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IMPACT OF VISIBILITY ON TRAFFIC INCIDENTS AT SIGNALIZED INTERSECTIONS – A CASE STUDY IN POLISH CITIES

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Abstract:

In urban agglomerations, signalized intersections are common. However, in traffic management, safety-focused strategies are often sacrificed for traffic efficiency by allowing simultaneous multiple conflicting movements. We identified this issue by analyzing the most dangerous signalized intersections in several Polish cities. Our research evaluated whether obstructed sight distances between major and minor traffic streams could be a significant problem at these intersections. To achieve this, we employed existing models of visibility analysis related to stopping sight distance. We determined the key parameter for stopping sight distance based on our vehicle speed studies. Tests were conducted using unmanned aerial vehicles over the intersections in the cities under consideration. Subsequently, we adapted available sight distance models to characterize conflicting streams with simultaneous green signals in a signal phase. We distinguished between major movements, including tram, pedestrian, and cyclist traffic, and minor streams, primarily involving turning vehicle movements at the intersection. Through this approach, we analyzed stopping sight distance and found that in about 60% of the cases studied, the obstructed sight distances led to a higher number of traffic incidents in the areas of conflict between major and minor traffic streams. The overall number of traffic incidents was more than 57% higher in areas with obstructed sight distance conditions, with the worst statistics involving incidents with vulnerable road users. This straightforward approach confirmed the findings of many studies that sight distance is one of the most critical factors influencing traffic safety. Based on our research findings, we recommend implementing safe traffic management strategies at intersections with obstructed sight distances, specifically multi-phase signalization. Additionally, due to the often-necessary compromise in phases involving pedestrian and cyclist traffic, we recommend conducting required sight distance analyses for vehicles turning left or right while conflicting with pedestrian or cyclist streams during a shared signal phase. Given the simplicity of the method, further research is needed to refine the approach, possibly by incorporating a stochastic model.

Keywords: *stopping sight distance, signalized intersection, traffic safety, vulnerable road user, driver's behavior*

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1. Introduction

Intersection sight distance analyses are among the key components of road safety assessments, encompassing factors such as the visibility of high-risk locations, clear traffic patterns, the number of conflict points, traffic capacity, and level of service. Regarding the required clear stopping sight distances, it is crucial to ensure no obstacles are obscuring the view between a vehicle on the major approach and a vehicle approaching the intersection from a minor approach (AASHTO, 2018, Austroads, 2023, Bąk et al., 2022). At signalized intersections, the importance of sight distance is often underestimated due to the perceived safety provided by the time separation of conflicting movements. However, certain signal phases simultaneously grant right-of-way to conflicting movements of vehicles, pedestrians, cyclists, and scooter riders, leading to a clear conflict between traffic efficiency and safety.

The research efforts were initiated to use a simple method for determining sight distance specifically for conflicting movements that simultaneously receive the right-of-way during certain signal phases. It became evident that such methods were essential for analyzing more complex signal phases. In particular, the issue of adequate sight distance was critical during signal phases where turning vehicle movements intersect with pedestrian and cyclist streams.

The objective of this verification was to determine whether traffic incident rates were indeed higher at locations with obstructed sight distances compared to those with satisfactory visibility for conflicting permitted movements on green signal phases. The aim was not to develop or improve existing models for assessing sight distance at intersections. We wanted to confirm our hypothesis that in the absence of proper driver sight distance at signalized intersections, there may be an increased number of traffic incidents, a trend noted by other researchers as well. This assumption proved correct, as confirmed by simple analysis methods that were modified to account for mutually conflicting traffic streams during simultaneous movement permissions.

2. Literature review

The reports (NCHRP, 1996 and NCHRP, 1997) are among the most important reference documents in the intersection visibility field of study. The methods and models described in these reports define the currently applied approaches to sight distances calculations. In such scenarios, drivers must anticipate potentially dangerous situations and evade them by choosing an appropriate defensive maneuver to stop the vehicle (AASHTO, 2018). The recommendations given for signalized intersections in (NCHRP, 1996 and NCHRP, 1997) make sight distance analysis an obligatory part of the design process in certain, specific cases. These cases include (AASHTO, 2018):

- the requirement to ensure appropriate sight distance to the first drivers in the queues on the receptive intersection legs,
- the requirement to ensure sight distance to right turn movements at intersections with right turn sign or signal,
- recommended sight distance analysis for optional straight and left turn movements,
- planned to switch to stop controlled operation on minor road legs.

In the first of the above listed cases, it would be difficult imaginable to have a new designed intersection where the first driver in any queue would not be able to safely see the first vehicles in the other queues at the intersection in question (except for the intersection with the center island). That said, we can still encounter exceptions to this rule in real-life engineering practice, primarily in densely developed urban settings and where bridge supports are located within the intersection area. In the second of the above cases, it must be noted that the procedure is obligatory for sight distance of the major road traffic from the perpendicular legs. Hence the analysis includes designation of clear sight distances for the minor leg traffic as for an unsignalized intersection. The third of the above procedures, a recommendation rather than a requirement, is intended to ensure sight distance of the oncoming major road traffic by drivers taking the left turn. The last procedure applies to situations where the traffic management systems allow for scheduled stop-controlled operation, for example late at night. Then it is necessary to ensure sight distances for the minor road approaches, like for unsignalized intersections, and procedure (AASHTO, 2018) applies accordingly. Noteworthy, some guidelines relating to sight distance assessment are not limited specifically to signalized intersections. For example, the sight distance models described in (Austroads, 2023; Bąk R. et al., 2022), consistent between themselves and designed for unsignalized intersections are similar to the models we find in (AASHTO, 2018).

Notably, that we have not got a detailed sight distance analysis method for simultaneously occurring conflicting vehicle movements. Similarly, one should not expect a requirement to calculate sight distances for vehicles where pedestrians or cyclists' traffic is allowed to pass the intersection at the same time. A relevant engineering guidance can be found in articles published back in the past century, dealing with the road safety of pedestrians (TECC, 1998) or cyclists (AASHTO, 1999). In the former, attention was drawn to appropriate sight conditions that need to be ensured for pedestrians. It recommended compact intersection layouts precluding simultaneous left and right turn movements, whether signal or green arrow controlled. As regards cyclists, the proposed sight distance models assume stopping of the vehicle before reaching the conflict point and cyclist's reaction time in the order of 2.5 s.

Methods for determining the traffic safety hazards due to limited stopping sight distance or drivers' reaction to them have been proposed in various publications on the subject. Research has shown that obstructed sight distances may compromise traffic safety on signalized intersections (Bauer and Harwood, 1998; CROW, 2009; Hauer, 2020; Szczuraszek and Klusek, 2019; Xuedong et al., 2018). The truth of this thesis is also supported by secondary evidence that can be found in other research papers. For example, intersection layout complexity (including added left-turn lanes) was indicated as an underlying cause or erratic driving (Fu and Liu, 2020). It was also found, that in urban areas the intersection safety requirements tend to be more relaxed, as compared to similar intersection located outside of town and cities (González-Gómez and Castro, 2020; Mahyari et al., 2021). A tendency to adopt overestimated the driver reaction times and braking decelerations in intersection design was pointed out in (Samson et al., 2022), not questioning the good effects of such overestimation on the overall traffic safety. The effect of the observed growing number of vehicles and vehicle types on the braking distance at signalized intersections was demonstrated in (Sushmitha et al., 2022). This article postulates considering in sight distance analyses the types of the vehicles concerned and the driving speeds. Also, the effect of unfavorable intersection approach path due to horizontal curvature was considered in signalized intersection sight distance analyses (Barricklow and Jacobson, 2004). It was strongly recommended to avoid such intersection layouts where sight distance is compromised.

Quite interesting are the findings of studies analyzing intersections where left turning vehicles get the right of way simultaneously with the oncoming straight-through traffic from opposite approach. Let us start with the studies reported in (Anjana and Anjaneyulu, 2015; Tang and Nakamura, 2008) which clearly demonstrated improvement of traffic safety after separation of conflicting movements on the analyzed signalized intersections. As reported in (Yan and Radwan, 2008), conflicting movements between the permitted left turning and oncoming straight through traffic could decrease the intersection capacity by up to 70% by increasing the headway and decision delay. Increasing shorter gap acceptance was also observed in the case of left or u-turning vehicles (Yan and Radwan, 2007), impacting the traffic safety at intersections. The clearance interval between conflicting movements was clearly recommended for larger intersections in (Song et al., 2014). High relevance of the queue length and time of the day to decisions of left turning drivers on intersections with conflicting movements and obstructed sight distance conditions was confirmed in (Jha and Ogallo, 2021). Solutions to the problem of mutual obscuring the view by conflicting movements were proposed in (Hussain and Easa, 2015) the left-turn lane is offset from the oncoming traffic lane, up to the desired probability of non-compliance level, using reliability analyses. The importance of intersection location in relation to other infrastructure elements for left-turn movements was indicated in (Yan et al., 2006). The methods and models proposed in these articles are designed to minimize the impact on the sight distance for left-turn traffic by way of appropriate traffic management. In the case of a U-turn movements, obstructed sight distance conditions do not have a significant role, except for the simultaneous permission of traffic from the lateral approach and vehicles entering the intersection on a "green arrow" signal, so-called Right-Turn-On-Red (Krukowicz et al, 2021).

The literature review carried out in connection with this study revealed a few noteworthy publications dealing with pedestrian traffic related issues. In Poland, the problem of pedestrian safety is very serious (Olszewski et al., 2015). The pedestrians' behavior on signalized intersections was analyzed in (Kirshnan and Marisamynathan, 2023), which included crash risk estimation, based on interviews and site inspections. The study reported in (Jin et al., 2014) showed that simultaneous movement of pedestrians and right-turning vehicles promotes risky behavior among the drivers. A traffic capacity decrease may also result from this arrangement. In (Easa, 2016) attention was drawn to a lack of guidelines for determination of pedestrians' sight distance on intersections. The models proposed therein are based on a constant clearance distance from the curbline of a pedestrian waiting at a crosswalk and a relatively small walking speed value. In (González-Gómez and Castro, 2019) the stopping sight distance of pedestrians is estimated assuming 5 s period to reach the crosswalk edge on unsignalized intersections only. General crosswalk sight distance guidelines for unsignalized intersections were developed in Poland (Gaca et al., 2021). As a minimum requirement, pedestrians stopping sight distance is 1 meter in front of the road edge. This distance increase to 3 meters near schools and hospitals. This method was used, for example, in road traffic safety surveys, such as the one carried out in Warsaw that covered all the crosswalks located in the city (Budzyński et al., 2018). Insufficient sight distances at intersections were found to increase the crash risk with pedestrians.

Notably, there are very view studies dealing with the behavior of other road users, such as cyclists, scooter riders, skaters, etc. In addition, as it was noted in (Eom and Kim, 2020), the rapid increase in the use of electromobility devices, in particular bicycles, makes the intersection design a growing challenge. The cyclist safety analysis reported in (Schröter et al., 2023) showed that it may be improved by separating the movements that are against cyclists, while, on the other hand, increasing the clearance gap between simultaneously occurring conflicting movements increases the risk of vehicle/cyclist accidents. There are also cyclist crossing design guidelines that consider the sight distance requirement (AASHTO, 1999). Their application is, however, limited to isolated cyclist crossings, located outside of intersections. For signalized road infrastructure stopping sight distance for cyclists must extend at least 4 m from the road edge when the conflicting movements are time-separated (Brzeziński et al., 2022). Without this time-separation this distance is increased to 12 meters as a minimum requirement. These problems in Poland were also characterized in (Brzeziński and Jesionkiewicz-Niedzińska, 2021).

There are also several technologically advanced methods for analyzing sight distances on signalized intersections. The examples include application of drones to identify potential view obstructions in sight analyses, as in the method proposed in (Congress et al., 2021). The study reported in (González-Gómez et al., 2021) proposed using LIDAR and GIS technologies in sight distance analyses related to protection of vulnerable road users. A few methods utilizing these technologies for different means of transport are characterized in (Jung et al., 2018). Application of sight distance data for estimating traffic safety on intersections was, in turn, attempted in (Hugesa et al., 2015).

Summing up, we can say that the issue of obstructed sight distance at signalized intersection has been studied only little so far. It focuses primarily on simultaneous occurrence of left-turn and opposite straight-through movements. It is worth noting that some researchers see the need for similar analyses concerning pedestrians and cyclists. What we miss, however, is a comprehensive sight distance assessment method designed specifically for signalized intersections with simultaneously occurring conflicting movements. Such a method should consider the possibility of implementing signal phases with simultaneous permission for different conflicting traffic streams. Most importantly, it should account for Intersection Sight Distance for major movements over Stopping Sight Distance for minor (turning) movements.

Attention is drawn to various factors that are missing in the analyses carried out so far, including tram traffic. Also, we have not found clear indication of speed(s) from which such analysis should be obligatory at signal-controlled intersections. Based on work (Hauer, 2015, Haque et al., 2016, Jiang and Wang, 2019), traffic analyses should be conducted objectively, using actual speed data. Recommended in those works is the use of the so-called operation speed value, represented by 85th percentile of speeds.

3. Methodology

The most important novelty of the method proposed in this study, compared to the existing method described in (AASHTO, 2018) lies in excluding the acceptable merging gaps in the priority traffic travel length calculation. Unlike existing methods (e.g. Austroads, 2023; Bąk R. et al., 2022), our method does not consider the minimum stopping length for major movements before conflict points with minor movements. Unlike the methods described in (Brzeziński et al., 2022; Gaca et al., 2021) we do not assume constant conflict point approach lengths for vulnerable road users (pedestrians, cyclists, etc.).

Using the basic stopping sight distance model (AASHTO, 2018) we assumed that the method to be used for sight distance determination on signalized intersections should make use of the relevant intersection users traffic speed data. Right of way granted by green light is bound to impart confidence in the road users, who on this basis would cross the intersection with less caution. Supporting evidence can be found in the findings of (Aarts and van Shagen, 2006; Datta et al., 2022; Li et al., 2019; Ni, 2020; Surisetty and Prasad, 2014; Zhao et al., 2016) or by comparing the traffic capacity calculation methods for vehicle movements on signalized vs. unsignalized intersections (HCM, 2016). For this reason, own speed survey data were used for the purposes of this study rather than generally applied intersection design input data (e.g., the speed limit). It was deemed appropriate to determine the sight distances (SD) for the following simultaneously occurring conflicting movements (Fig. 1) between:

a) left-turning vehicles (granted the right of way by the main signal) and:
   - trams moving straight-through the intersection SD_T-to-SD_L (see Fig. A.1),
   - vehicles from the opposite direction, heading straight-through the intersection SDS-to-SDL (Fig. A.2) or taking right turn SDR-to-SDL (Fig. A.3),
   - cyclists crossing the street at intersection exit leg SDexC-to-SDL (Fig. A.4),
   - pedestrians crossing the street at intersection exit leg SDexP-to-SDL (Fig. A.5),
b) right-turning vehicles (granted the right of way by the main signal) and:
   - cyclists crossing the street at intersection exit leg SDexC-to-SDR (Fig. A.6),
   - pedestrians crossing the street at intersection exit leg SDexP-to-SDR (Fig. A.7),
c) turning vehicles given the right of way by the green arrow signal (right-turn-on-red) and:
   - vehicles from the side direction, heading straight-through the intersection SDS-to-SDGA (Fig. A.8),
   - cyclists crossing the street at the same intersection approach SDenC-to-SDGA (Fig. A.9),
   - pedestrians crossing the street at the same intersection approach SDenP-to-SDGA (Fig. A.10).

Figures A.1 to A.10 are presented in the Appendix to the article.

It has been determined that the vehicle drivers in the minor movements should be ensured sight distance of the user of the road in the major vehicle movements in such a t_{stop} time that they would be able to perform the maneuver of stopping before the edge of the collision corridor of the major traffic stream. The sight triangle limits will be set by the swept path edges of simultaneously occurring conflicting movements. A constant braking deceleration of d, no influence of longitudinal grade i of the intersection approach and constant operation speed of vehicles v_{85} is assuming. Travel length of the major movement, required to allow observation by permitted turning minor movement may be calculated as an Intersection Sight Distance using the following equation:

$$SD_X = \frac{v_X \cdot t_{stop,Y}}{3.6} + l_{veh} \quad , \quad [m] \tag{1}$$

$$t_{stop,Y} = \frac{v_Y}{3.6 \cdot d} + t_r \quad , \quad [s] \tag{2}$$

where: SD_X – intersection sight distance of major movement vehicles X before conflict area with permitted turning movement Y [m], $t_{stop,Y}$ – critical approach time to conflict area between decelerating permitted movement vehicles Y and major movement vehicles X or pedestrians / cyclists Z [s], v_X – major movement speed [km/h], v_Y – minor turning movement speed [km/h], d – deceleration [m/s^2], t_r – driver reaction time [s], l_{veh} – average vehicle length [m].

Taking the same assumptions, the Stopping Sight Distance for permitted turning movements may be calculated as:

$$SD_Y = \frac{t_r \cdot v_Y}{3.6} + 0.039 \cdot \frac{{v_Y}^2}{d} \quad , \quad [m] \tag{3}$$

where: SD_Y – stopping sight distance of permitted turning movement vehicles Y before conflict area with major movement vehicles X or pedestrian / cyclist Z [m], and other variables as previously.

As regards sight distance of vulnerable road users, the observation area offered to the drivers should be extended beyond the pedestrian or cyclist crossing length, this in line with the findings of (Gruden et al., 2022; Ling and Wu, 2004; Mohammadi et al., 2023; Yang et al., 2022). A constant speed of pedestrians, cyclists or electric scooter riders during effective braking time t_{stop} of the permitted turning movement vehicles stopping before the conflict area is assuming as previously. Hence, a Crossing Sight Distance of vulnerable road users may be calculated using the following equation:

$$SD_Z = \frac{v_Z \cdot t_{stop,Y}}{3.6} + l_{uru} \quad , \quad [m] \tag{4}$$

where: SD_Z – crossing sight distance of a vulnerable road user to conflict area with permitted turning movement vehicles Y [m], v_Z – vulnerable users' speed [km/h], l_{uru} – average vulnerable users' length [m], and other variables as previously.

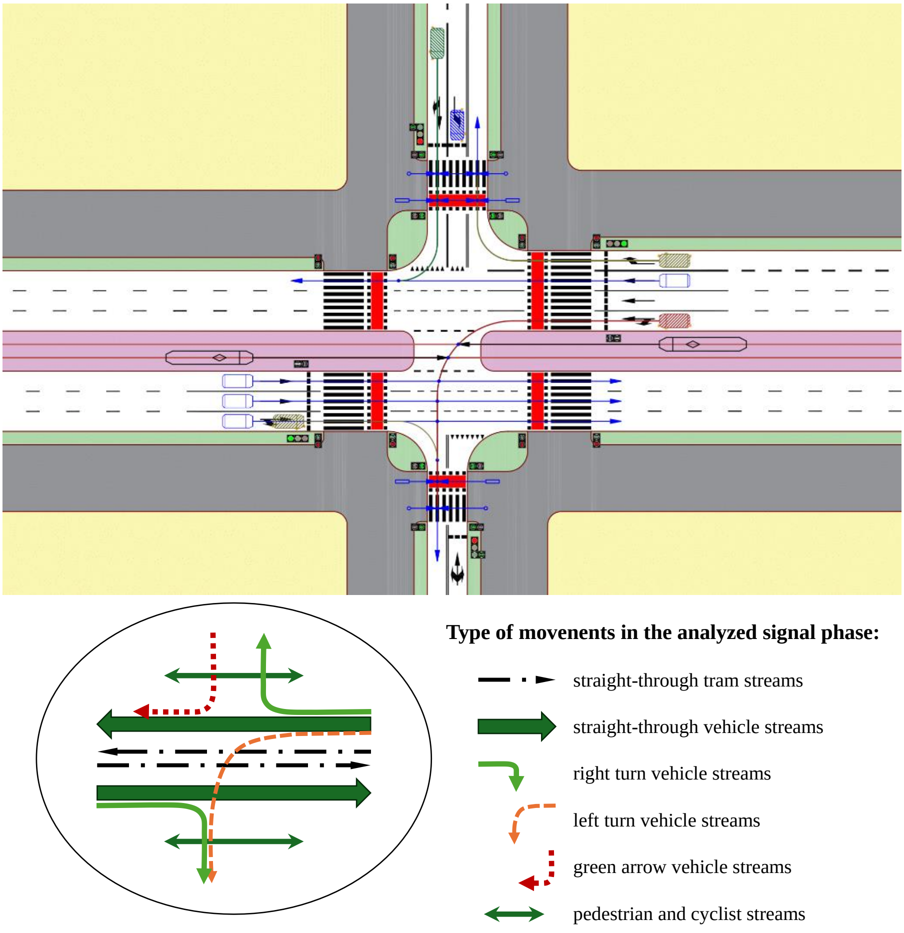


Fig. 1. Trajectories of permitted movements in a single signal phase for which the sight distance conditions are verified.

Thus, the sight 'triangle' determined with the above method is a part of intersection area composed of approach sections to a common conflict area between simultaneously occurring movements. The lengths of these approach sections give the minimum sight distance for minor permitted turning movement vehicles to stop before reaching an identified conflict area. The relevant distance was assumed to be included in the critical stopping time calculated for vehicles in the permitted turning movement. In all cases, vehicles in the permitted turning movement must be able to stop safely before reaching a conflict area with vehicles or pedestrians in a major movement. The sight lines are, therefore, determined for the most distant swept path edge of major movements rather than for the driving trajectory on the traffic lane center lines. This is particularly relevant to the irregular use of the roadway surface by pedestrians or cyclists crossing the street via legal crossing facilities. The braking distance for minor permitted turning movement is measured to the nearest edge of conflict point with major movement in question. For permitted turning movements on curves the sight distances should be determined using a tangent line drawn from the inner edge of the major movement swept path to the curve apex of the permitted turning movement trajectory. The observation target must not be obscured higher than 1.1 m (AASHTO, 2018). In our research, we used 0.6 m high observation targets for sight distance determination purposes (Bąk et al., 2022).

4. Field research

The above-mentioned models require estimation of the basic traffic characteristics. Some of them have been adopted arbitrarily from Polish studies and compared to international study results (*AASHTO, 2018; HCM, 2016*). These characteristics are compiled further on in this article (Table 3).

Semi-automatic speed detection method was used to collect the required data in the 2022 traffic surveys carried out on twelve signalized intersections located in Bydgoszcz and Toruń, Poland. Video recordings of 1080p resolution were captured at 25 fps sample rate by pole-mounted cameras or using a drone flying over these intersections and then process for the purposes of this analysis. Numerical maps were obtained for the analyzed intersection area from the mapping archives, on which the test sections corresponding to the travel lengths between the test points were plotted. In most cases, these were swept paths crossing the central area of the analyzed intersections, limited by the crosswalk outer edges. The speeds were calculated based on the respective entry and exit times only in free flow conditions, this to exclude any effect of any proceeding or following vehicles. The entry and exit times were determined by recording the vehicle rear at the test points, considering the entire vehicle silhouette. In the case of turning movements, the speeds were determined for the pre-set trajectory radius ranges (r = 5÷45 m). The speeds of trams were determined for straight-through movements only. The video analyses were carried out by specialists equipped with special software allowing real-time retrieval of data in slow-motion (0.5x normal speed). The data were logged in a spread sheet, giving the captured frame number for each observed vehicle. Knowing the length of travel through the test section, it was possible to calculate the spot speeds to 1 km/h accuracy. All the test sections were in the central area of signalized intersections having max. 3% longitudinal gradients. Steeper intersections were excluded. The average sectional speed error for the entire test range assumed of the law of error transmission. On this basis, a root mean squared estimation error (RMSE) of ±1.6 km/h was calculated for all tested areas. The error in the measurement of the car's transit time through the measurement base was arbitrarily assumed to be ±0.1 s.

The main part of the survey was carried on six intersections located in Bydgoszcz and six in Toruń (each group including two regular and two channelized ones and two having a center island). Descriptive statistics of the study results are compiled in Table 1 and in Figure 2. The speed distributions into the straight-through, left-turn and right-turn movements were obtained using *Shapiro-Wilka* test (Aczel and Sounderpandian, 2009). The null hypothesis of normal distribution of the free-flow speeds was not confirmed at $\alpha = 0.05$ confidence level. Using the non-parametric *Kruskal-Wallis* test it was found that there were not statistically significant differences between the two cities for neither of the test samples (straight-through, left- and right-turning movements respectively) at α = 0.05 statistical significance level. On the other hand, statistically significant differences were found between the respective movement directions (straight-through, left- or right turn) and turning radii (the greater the radius, the shorter the travel time through the intersection). This was expected based on the research results (Aarts and van Shagen, 2006). The relationship in terms of type of intersection was also analyzed. The division was made based on (Bąk et al., 2022) into:

– Simple: defined as intersections of roads with a generally accessible surface where collision traffic streams intersect, without traffic channelization elements (apart from pavement guiding lines).
– Channelized: at least one of the intersecting roads has a dividing lane, and the main collision plane may or may not have channelization with curbed islands or marked exclusion zones.
– Rotary: a channelized intersection where the collision area has a central island around which left-turning traffic moves and the road around the island can also serve as a vehicle accumulation area.

Based on the divided data, a *Kruskal-Wallis* test for speed relative to the examined variables was conducted. Since the statistical significance of at least one of the examined groups was confirmed, a *Dunn* test was conducted in the next stage to determine which specific groups differ from each other. The results of this test are summarized in Table 2. It follows that the free-flow speed movement through an intersection with traffic lights depends on many factors.

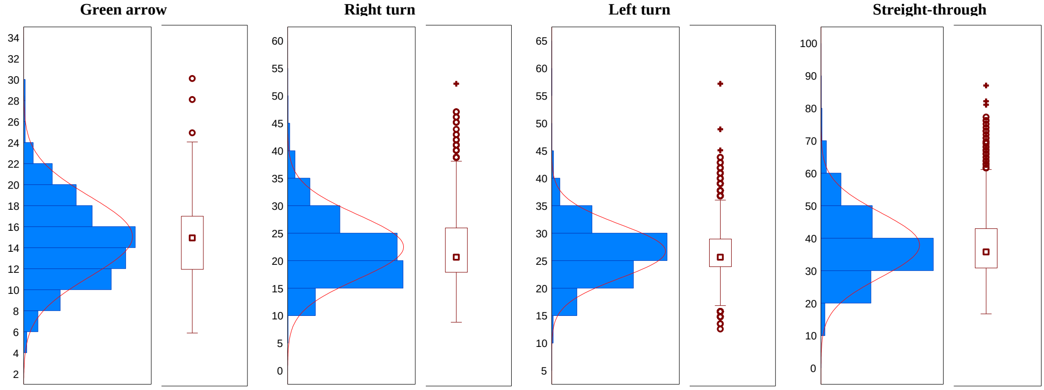


Fig. 2. Histograms and boxplots for tested values of free-flow speed movements at signal-controlled intersections.

Table 1. Speed statistics for free flow condition on the analyzed signalized intersections located in Bydgoszcz and Toruń [km/h]

Parameter:	**Movement type:**				
	green arrow	**right turn**	**left turn**	**straight-through**	**trams**
Sample size	326	2,382	2,155	2,280	770
Min.	6	9	13	17	8
Max.	30	49	57	87	27
Median	14.8	20.6	25.6	35.7	15.0
Mean	15.0	21.6	25.9	37.7	15.3
Standard deviation	3.8	4.9	4.4	9.9	3.1
15th percentile	11.1	16.1	20.8	27.8	11.9
85th percentile (operating speed)	19.1	26.3	29.7	46.9	18.0
Shapiro-Wilk W value	0.983	0.950	0.983	0.958	0.985
***p*-value**	<0.01	<0.01	<0.01	<0.01	<0.01

Table 2. Matrix of Dunn's test results for the tested variables

	$V_{SI,ST}$	$V_{SI,LT}$	$V_{SI,RT}$	$V_{CI,ST}$	$V_{CI,LT}$	$V_{CI,RT}$	$V_{RI,ST}$	$V_{RI,LT}$	$V_{RI,RT}$	$V_{SI,GA}$	$V_{CI,GA}$	$V_{RI,GA}$
$V_{I1,ST}$		Z=15.7 p<0.01	Z=29.0 p<0.01	Z=14.1 p<0.01	**Z=1.5 p>0.90**	Z=16.2 p<0.01	Z=17.3 p<0.01	Z=7.7 p<0.01	Z=9.8 p<0.01	Z=15.6 p<0.01	Z=22.5 p<0.01	Z=8.5 p<0.01
$V_{I1,LT}$	Z=15.7 p<0.01		Z=8.7 p<0.01	Z=28.5 p<0.01	Z=17.5 p<0.01	**Z=3.3 p=0.07**	Z=31.2 p<0.01	Z=10.0 p<0.01	Z=8.6 p<0.01	Z=6.8 p<0.01	Z=8.4 p<0.01	**Z=3.1 p=0.12**
$V_{I1,RT}$	Z=29.0 p<0.01	Z=8.7 p<0.01		Z=46.3 p<0.01	Z=32.0 p<0.01	Z=15.4 p<0.01	Z=49.6 p<0.01	Z=23.4 p<0.01	Z=22.1 p<0.01	**Z=2.5 p=0.80**	**Z=2.0 p>0.90**	**Z=0.3 p>0.90**
$V_{I2,ST}$	Z=14.1 p<0.01	Z=28.5 p<0.01	Z=46.3 p<0.01		Z=13.2 p<0.01	Z=33.7 p<0.01	Z=3.5 p=0.03	Z=23.8 p<0.01	Z=26.8 p<0.01	Z=22.1 p<0.01	Z=33.4 p<0.01	Z=13.3 p<0.01
$V_{I2,LT}$	**Z=1.5 p>0.90**	Z=17.5 p<0.01	Z=32.0 p<0.01	Z=13.2 p<0.01		Z=18.7 p<0.01	Z=16.6 p<0.01	Z=9.7 p<0.01	Z=12.0 p<0.01	Z=16.4 p<0.01	Z=24.1 p<0.01	Z=8.9 p<0.01
$V_{I2,RT}$	Z=16.2 p<0.01	**Z=3.3 p=0.07**	Z=15.4 p<0.01	Z=33.7 p<0.01	Z=18.7 p<0.01		Z=37.3 p<0.01	Z=9.1 p<0.01	Z=7.2 p<0.01	Z=8.9 p<0.01	Z=12.3 p<0.01	Z=4.2 p<0.01
$V_{I3,ST}$	Z=17.3 p<0.01	Z=31.2 p<0.01	Z=49.6 p<0.01	Z=3.5 p=0.03	Z=16.6 p<0.01	Z=37.3 p<0.01		Z=27.3 p<0.01	Z=30.3 p<0.01	Z=23.5 p<0.01	Z=35.7 p<0.01	Z=13.3 p<0.01
$V_{I3,LT}$	Z=7.7 p<0.01	Z=10.0 p<0.01	Z=23.4 p<0.01	Z=23.8 p<0.01	Z=9.7 p<0.01	Z=9.1 p<0.01	Z=27.3 p<0.01		**Z=2.1 p>0.90**	Z=12.4 p<0.01	Z=17.9 p<0.01	Z=6.4 p<0.01
$V_{I3,RT}$	Z=9.8 p<0.01	Z=8.6 p<0.01	Z=22.1 p<0.01	Z=26.8 p<0.01	Z=12.0 p<0.01	Z=7.2 p<0.01	Z=30.3 p<0.01	**Z=2.1 p>0.90**		Z=11.7 p<0.01	Z=16.8 p<0.01	Z=5.9 p<0.01
$V_{I1,GA}$	Z=15.6 p<0.01	Z=6.8 p<0.01	**Z=2.5 p=0.80**	Z=22.1 p<0.01	Z=16.4 p<0.01	Z=8.9 p<0.01	Z=23.5 p<0.01	Z=12.4 p<0.01	Z=11.7 p<0.01		**Z=1.1 p>0.90**	**Z=1.1 p>0.90**
$V_{I2,GA}$	Z=22.5 p<0.01	Z=8.4 p<0.01	**Z=2.0 p>0.90**	Z=33.4 p<0.01	Z=24.1 p<0.01	Z=12.3 p<0.01	Z=35.7 p<0.01	Z=17.9 p<0.01	Z=16.8 p<0.01	**Z=1.1 p>0.90**		**Z=0.4 p>0.90**
$V_{I3,GA}$	Z=8.5 p<0.01	**Z=3.1 p=0.12**	**Z=0.3 p>0.90**	Z=13.3 p<0.01	Z=8.9 p<0.01	Z=4.2 p<0.01	Z=13.3 p<0.01	Z=6.4 p<0.01	Z=5.9 p<0.01	**Z=1.1 p>0.90**	**Z=0.4 p>0.90**	

Indications: *V* – tested values for: *SI* – simple intersection, *CI* – channelized intersection, *RI* – rotary intersection, and for type of relation movements: *ST* – straight-through, *LT* – left turn, *RT* – right turn, *GA* – green arrow (right-turn-on-red)

Therefore, a linear regression model was built, considering the examined factors for the operation speed (85th percentile). The final form of this model for straight-through relation on simple signal-controlled intersection is describe on (5) formula. Based on the obtained statistics for this model, it can be concluded that it explains the variability of the operation speed at a high level, is statistically significant, and does not have issues with autocorrelation of residuals.

$$\begin{aligned} v_{85\%} = {} & 41.34 + 3.92 \cdot f_{CI} + 6.88 \cdot f_{RI} \\ & -16.07 \cdot f_{LT} - 19.00 \cdot f_{RT} \\ & -25.49 \cdot f_{GA} \ [km/h] \end{aligned} \tag{5}$$

$R^2 = 0.961$; Adj.$R^2 = 0.928$; F-statistic = 29.29 with p-value < 0.01 ; Durbin-Watson = 1.644
where: $v_{85\%}$ – 85th percentile vehicle speed [km/h], f – a variable describing a given feature (0 or 1 for a categorical variable: f_{CI} – channelized intersection, f_{RI} – rotary intersection, f_{LT} – left turn relation, f_{RT} – right turn relation, f_{GA} – green arrow relation).

Considering statistically significant differences that were obtained for turning movements, depending on the vehicle trajectory radii, it seemed appropriate to develop operation speed determination model that would consider the turning movement direction and trajectory radius. On this basis, we obtained moderately goodness-of-fit ($R^2 \sim 0.60$) for the right and left turning movement. A general model that did not differentiate between movement directions was also developed with quite good goodness-of-fit ($R^2 \sim 0.70$). It is noted that the model accounting for the turning radius of the trajectory shows less accuracy in estimation. The best statistically fitted models for the discussed turning movements are presented below:

$$v_{turn,85\%} = 8.7084 \cdot ln(r) + 1{,}7504 \ [km/h] \tag{6}$$
$R^2 = 0.6868$ ($r_{min} = 5\ m$, $r_{max} = 45\ m$)

$$v_{left,85\%} = 13.3 \cdot r^{0.2537} \ [km/h] \tag{7}$$
$R^2 = 0.5885$ ($r_{min} = 12\ m$, $r_{max} = 45\ m$)

$$v_{right,85\%} = 9.5358 \cdot r^{0.3459}\ [km/h]$$
$$R^2 = 0.6090\ (r_{min} = 5\ m,\ r_{max} = 25\ m) \quad (8)$$

where: $v_{turn,85\%}$ – 85th percentile vehicle speed for turning relation [km/h], $v_{left,85\%}$ – 85th percentile left turn vehicle speed [km/h], $v_{right,85\%}$ – 85th percentile right turn vehicle speed [km/h], r – turning movement trajectory radius at signal-controlled intersection, [m], ln – natural logarithm.

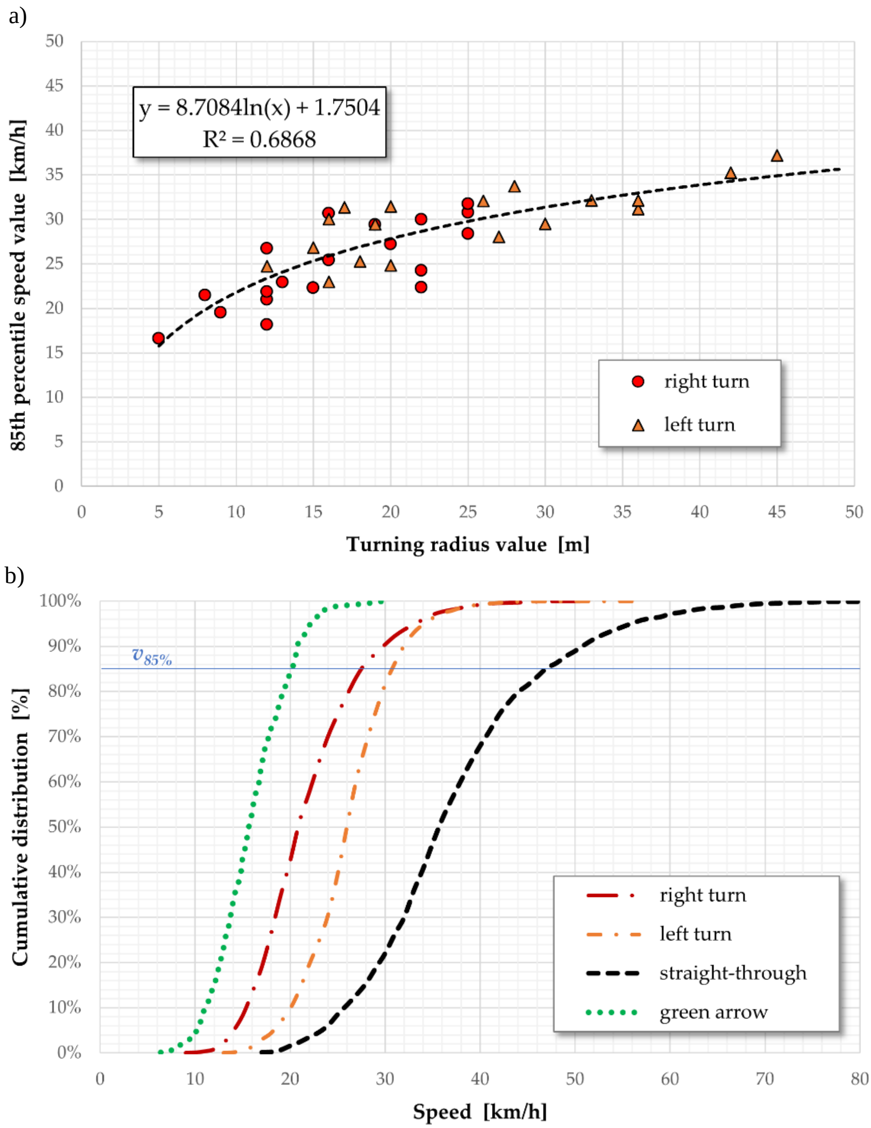


Fig. 3. 85th percentile speeds vs. vehicle trajectory radius of left and right turn movements (a) and cumulative speed distribution function vs. type of relation movements (b) on analyzed signal-controlled intersections in Poland

The last parameter required to carry out the analyses was vehicle length. Brand and model were logged for each vehicle during peak hours at the analyzed intersections in Bydgoszcz. A semi-automatic method was used for this, employing a digital video camera. Then, the length data were retrieved from the relevant car manufacturers' catalogs. Non-typical vehicles that could not be found in the available catalogs and unidentified vehicles were excluded from the analysis. As a result, 1,180 light and 220 heavy vehicles were identified in total, with average lengths of 4.48 m and 8.84 m, respectively, and standard deviations of 0.63 m and 2.41 m. The tram lengths were arbitrarily adopted based on the gathered rolling stock information in the analyzed cities. All the required calculation parameters are compiled in Table 3. Figure 4 (A-B) shows the sight distances for signalized intersections, based on input parameters for the models (1), (3) and (4). The data presented in Figure 4 (A-B) illustrate the required sight distance for drivers depending on the selection speed parameters, also different than those presented in Table 3.

The authors deliberately refrain from more detailed analyses of the examined speeds, in line with the objective of this article. It has been decided that the results of these detailed studies will be described in a separate article.

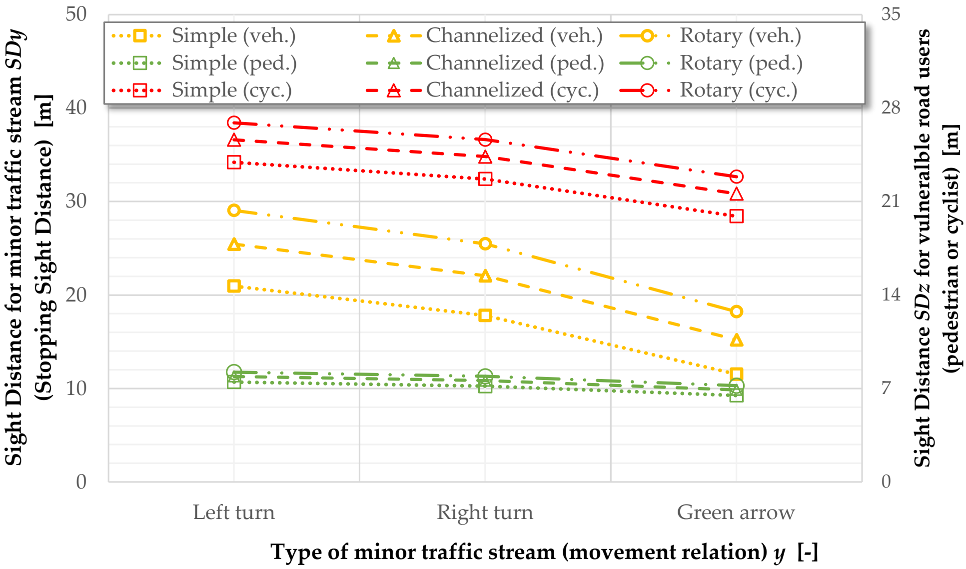
5. Results

The conflicting movements sight distance analysis model adopted as part of this study was applied to selected signalized intersections located in Toruń, Bydgoszcz, and Warsaw. The test sites comprised the most dangerous intersections based on data on the number of road incidents (*RI*). In Poland, traffic incident data are gathered by the Police and logged in the accident register (*KGP, 2023*). These data were used as input for further analyses of this study. It should be emphasized that the data analyzed represent only official reports of traffic incidents by vehicle drivers, which were then verified and plotted on a numerical map.

Table 3. Input parameters for sight distance calculations for signalized intersections

No.	Parameter:	Value:			
		unit	**average**	**85th percentile**	**adopted in analyses**
1.	Speed of trams $v_{x,tram}$	km/h	15.3	18.0	20.0
2.	Speed of vehicles in a straight-through major movement $v_{x,}$, v_y		29.3	37.2	model (5)
3.	Speed of vehicles in the right-turn major or minor movement $v_{x,}$, v_y		21.6	26.3	model (5)
4.	Speed of vehicles in the left-turn minor movement v_y		25.9	29.7	model (5)
5.	Speed of the vehicles in permitted movement on a green arrow signal v_y		15.0	19.1	model (5)
6.	Speed of vehicles in turning movement, depending on the turning *r* radius $v_{x,}$, v_y		—	model (6)	—
7.	Pedestrian speed (Gaca et al., 2021; ITS, 2018) v_z		5.0	5.4	5.0
8.	Speed of cyclists and electric scooters (Brzeziński et al. 2022; ITS 2021) v_z		18.6	21.1	20.0
9.	Driver response time, as adopted in engineering calculations (AASHTO, 2018, Bąk et al. 2022) $t_{r.}$	s	2.0	—	2.0
10.	Tram braking deceleration (Bąk et al. 2022) $d_{,tram}$	m/s^2	1.5	—	1.5
11.	Deceleration of straight-through vehicles (Bąk et al. 2022) $d_{,S}$		3.4	—	3.5
12.	Deceleration of turning vehicles (Bąk et al. 2022) $d_{,Turn}$		3.6	—	
13.	Light vehicle length $l_{veh,l}$	m	4.5	—	5.0
14.	Heavy vehicle length $l_{veh,h}$		8.8	—	10.0
15.	Area occupied by a single pedestrian: adult; child; person on a wheelchair; person with a pram or stroller; measured lengthwise (Neufert, 2012) l_{ped}		0.5; 0.9; 1.1; 2.0	—	2.0
16.	Area occupied by a cyclist, measured lengthwise (Neufert, 2012) l_{cyc}		1.9	—	

a)



b)

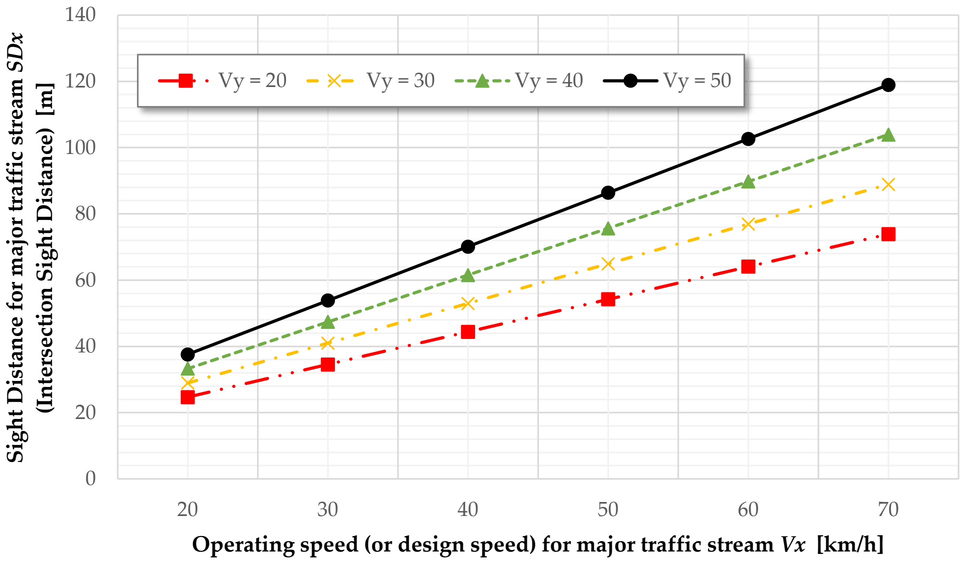
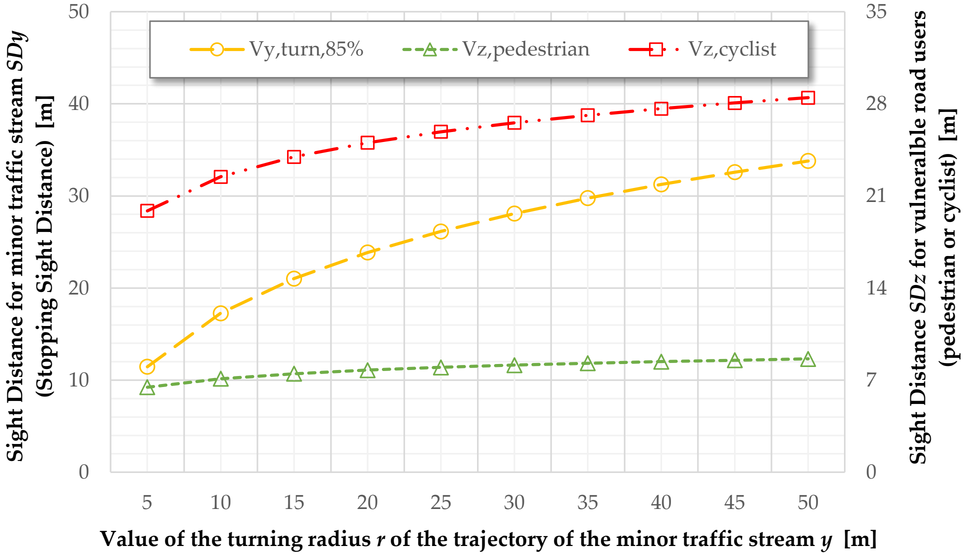


Fig. 4.A. Compilation of signalized intersection sight distances for:

a) permitted minor turning movement Y required to see major vehicles of permitted movement X and pedestrians or cyclists of major movement Z, in relationship to type of intersection (using model (5)),

b) major movement X required to see minor vehicles of permitted turning movement Y, depending on the arbitrarily adopted operation vehicle speed of turning movement Y.

c)



d)

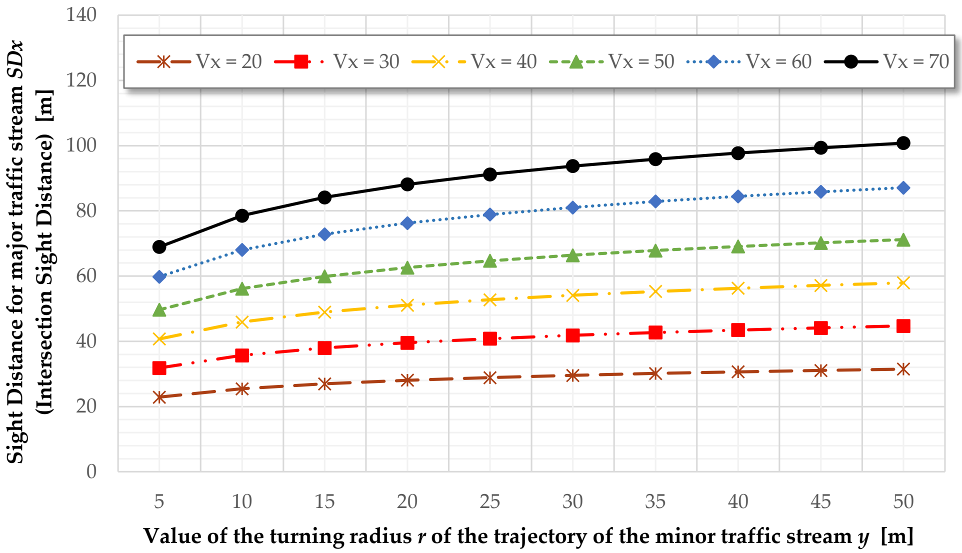


Fig. 4.B. Compilation of signalized intersection sight distances for:

c) permitted minor turning movement Y required to see pedestrians or cyclists of major movement Z, depending on the actual turning radius (using model (6)),

d) major movement X required to see minor vehicles of permitted turning movement Y, depending on the actual turning radius (using model (6)).

The studied intersections in Toruń (Szczuraszek et al., 2019) and Bydgoszcz (Bebyn et al., 2023) were selected based on equivalent road traffic incident data for a three-year period. The selected intersections exceeded the ERI_{crit} limit of equivalent incidents ERI. This limit was calculated with the following equation:

$$ERI_{crit.} = ERI_{av} + 2 \cdot \sigma_{ERI} \quad , \quad [-] \tag{9}$$

where: $ERI_{crit.}$ – number of equivalent traffic incidents above which an intersection is classified in the 'most dangerous' group, ERI_{av} – average number of equivalent road incidents on intersections in each city, σ_{ERI} – standard deviation of equivalent road incidents on intersections in each city.

For this analysis, an equivalent road incident is any incident of moderate material consequences (Bebyn et al., 2007; Szczuraszek, 2008):

$$\begin{aligned} ERI_i = \eta_{f,i} \cdot \rho_f + \eta_{h,i} \cdot \rho_h \\ +\eta_{l,i} \cdot \rho_l + \eta_{d,i} \cdot \rho_d [-] \end{aligned} \tag{10}$$

where: ERI_i – equivalent i-th road incident with moderate material consequences $\eta_{d,i}$, $\eta_{h,i}$, $\eta_{l,i}$, $\eta_{v,i}$ meaning the number of: fatalities (f), heavy injuries (h), light injuries (l) damaged vehicles (d) respectively; ρ_d, ρ_h, ρ_l, ρ_v – weights of the respective incidence consequences (Jaździk-Osmólska et al., 2022): fatality (27,06), heavy injury (35,13), light injury (0.52), vehicle damage only (0.50); these weights represent the relative cost of these consequences, calculated in relation to an average collision, here called equivalent road incident.

In the case of the intersections located in Warsaw, they were identified as the most dangerous signalized intersections in the city based on (FRIL, 2022). The accident rates were analyzed over a three-year period from 2018 to 2022, when the highest rates were noted. The intersections for which sight distance analyses were carried out based on earlier assumptions are compiled in Table 4, giving the road incident types and numbers. Sight distance analysis was investigated for all relations in the implemented signal phase configurations at these intersections. Figure 5 shows diagrams of road accidents and sight distances for one of the signal phases that occurred at one of the most dangerous intersections in Warsaw (Iwanowicz, 2023).

If any objects that could compromise drivers' and/or pedestrians' perception were identified within the established sight distances, these sight distances were classified as obstructed sight distances. Otherwise, they were classified as clear sight distances. These obstructions included any feature or group of features located within the right of way. The classification of these objects is presented in Table 5 along with their percentage share in the analyzed sight distances for permitted turning movements. It was assumed that the obstacles included also stopped vehicles on the adjacent, inside lanes in relation to the permitted movement vehicles on the green arrow signal in the same intersection approach. In other cases, moving or stopped vehicles were not considered an obstacle to drivers' or pedestrians' sight distance. Those findings were adopted arbitrary based on own field experience.

The above data allow us to connect a higher number of traffic incidents on signalized intersection with simultaneously occurring conflicting movements. This connection was confirmed by the non-parametric *Wilcoxon* test at $\alpha = 0.05$ significance level. The p-value of this test was 0.0202. The equivalent number of road incidents was also compared giving $p = 0.0132$, i.e. confirming statistically significant difference in this case.

The following conclusions can also be drawn based on the data relating to the analyzed obstructed sight distances at signal-controlled intersections: 15.0% more frontal crashes, 23.8% more right-angle crashes, 54.6% more vehicle-pedestrian crashes, and a stunning 233.3% more vehicle-cyclist and vehicle-scooter crashes (9 incidents with clear sight distance and 30 incidents with obstructed sight distance).

This data may indicate that at signalized intersections, where drivers of minor permitted movements have their perception considerably compromised by obstructing obstacles, the primary road crash victims are vulnerable users. Attention is drawn to the fact that bicycle infrastructure in Poland is not always present at signalized intersections.

Table 4. Number of road incidents* involving cars from conflicting movements at the most dangerous signalized intersections - own work based on (Bebyn et al., 2023; Iwanowicz, 2023; Szczuraszek et al., 2019 and Komenda Główna Policji, 2023)

No.	City and period	Intersection location	Clear sight distance		Obstructed sight distance	
			RI	***ERI***	***RI***	***ERI***
1.	Toruń 2016-2018	53°01'17.4"N 18°38'52.3"E	4	4.04	6	76.28
2.		53°01'27.6"N 18°37'58.2"E	6	41.17	1	1.00
3.		53°00'34.6"N 18°35'58.6"E	2	2.00	4	39.19
4.		53°01'38.8"N 18°36'39.9"E	1	1.00	3	38.17
5.		53°01'34.5"N 18°36'05.6"E	0	0.00	2	37.15
6.	Bydgoszcz 2018-2020	53°07'32.3"N 17°59'10.1"E	2	37.15	1	36.13
7.		53°08'13.2"N 17°57'52.6"E	0	0.00	3	38.17
8.		53°07'36.0"N 18°02'27.6"E	4	4.00	6	6.02
9.		53°06'53.0"N 18°01'00.0"E	2	2.04	5	5.00
10.		53°07'14.7"N 18°03'24.5"E	4	4.02	2	2.04
11.		53°07'22.9"N 18°01'08.8"E	0	0.00	5	5.02
12.		53°08'14.6"N 18°00'55.0"E	1	1.00	3	3.06
13.		53°06'29.8"N 18°02'03.1"E	2	2.02	2	2.00
14.		53°07'17.7"N 17°59'12.1"E	2	2.02	1	1.02
15.		53°08'03.3"N 18°02'11.0"E	0	0.00	3	3.00
16.		53°07'32.8"N 17°59'29.8"E	3	3.00	0	0.00
17.		53°07'15.4"N 18°02'06.1"E	0	0.00	2	2.02
18.		53°07'01.4"N 18°02'01.9"E	1	1.00	0	0.00
19.	Warsaw 2018-2020 or 2020-2022	52°11'35.3"N 20°57'38.7"E	3	3.06	10	239.83
20.		52°14'13.2"N 20°58'48.6"E	1	36.13	7	182.69
21.		52°14'32.7"N 21°06'07.8"E	3	108.39	2	37.15
22.		52°10'13.4"N 21°02'26.7"E	4	66.23	4	74.30
23.		52°14'08.1"N 20°58'50.3"E	1	1.02	5	110.43
24.		52°14'23.6"N 20°58'45.9"E	1	36.13	2	72.26
25.		52°14'39.2"N 20°58'38.7"E	4	74.30	0	0.00
26.		52°13'48.8"N 21°01'50.2"E	1	1.02	2	72.26
27.		52°13'54.9"N 20°59'33.1"E	1	36.13	2	37.15
28.		52°15'17.0"N 21°02'05.3"E	1	36.13	1	28.06
29.		52°12'58.7"N 20°58'52.0"E	5	5.10	6	41.23
30.		52°13'35.2"N 20°59'44.9"E	2	2.04	4	39.19
31.		52°15'59.1"N 20°58'37.6"E	0	0.00	2	2.04
32.		52°15'20.1"N 21°02'03.4"E	0	0.00	0	0.00
33.		52°14'23.4"N 21°06'51.0"E	0	0.00	0	0.00
Intersection average:			**1.85**	**15.46**	**2.91**	**37.33**
Total:			**61**	**510.14**	**96**	**1,231.86**
Relative difference:					**57.38%**	**141.47%**
Type of intersection			**Average values**			
1.	Intersection without traffic channelization (Simple)		1.50	10.29	2.50	37.64
2.	Intersection with a median dividing the main roadways (Channelized)		1.73	24.09	1.36	20.54
3.	Intersection with a median dividing the main and subordinate roadways (Channelized)		2.43	21.38	3.71	52.79
4.	Intersection with a median dividing the main and subordinate roadways and with center island (Rotary)		1.22	5.14	2.22	13.95
5.	Intersection with a median dividing the main and subordinate roadways and with center island and with road overpass (Rotary)		2.00	2.02	5.50	40.65

* - including side-impact or frontal crashes, hitting a pedestrian, cyclist or scooter-rider and excluding turning movement prohibition violations

Table 5. The percentage of identified obstacles in the sight distances at the analyzed signal-controlled intersections [%]

No.	Objects in stopping sight distance (excluding traffic lights or signs with masts)	Type of movement*:		
		left turn	**right turn**	**green arrow**
1.	Buildings or architectural objects (e.g. monument)	0.0	**36.4**	15.2
2.	Guardrails, barriers with spaced vertical bars or opaque infill	12.1	18.2	9.1
3.	Plot fencing	0.0	15.2	9.1
4.	Large sign boards or long warning boards	3.0	3.0	0.0
5.	Groups of masts, streetlights and tram catenary masts	**33.3**	15.2	21.2
6.	Single masts or arms thicker than 100 mm	18.2	30.3	21.2
7.	Bridge supports	0.0	0.0	3.0
8.	Traffic control or lighting control or other cabinets	0.0	21.2	12.1
9.	Ticket machines or parcel lockers	0.0	3.0	0.0
10.	Cycle racks	0.0	6.1	9.1
11.	Shelters or tram platforms with large groups of passengers	9.1	0.0	0.0
12.	Vehicles parked in parking bays, on footways or in parking lots	0.0	3.0	12.1
13.	Noise barriers	0.0	6.1	3.0
14.	Medium-high or larger plants	12.1	**36.4**	12.1
15.	Trees	9.1	9.1	18.2
16.	Ads	0.0	9.1	6.1
17.	Multi-lane intersection approach (potentially with vehicles stopped in adjacent lanes, waiting for the green signal)	-	-	**78.8**

* - based on Figures in the attachment (A.1 – A.5 for left turn, A.6 – A.7 for right turn and A.8 – A.10 for green arrow)

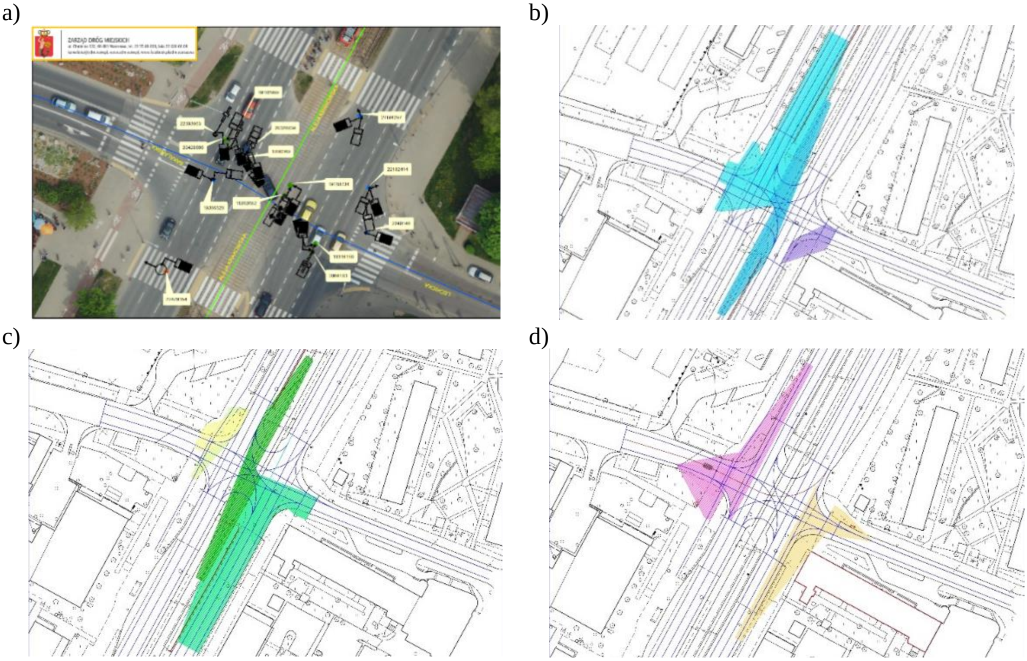


Fig. 5. Example layout plans showing road accident diagram on the most dangerous signalized intersection in Warsaw (a) with marked sight distances for left and right turn movements from the southern (b) and northern (c) approaches, as well as on the green arrow signal from the lateral west-east approaches (d). Source: own work based on Iwanowicz, 2023

The impact of available independent variables on the number of traffic incidents for conflicting streams with permissible simultaneous movement in a single signal phase within areas of obstructed sight distance was examined in the next step of the analysis. For this purpose, a linear *OLS* regression analysis was conducted using the following model:

$$RI_{OSD} = \beta_0 + \beta_1 \cdot f_{IT} + \beta_2 \cdot f_{PHT} + \beta_3 \cdot f_{NSP} + \varepsilon \; [-] \quad (11)$$

where: RI_{OSD} – number of traffic incidents for conflicting streams with simultaneous movement allowed in the signal phase and in obstructed sight distance condition, β_0 – intercept, β_1, β_2, β_3 – regression coefficients for the respective variables, f_{IT} – categorized variable representing the type of intersection (simple, channelized, rotary), f_{PHT} – variable representing the peak hour traffic volume at the intersection, f_{NSP} – variable representing the number of signal phases, ε – residual error term.

Additionally, given that the dependent variable is represented as a count data, a *Poisson* regression analysis was also conducted. Due to the high variability in the data, a *Negative-Binomial* regression analysis was performed as well. The results of these analyses are summarized in Table 6.

Based on the data obtained from this analysis, the following conclusions can be drawn. The overall model shows a relatively low goodness of fit to the variables, as suggested by the R^2 and AIC values. Nevertheless, only the variable determining the number of signaling phases proves statistically significant. More signal phases mean fewer traffic incidents, which is as expected. The *p*-value for the *F*-test indicates that the model is not significant at the 0.05 level, meaning that the independent variables may not explain a significant portion of the variance in the dependent variable. This implies that more detailed studies should be undertaken regarding the analysis of the impact of obstructed sight distance on the number of traffic incidents at signalized intersections, to link this aspect with other variables.

Table 6. Regression analysis results for the tested variables in model (11)

No.	Variable	Coeff.	Std error	*t* or *z* value	*p*-value	95% conf. interval	VIF
OLS Regression Results							
1.	B_0 (const.)	3.1846	1.585	2.009	0.054	-0.062 ; 6.431	16.642
2.	f_{PHT}	0.0007	<0.001	1.420	0.167	-0.0004 ; 0.002	1.870
3.	f_{NSP}	-1.0197	0.405	-2.521	**0.018**	-1.848 ; -0.191	1.574
4.	$f_{IT,channelized}$	0.1976	1.454	0.136	0.893	-2.781 ; 3.176	3.473
5.	$f_{IT,rotary}$	0.6854	1.836	0.373	0.712	-3.075 ; 4.446	4.964
	R^2 = 0.211 ; Adj. R^2 = 0.098 ; F-statistic = 1.872 with *p*-value = 0.143 ; AIC: 151.2 ; Durbin-Watson = 1.491						
Poisson Regression Results							
1.	B_0 (const.)	1.3102	0.473	2.768	**0.006**	0.382 ; 2.238	–
2.	f_{PHT}	0.0002	<0.001	1.569	0.117	-0.000048 ; 0.0002	–
3.	f_{NSP}	-0.3912	0.126	-3.100	**0.002**	-0.638 ; -0.144	–
4.	$f_{IT,channelized}$	0.0850	0.407	0.209	0.835	-0.713 ; 0.883	–
5.	$f_{IT,rotary}$	0.3640	0.523	0.696	0.486	-0.660 ; 1.388	–
Negative-Binomial Regression Results							
1.	B_0 (const.)	1.3603	0.877	1.551	0.121	-0.359 ; 3.079	–
2.	f_{PHT}	0.0002	<0.001	0.929	0.353	-0.0002 ; 0.001	–
3.	f_{NSP}	-0.4632	0.234	-1.976	**0.048**	-0.923 ; -0.004	–
4.	$f_{IT,channelized}$	0.0400	0.775	0.052	0.959	-1.480 ; 1.560	–
5.	$f_{IT,rotary}$	0.4555	1.000	0.455	0.649	-1.505 ; 2.416	–

6. Discussion

These sight distance analyses were conducted using existing models. The models used for the analyzes were adapted to account for the sight distances of intersecting conflicting traffic streams, allowing simultaneous movement during the green signal phases. The operation free-flow speed data used to determine SD_X, SD_Y, and SD_Z should be interpreted cautiously, considering the limitation to a small number of cities, all located in Poland. That said, these data turned out to be useful and defined the direction of further research to obtain more reliable speed parameters for conflicting movements at signal-controlled intersections. The authors are aware of the adopted accuracy of the study method employed for speed analyses in this study and the arbitrariness of some of the assumptions taken herein. Accelerations and decelerations on the way to the conflict areas were not considered. Also, the influence of slope gradients and the slope lengths was not considered. The speed of vehicles in the straight-through movement may, as well, depend on the size of the intersection central area rather than on the intersection type. This is identified as a necessary direction for future research. Still, we have managed to demonstrate that obstacles in the driver's sight distances can increase the risk of traffic incidents at signalized intersections in the tested areas, using non-stochastic models.

In addition, the authors are aware that multi-phase traffic signals could decrease the accident rate at most intersections. Time separation of conflicting movements involving the highest risk of accidents seems to be the optimal choice from a traffic safety perspective. However, many traffic control departments choose to allow simultaneously occurring conflicting movements at intersections to maintain higher traffic capacity throughout the city's road system. The argument of time loss is also used, as multiphase or group-based signal control is deemed to increase travel time compared to simple two-phase control (Islam et al., 2022, Li and Sun, 2016). The authors would like to emphasize that the tool developed as part of this study clearly showed that obstructed sight distances could be a significant factor in increasing the accident risk in simultaneously occurring conflicting movements. In addition, it should be emphasized that the increased accident risk particularly pertains to more severe traffic incidents, especially those involving vulnerable road users. This tool, illustrated in the Appendix, enables traffic engineers and traffic management departments to effectively advocate for the improvement of intersection sight distance conditions, thus eliminating unnecessary safety risks on road infrastructure elements, mainly due to vegetation or other adjacent medium-sized infrastructure objects.

It is also worthwhile noting that the authors are fully aware of the current AI and self-driving developments (Yan and Li, 2023). Nevertheless, they believe it will take time for these systems to be implemented on a mass scale, and until then appropriate sight distances at intersections must remain in place. This is particularly relevant to the interaction between vehicles and vulnerable road users, such as pedestrians, cyclists, or scooter-riders. These three types of road users are characterized by the most unpredictable movement patterns and behaviors.

The results of the speed differences in the surveys show the need to analyze them more closely in terms of the geometric features of the intersections (e.g., by size or degree of traffic channeling). The SD_Y model used in this study does not consider the effect of the longitudinal slope of the carriageway surface, which influences the stopping distance. This factor was intentionally omitted due to a lack of supporting studies. Assuming a similar effect of this factor on drivers' behaviors at intersections in Poland and other countries, a correction factor ϖ_G may be applied to the obtained SD_Y value, by multiplying the output of model (3) using the data given in Table 9-5 of (AASHTO, 2018) after conversion.

7. Conclusions

At the intersection planning stage, designers or traffic safety auditors are required to provide sight distance plans as part of the documentation package. As shown in the literature review, it is difficult to find a comprehensive and objective method for such analysis at signal-controlled intersections (e.g., in Poland, only sight distance analysis for minor approaches is mandatory). Often, only two-phase signaling is applied at intersections, allowing simultaneously occurring conflicting movements, which may include vulnerable road users (including right-turn-on-red movements with a green arrow signal). This critical aspect tends to be completely ignored in typical sight distance analyses carried out at the planning or safety audit stages of road projects. The same applies to traffic safety assessments of existing

road infrastructure elements, where visibility is examined primarily subjectively in the field.
Traffic control at signalized intersections should, to ensure safety, separate conflicting traffic streams in time; however, this is not always possible or practiced. By demonstrating the statistical significance of road incidents under obstructed sight distance conditions, the authors recommend the method used in this work, including sight distance analysis, as part of the road designer's or traffic safety auditor's duty. Sight distance analyses should include collision movement pairs with simultaneous traffic clearance. We were able to demonstrate that the presence of obstructions within the sight distance correlates with an increased accident rate, including major accidents involving pedestrians, cyclists, and scooter-riders. Therefore, it seems fair to conclude that sight distance analyses at signal-controlled intersections should be conducted in terms of traffic distribution in the signaling program. This approach differs from the approach established in many road infrastructure design guidelines, which typically require that stopping sight distance be met exclusively for the minor legs of the intersection. It is therefore necessary to consider the signaling phases that result in pairs of collision traffic streams with permissible simultaneous traffic clearance, for which sight distances should be maintained. This applies to sight distance conditions in vehicle-pedestrian and vehicle-bicycle interactions. Total time separation of conflicting movements is recommended in densely populated cities with unfavorable urban planning and high volumes of pedestrians, cyclists, and scooter-riders.
One of the most frequently identified obstacles in the stopping sight distances was architectural objects or vegetation, and for the green arrow signal, vehicles stopped on a multi-lane approach. The authors draw attention to this fact because these obstacles significantly limit drivers' ability to correctly perceive other road users when making a turning maneuver at an intersection. In such cases, particularly with high traffic volumes, conflicting traffic streams should be separated. This applies to potential collisions with vulnerable road users. For plants and trees in the immediate vicinity of the intersection, ongoing care and maintenance is recommended.

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Author contributions CRediT
Conceptualization (D.I), Data curation (D.I.), Formal analysis (D.I., R.K.), Funding acquisition (D.I.), Investigation (D.I., R.K.), Methodology (D.I., R.K.), Project administration (D.I.), Resources (D.I.), Software (D.I.), Supervision (D.I.), Validation (D.I.), Visualization (D.I.), Writing – original draft (D.I., R.K.), Writing – review and editing (D.I.).

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Appendix

A method of determining sight distances for major and minor traffic movements at signalized intersection

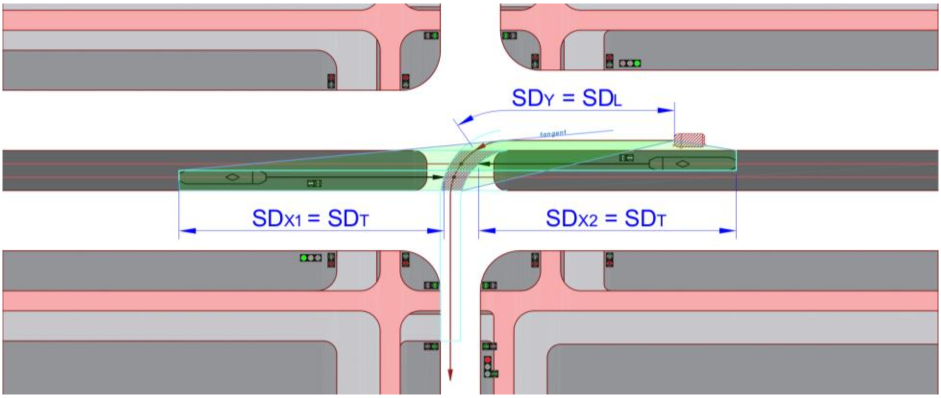

Fig. A.1 Method of determining the required stopping sight distance for a stream of vehicles turning left while allowing the tram stream to move straight-through on green signal

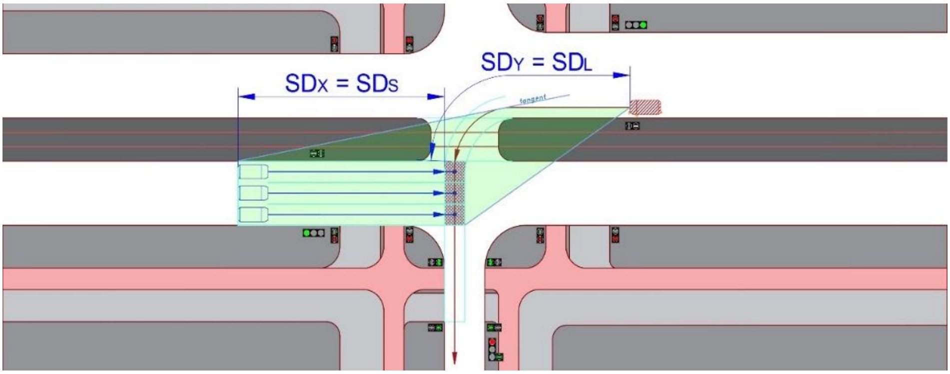

Fig. A.2 Method of determining the required stopping sight distance for a stream of vehicles turning left while allowing the vehicles from the opposite approach move straight-through on green signal

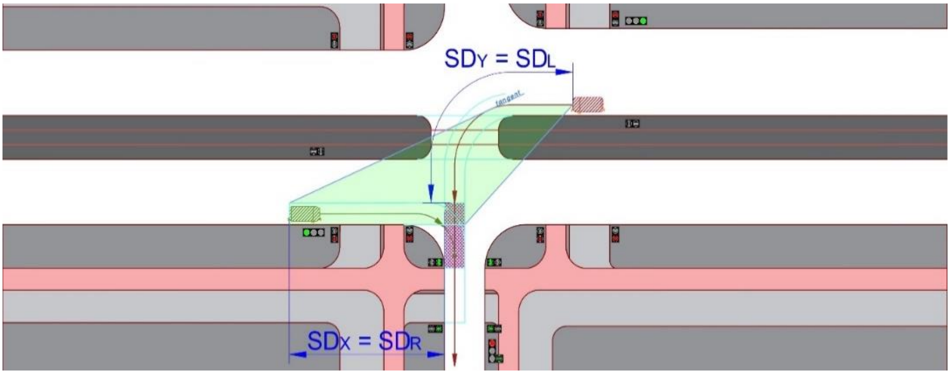

Fig. A.3 Method of determining the required stopping sight distance for a stream of vehicles turning left while allowing the vehicles from the opposite approach turn right on green signal

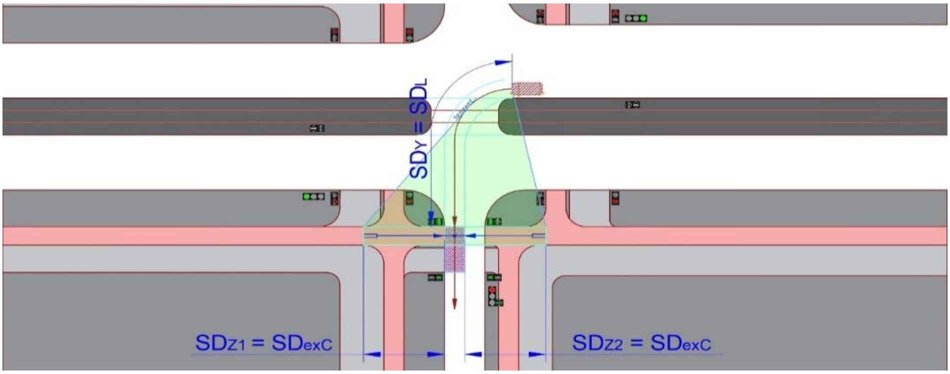

Fig. A.4 Method of determining the required stopping sight distance for a stream of vehicles turning left while allowing cyclists pass through the bicycle crossing at the exit on green signal

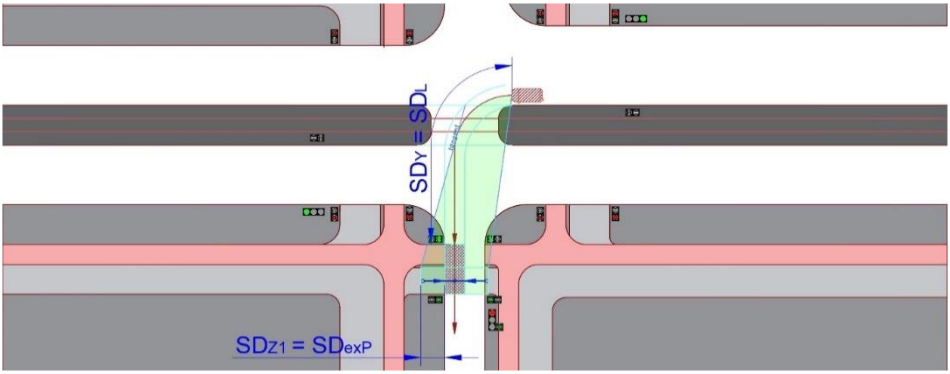

Fig. A.5 Method of determining the required stopping sight distance for a stream of vehicles turning left while allowing pedestrians pass through the pedestrian crossing at the exit on green signal

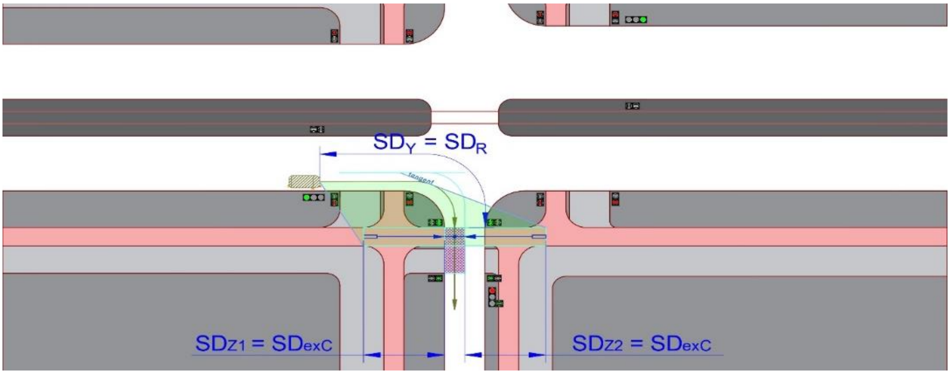

Fig. A.6 Method of determining the required stopping sight distance for a stream of vehicles turning right while allowing cyclists pass through the bicycle crossing at the exit on green signal

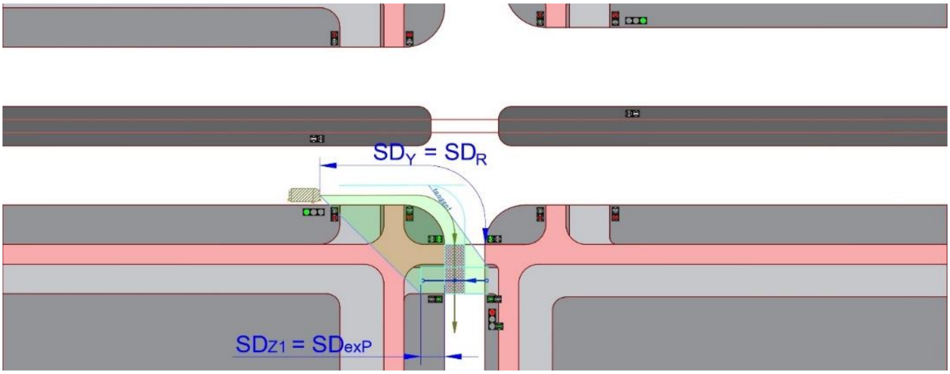

Fig. A.7 Method of determining the required stopping sight distance for a stream of vehicles turning right while allowing pedestrians pass through the pedestrian crossing at the exit on green signal

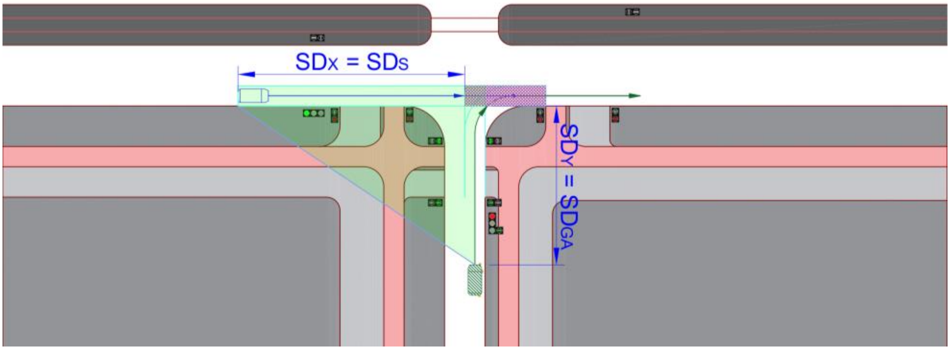

Fig. A.8 Method of determining the required stopping sight distance for a stream of vehicles turning right on red (green arrow) while allowing vehicles from a side approach move straight-through on green signal

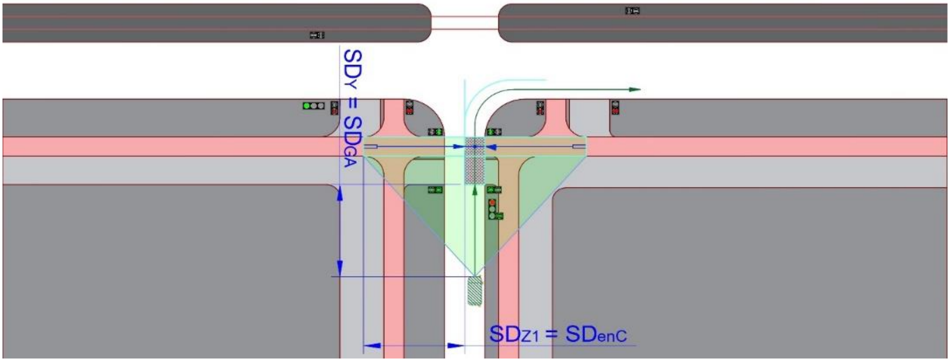

Fig. A.9 Method of determining the required stopping sight distance for a stream of vehicles turning right on red (green arrow) while allowing cyclists pass through the bicycle crossing at the intersection approach on green signal

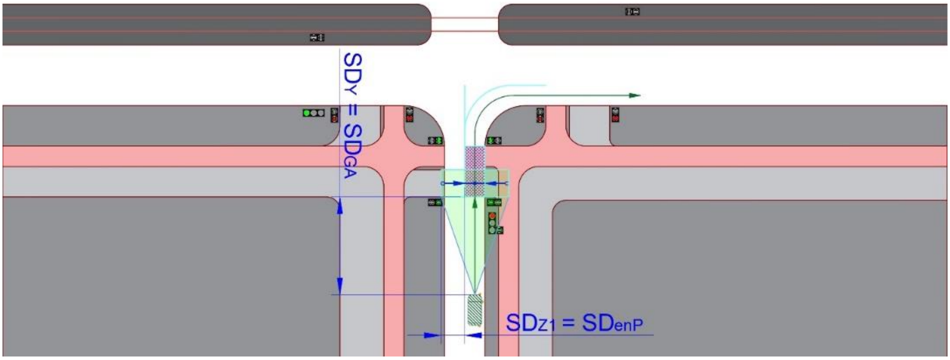

Fig. A.10 Mxethod of determining the required stopping sight distance for a stream of vehicles turning right on red (green arrow) while allowing pedestrians pass through the pedestrian crossing at the intersection approach on green signa