn from minor road and merging.

MGSD is measured from the point of conflict (between approaching and entering vehicles) back along the center of the travel lane of the approaching vehicle, and it is measured from a point 1.1 m (driver's eye height) to a point 0.65 m (object height

– typically a vehicle indicator light) above the travelled way. It is dependent upon the length of the gap being sought and on the observation angle to approaching traffic.

2.4. Comparison of guidelines and approaches

In this section a few selected guidelines are compared concerning their regulations related to stopping sight distance and minimum gap sight distance.

2.4.1. Minimum Gap Sight Distances vs. Stopping Sight Distances

Fig. 2. shows a comparison of minimum gap sight distances and stopping sight distances. It is remarkable that although the two concepts, i.e. gap acceptance on the minor road and stopping on the major road have different backgrounds, but their outcome in terms of required sight distances are similar. Both distances are depending on speed on the major road: gap sight distances show a linear, while stopping sight distances a parabolic function. For cars with lower minimum gaps, the SSD function is quite close to the minimum gap sight distances. However, for trucks with higher minimum gaps, the required sight distance is underestimated by the SSD function.

2.4.2. Stopping Sight Distances in different countries

Fig. 3. shows a comparison of minimum gap sight distances and stopping sight distances along a major road for various countries. For the calculation of SSD and SISD or/and MGSD the following variables are assumed: $Dt = 5$ sec, $d = 0.36$, $a=0$, $t_c = 7.5$ sec. Beside the aforementioned countries (USA, Australia) a few European countries such as Germany, Great Britain, Hungary, Poland, and Switzerland were considered.

The shortest sight distance is required for Swiss intersections (SUI). It also has to be noted that in the German guidelines for roads outside urban areas, abbreviated as RAL (FGSV, 2012), sight distances are linked to design categories, instead of speed. Out of the four design classes, three (EKL 2, 3, 4) are shown here.

The GB guidelines define higher sight distances compared to the other European countries. However, their regulations provide options to calculate values one class below standard (Highways England, 2020/1).

In general, European SSD values are quite similar to each other. However, the US and Australian guidelines based on gap acceptance criteria recommend higher sight distances. In addition, European guidelines would need a clearer distinction between stopping sight distances and sight distances needed for minimum gaps.

3. Autonomous car sensors for environment detection

Design guidelines usually consider visibility investigation as a two-dimensional task, but in reality, it should be three-dimensional. The recent survey methods like laser scanning and photogrammetry give effective methods to check the spatial sight distances in detail (Jung et al., 2018). Results of these are point clouds consisting of a huge number of points measured in 3D coordinates in one space. This three-dimensional counterpart of sight distance at intersections can be called sight plane. The evaluation of these point clouds from the aspect of visibility requires lots of calculations, these analyses need less operation in 2D than in a complete 3D point cloud space.

Laser scanners and LIDARs on AVs are similar instruments based on the same technology (Fig. 4.). The improvement of self-driven vehicles provided new solutions to the point cloud evaluation, moreover the LIDAR sensors on AVs themselves survey the sight distances more efficiently, which is also useful to identify the hazardous parts of road networks.

Today autonomous vehicles are appearing on our roads and have different capabilities to acquire information from their environment. The following sections will analyze the vision skills of human and autonomous cars from three vision aspects; these are distance measuring, angle of view and angular resolution.

For the right navigation and control, it is required to survey and continuously detect the environment of the vehicle. Several technologies are available to fulfill this task. The radar detection system uses radio waves to determine the range, angle, or speed of objects. LIDAR (Light Detection and Ranging) sensor continually fires off beams of laser light, and then measures how long it takes for the light to return to the sensor.' (Cameron, 2017). The ultrasonic devices are used to detect objects and measure distances in short ranges. Lastly, the digital camera detects light, and it is able to object detection and segmentation. It can detect traffic signs, traffic lanes, vehicles, or pedestrians.

Advantages of the camera are the good resolution and classification. However, it is weak in darkness, in bad weather conditions and its ability to distance measurements is limited. The LIDAR is strong in bad lighting conditions and field surveying. It is also able to do classification, but the resolution of LIDAR data is much lower and noisier than that of camera records (Schoettle, 2017). Radars can complement the LIDAR and the camera, as they perform better under bad weather conditions and are also better at speed estimation. To increase efficiency, the three different sensors have to work together.

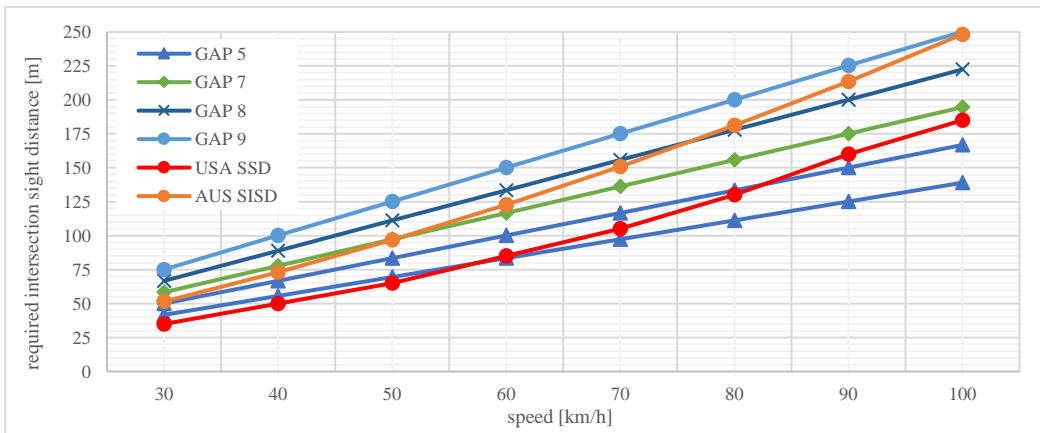


Fig. 2. Comparison of minimum gap sight distances and stopping sight distances

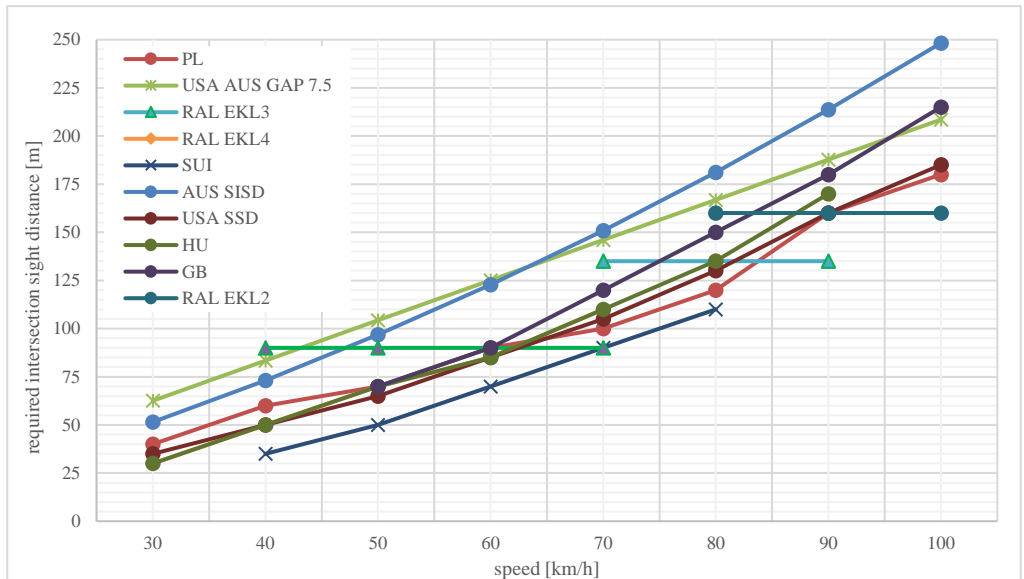


Fig. 3. Comparison of stopping sight distances in some countries

The LIDAR unit is particularly important on autonomous cars since it surveys the horizontal and vertical angles as well as the distance of the reflected pulses. The direct information from this sensor is three-dimensional polar coordinates with 2-3 cm accuracy. By means of evaluation, it is possible to determine the shape of objects. The LIDAR technology is used already at the first level of automation similar to additional systems such as Adaptive Cruise Control (ACC), or Emergency Brake Assist.



Fig. 4. Principle of operation of a laser scanner and a LIDAR

4. Human vision abilities and Lidar sensors

Considering safety, the human vision has three main features: visibility, environment, and human factors. Visibility depends on part of the day, season and weather conditions. The environment means here possible obstacles of the built or natural environment e.g. walls, fences, trees, bushes, traffic signs, other moving vehicles or blind spots. The third feature is the human factor which has two parts: 1) human visual ability, e.g. visual acuity or angle of view, and 2) conditions such as drowsiness or concentration. Among these factors the location of objects is measurable, and it is possible to determine the human visual abilities. Thanks to its maps and sensors AVs can precisely measure the environment, they are not influenced by drowsiness or other human weaknesses. All of these factors increase the safety of AVs.

The human vision and LIDAR's technical parameters are the two pillars of comparison. Many people are worried about driverless vehicles as car driving is a complex task and requires complicated tools. For humans the most significant sensor is our vision. The LIDAR itself is unable to replace the vision but it can detect obstacles, measure the distance, location and size, providing enough information to avoid

a collision. Moreover, due to its precise environment detection, it is also possible to recognize objects which can hide another road user, so potential risky situations can be identified. For these aspects, clear visibility is also important for AVs. The goal of the comparison of human vision and LIDAR capabilities is to define the minimum performance expected. This comparison below is done along three indicators, distance, field of view and angular resolution. As for distance, human eyes are able to see to the horizon if there are no obstacles in between and there are good light conditions. The distance of the horizon depends on the eye height; the driver can see up to 3.5 km distance if the eye height is one meter. The maximum range of LIDAR sensors varies by models, it is in general between 120 and 300 m. Fig. 5. shows the results of a Pandar64 360 degree LIDAR measurement from different distances (Hessai, 2019), where with increasing distance the number of points detected decreases.

Distance estimation by humans might be a problem. According to a study (Strasuss et al., 2009) people underestimate large distances between 6 and 120 m, the average estimation error was -8.6% and the median was 22% . The error extremes were ranging between -96% and $+71\%$ showing that people's abilities of distance estimation are different. On the other hand, LIDARs can work with 1-3 cm accuracy to measure distances.

The second indicator is the field of view. A human from the driver's seat has a limited field of view due to the vehicle frame and limitations in eye move-

ment and neck rotation. Giving value to these parameters is not easy. The design guideline for New Zealand rail crossings (NZTA, 2012) defines the maximum field of view angle as 110° to the left and 140° degrees to the right. Drivers in actual situations might turn their head more but this may lead to errors in detection of oncoming vehicles.

LIDAR sensors can take accurate measurements in a long range and they can be mounted on the top of the vehicle. There are two different implementations of this: the 360-degree LIDAR and the solid-state LIDAR. The latter has $100 - 120^\circ$ field of view.

The third indicator is the angular resolution (visual acuity), which is one-degree minute (0.017 degree) for humans on average. That is the smallest angle of view to isolate two different objects. From one-meter distance, two objects of 0.3 mm or larger can be distinguished, or a 1-meter-high vehicle can be distinguished from the road in theory as far as from 1.7 km distance, with perfect eyes and daylight, without considering the earth's curvature.

Certain LIDAR developer companies give separate values to angular resolution in a horizontal and vertical direction. According to technical parameters available online, the best value is 0.03° for both the solid-state LIDAR and the 360° LIDAR. These values do not reach the human capabilities. Solid-state LIDARs have a larger range of distance measurement; however, their disadvantage is the small field of view, which is important to sense the required sight distance. Table 2. summarizes the above discussed indicators.

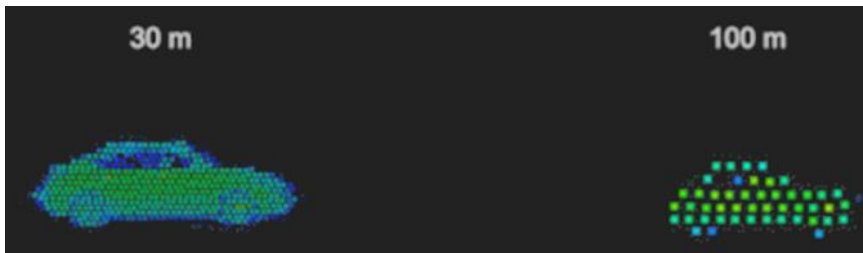


Fig. 5. LIDAR measurement from different distances (Hessai, 2019)

Table 2: Human eye and LIDAR's parameters

Factor	Human	360° LIDAR	Solid-State LIDAR
Distance	~ 3.5 km, large deviation at distance estimation	120 – 300 m	250 – 300 m
Horizontal field of view	$200^\circ - 220^\circ$	360°	$100^\circ - 120^\circ$
Horizontal angular resolution	0.017°	$0.03^\circ - 0.2^\circ$	$0.03^\circ - 0.1^\circ$

5. Calculations of the required indicators at intersections

The previous section compared the human vision and the LIDAR sensing abilities considering three important vision indicators. This section is about the required values of these indicators.

To illustrate this a particular vehicle movement is investigated, namely a left turning movement at a STOP controlled intersection. Considering the differences between conventional and self-driving vehicles, different time gaps were used. A study by Dixit et al. (2016) estimated that autonomous vehicle's reaction time is 0.8 sec., which is lower than the human reaction time ranging between 1.2 sec. and 2.2 sec (Guzek et al., 2012). For simplicity, a 1 second difference was assumed in reaction times. Differences between the dynamic properties of conventional and autonomous vehicles were not considered. Similar assumptions were used by Schoettle (2017) for ideal conditions with a 1.6 s for humans and 0.5 s reaction time for AVs, the difference being 1.1 s.

In Table 3. sight distances of the AASHTO (2018) Handbook for the left turning case derived from 7.5 seconds and the recalculated sight distances with 6.5-second time gap for autonomous vehicles are shown. The required sight distances for autonomous vehicles are 10 to 40 meters shorter than for conventional vehicles, as one second shorter time gap means 15% shorter required sight distance. The required sight distances in Table 3 are valid for both left and right side.

It has to be mentioned that at speeds over 100 km/h these sight distances are irrelevant, as in general no crossing is allowed on these roads.

The difference in sight distances ΔSD in Table 3. for conventional and autonomous vehicles can be calculated accurately from the following formula (3):

$$\Delta SD = \frac{(t_R^{CC} - t_r^{AC}) * V}{3,6} \quad (3)$$

where:

t_R^{CC} – conventional vehicles' reaction time [sec],

t_r^{AC} – autonomous vehicles' reaction time [sec],

V – speed on the major road [km/h].

The required sight distances for crossing and right turning maneuvers can be calculated similarly to Ta-

ble 3 with 6.5 seconds for human drivers and 5.5 seconds for autonomous vehicles. The required sight distances will be less but the difference ΔSD will remain the same.

5.1. Distance requirements

The sight triangle has three vertices: sd , d and s (Fig. 6.), sd means the distance along the major road, which is slightly different from d that can be observed in reality.

A left turning situation was assumed with a stopped vehicle 3 meters away from the edge of the intersection. Lane width was assumed to be 3.5 m, thus the s equals 6.5 m in case of a rectangular arrangement. If the angle is 60° , the value of s will grow to 7.04 m. Due to geometric relationships in case of a rectangular connection the sight distance sd is longer than d , whereas the opposite is true in case of a 60° angle. The results of sd and d are not significantly different since leg s is much shorter than the other legs of the triangle (see Table 4.). A similar calculation was made for right-side visibility and for the skewness in the other direction with almost identical results. It is not shown here.

5.2. Angle of view requirements

The second indicator is the field of view which drivers have to observe to oversee the required sight distance. The angle of view is marked with δ in Fig. 5. and 6. The size of this angle depends on the length of the sight distance and the angle of the intersection. In case of the above-mentioned traffic situation, the required angles of view are given in Table 5. The calculation did not yield significant differences between autonomous and human drivers. A similar calculation was made for right-side visibility and for the skewness in the other direction with almost identical results. It has to be mentioned that for skew intersection angles the required angle of view can be larger than the values given by NZTA above and this can be considered as a risk factor at such interchanges.

5.3. Angular resolution requirements

The third indicator in relation to visual acuity takes into consideration that with increasing distance the resolution is decreasing. A vehicle appears at the end of the required sight distance where the acuity is the weakest. In this moment the driver has to observe the oncoming car, take a decision and use the time

gap to cross the junction. Let's assume a four-meter-long car at the end of the required sight distance, from the point of view of the car on the minor road. One has to determine the angle of view marked with Δ in Fig. 7. which is required to notice the full length of the oncoming car on the main road (Table 6.).

With increasing speed and sight distance the angular resolution decreases. The calculated values correspond to the human visual acuity and to the best-known LIDAR resolution. Again, the results are comparable for any particular speed.

Table 3. Required intersection sight distances for left turning conventional and autonomous vehicles

Design Speed (km/h)		30	40	50	60	70	80	90	120
Conventional passenger cars	SD (m)	65	85	105	130	150	170	190	255
Autonomous vehicles	SD (m)	55	70	90	110	125	145	165	215
Difference in SD	Δ SD (m)	10	15	15	20	25	25	25	40

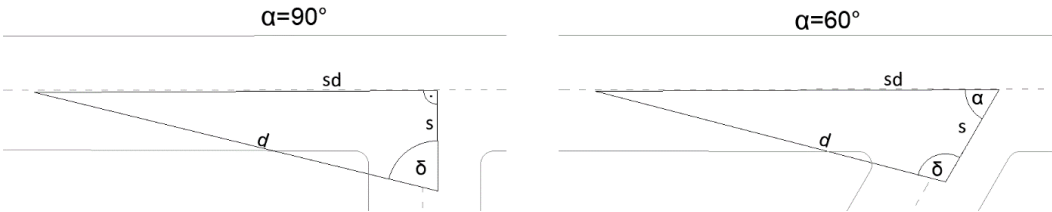


Fig. 6. Sight triangle parameters (SD, d, δ)

Table 4. Required distances (d)

Speed (km/h)	Human driver			Autonomous vehicle			Difference (m)	
	sd (m)	distance d (m)		sd (m)	distance d (m)		90°	60°
30	65	65.3	61.8	55	55.4	51.8	9.9	10.0
50	105	105.2	101.7	90	90.3	86.7	14.9	15.0
70	150	150.1	146.6	125	125.2	121.6	24.9	25.0
90	190	190.1	186.6	165	165.2	161.6	24.9	25.0
120	255	225.1	251.6	215	215.1	211.6	40.0	40.0

Table 5. Required angles of view (δ)

Speed (km/h)	Human driver			Autonomous vehicle			Difference	
	sd (m)	Joining angle		sd (m)	Joining angle		90°	60°
30	65	84.3°	114.3°	55	83.3°	113.2°	1.0°	1.1°
50	105	86.5°	116.6°	90	85.9°	116.0°	0.6°	0.6°
70	150	85.5°	117.6°	125	87.0°	117.1°	0.5°	0.5°
90	190	88.0°	118.1°	165	87.7°	117.8°	0.3°	0.3°
120	255	88.5°	118.6°	215	88.3°	118.3°	0.3°	0.3°

Table 6. Minimum required angular resolution

Speed (km/h)		30	40	50	60	70	80	90	120
Human driver	sd (m)	65	85	105	130	150	170	190	255
	Δ°	0.33	0.19	0.13	0.08	0.06	0.05	0.04	0.02
Autonomous vehicle	sd (m)	55	70	90	110	125	145	165	215
	Δ°	0.45	0.29	0.17	0.12	0.10	0.07	0.06	0.03

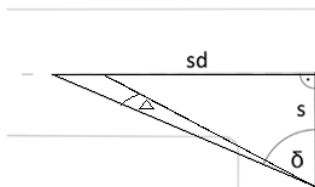


Fig. 7. Required angular resolution

5.4. The case of bicycles and scooters

Bicycles and scooters on the main road represent a separate visibility problem. Their position within the cross-section is not so well predictable, sometimes they use the sidewalk. This is dangerous not only due to pedestrian conflicts but also due to their reduced visibility from the minor road. However, this position was not considered here; their location was taken at the near edge of the pavement. Their size is smaller than the car and their speed was taken for 10, 20 and 30 km/h. Similarly to the previous method, the required sight distance, from the point of view of the car on the minor road was calculated. The required angle of view was also calculated for human driven and autonomous vehicles (Table 7.).

The autonomous car has here a similar advantage than in the previous cases. The calculated required angular resolution values correspond to the human visual acuity and to the best-known LIDAR resolution. The results show that concerning visibility, the smaller size of these vehicles is counterbalanced by their lower speed. Pedestrians were not considered in this study, due to their frequently unpredictable behavior.

6. Summary

This study investigated the visibility requirements at priority intersections. An overview of sight terms prescribed in various guidelines was given indicating the differences in their components and calculation. Visibility requirements at intersections are defined by sight distances in design guidelines. The required lengths are determined by speeds on the main road and by the time gap which is required to cross the intersection from the minor road. The relationship between speed, stopping sight distance and sight distances needed for minimum gaps was analyzed. It is remarkable that guidelines based on gap acceptance prescribe stricter values (e.g. Australia) compared to those countries (e.g. Hungary, Germany, Poland) where sight distances are based on other criteria.

Table 7. Minimum required sight distances and angular resolutions to recognize bicycles and scooters

	Speed (km/h)	10	20	30
Human driver	<i>sd</i> (m)	20	40	65
	Δ°	0,24°	0,06°	0,02°
Autonomous vehicle	<i>sd</i> (m)	20	35	55
	Δ°	0,24°	0,09°	0,04°

In general, human capabilities are built in the formulas of sight distances; it was investigated whether rapidly evolving autonomous vehicles would show different requirements. Many literature sources pointed out that autonomous vehicles have a lower reaction time than humans, thus their required sight distances can be lower.

The LIDAR sensors of autonomous vehicles are suitable to observe visibility. Based on the required sight distances and other geometric parameters, minimal values of technical indicators of LIDAR's were defined, which have to be fulfilled for safe crossing. Visibility requirements were defined by three vision indicators: distance, angle of view and resolution abilities of autonomous vehicles and human drivers. The investigated traffic situation was a left-turn movement in a STOP-controlled intersection. These indicators were calculated separately for autonomous vehicles and human drivers for various speeds on the main road and for intersections with 90° and 60° angles. It was shown that the required sight distances are 10 to 40 meters shorter for autonomous vehicles than for conventional ones. As for the angle of view and angular resolution no significant differences were found.

If we think about changing visibility requirements in design guidelines, it is true that reduced visibility ranges can only be applied after the elimination of human-driven vehicles from traffic. However, we have to be aware that the current guidelines are often unachievable. Many of the existing intersections do not have the required size of their sight fields, or there are obstacles placed within the sight field, causing object occlusion. Although this study was not able to go into details of object occlusion, we can assume that autonomous vehicles can or will be able to tackle this problem better than humans. The reason behind is that the self-driving vehicle can explore both directions simultaneously, while the human driver has to turn his head, which takes time. Furthermore, lidar sensors can be placed in several locations on the body of an autonomous vehicle to

increase visibility. All these together give an additional advantage to the autonomous vehicle.

Concluding the above studies, the detailed assessment of the sight conditions can be mentioned as a further research direction. Instead of unrealistic requirements like "should be free from any obstacles" a detailed evaluation of the amount, nature, and position of obstacles in the sight field would lead to more realistic requirements which could be really met in practice. The case of occluded intersections and decision-making in difficult situations are challenges for autonomous vehicles, too, but research in this direction has started already (e.g. Narkrsi, 2021, Wang, 2020).

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