RESEARCH REPORT NO. 2

THE INFLUENCE OF ROAD GEOMETRIC ELEMENTS ON ENSURING ROAD SAFETY

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CONTENTS

1. INTRODUCTION 2
2. GEOMETRIC ELEMENTS OF THE ROAD AND TRAFFIC SAFETY 4
3. CASE STUDIES 30
I. Motorway – Two Sections 30
I.1 Study 1 30
I.2 Study 2 35
II. Road 39
III. Intersection 49
4. CONCLUSIONS 62
REFERENCES 64

1. INTRODUCTION

The number of fatalities resulting from road traffic crashes occurring on horizontal curves remains alarmingly high. Approximately 50% of all road crashes occur on curved sections [1], [2], [3], [4], while nearly 76% of these crashes involve a single vehicle leaving the carriageway [4].

The improper perception of a horizontal curve may lead drivers to select a speed that is inappropriate for the geometric characteristics of the road. In most situations, drivers focus primarily on interactions with other road users and the surrounding environment, while paying insufficient attention to roadway geometry.

Proper geometric road design is therefore essential and requires careful consideration of key design parameters, including horizontal curve radius, horizontal curve length, sight distance, longitudinal grade, and vertical alignment.

According to the World Health Organization (WHO, 2015), approximately 1.2 million people lose their lives each year in road traffic crashes worldwide, while up to 50 million people suffer injuries, making road traffic accidents one of the leading global public health concerns. As worldwide mobility is expected to continue increasing in the coming years, reducing road traffic casualties remains a major challenge for modern societies.

Beyond the tragic loss of human life, road crashes impose substantial economic costs, hindering economic development and reducing national competitiveness. Driving performance is influenced by numerous interrelated factors. From an infrastructure perspective, these include roadway geometric design, access control on secondary roads, pavement condition, and roadside safety devices.

The importance of roadway design also derives from its influence on highway capacity, user comfort, and infrastructure durability. Vehicle maintenance, human factors, environmental conditions, and legal regulations are additional factors that significantly affect driving performance.

Improvements in geometric design criteria and highway operating policies can make a substantial contribution to improving road safety.

Consequently, there is a need to develop new tools and methodologies that enable designers to evaluate design solutions, better understand the causes of road crashes, and incorporate lessons learned into improved design standards and engineering practices.

Such developments will contribute to more consistent, sustainable, and safer design criteria for new roads and highways, while also supporting more effective rehabilitation and upgrading strategies for the existing road network.

Although the planning, construction, operation, and maintenance of roads and highways require considerable financial investment, road traffic crashes remain an inherent risk associated with roadway operation and must therefore be minimized. Consequently, further efforts are required to develop advanced methods that enable designers to assess roadway designs, identify accident mechanisms, and improve future design standards based on accumulated experience.

The importance of geometric design in ensuring the safe operation of highways is widely recognized in international highway design guidelines. Indeed, horizontal and vertical alignment constitute the fundamental aspects that must be considered during highway design.

Road design involves the complete three-dimensional alignment and geometric design of all roadway elements with the objective of ensuring adequate sight distance, safety, and driving comfort.

Because the construction and management of road infrastructure require substantial financial resources, roadway design should be optimized to achieve an appropriate balance between safety, functionality, and economic efficiency.

Sight distance represents one of the most important geometric design parameters used to determine roadway geometry. Furthermore, sight distance analysis can be applied to existing roads and highways to identify potential deficiencies in design or maintenance that may adversely affect traffic safety. Consequently, the development of reliable methodologies for estimating Available Sight Distance (ASD) is of particular importance.

Despite the inherently three-dimensional nature of road infrastructure, many design engineers still evaluate roadway geometry by considering horizontal alignment, vertical alignment, and cross-section independently. However, satisfactory design solutions can only be achieved when these three geometric components are properly coordinated.

During the design process, engineers must recognize that drivers do not perceive the roadway in the same manner as it appears on engineering drawings. Roads and highways with well-coordinated horizontal and vertical alignments enable drivers to interpret the roadway geometry more accurately, anticipate the roadway path, and consequently travel under safer conditions.

Providing drivers with adequate forward visibility is essential for the safe and efficient operation of vehicles on highways. Consequently, sight distance is one of the fundamental parameters in highway geometric design (AASHTO, 2011). Vehicles are operated by drivers whose behaviour and speed selection vary considerably depending on their experience and driving skills.

A driver travelling along a highway section must continuously perceive information from the driving environment in order to operate the vehicle safely. The carriageway, roadway edges, traffic signs, pavement markings, and the presence of other road users constitute fundamental components of the driving environment that must be clearly visible.

Therefore, highway designers must provide sufficient sight distance to enable drivers to maintain vehicle control, respond appropriately to traffic and environmental conditions, and perform driving manoeuvres safely.

Highway design standards define the sight distance required for performing essential driving manoeuvres, including emergency stopping, overtaking, decision-making, and merging into the traffic stream. A minimum required sight distance enables the vast majority of drivers to perform these manoeuvres safely and comfortably without compromising traffic safety. The literature provides designers with analytical models for estimating these distances, which depend primarily on vehicle speed together with several additional influencing factors.

Stopping Sight Distance (SSD) is commonly defined as the distance travelled by a vehicle during an emergency stopping manoeuvre, measured from the instant when the hazard is first perceived until the vehicle comes to a complete stop (Ministerio de Fomento, 2016).

This manoeuvre consists of two components: the distance travelled during the driver's perception–reaction time and the braking distance required to bring the vehicle to a complete stop.

2. GEOMETRIC ELEMENTS OF THE ROAD AND TRAFFIC SAFETY

Proper geometric design of horizontal alignment, vertical alignment, and cross-sectional elements is essential for ensuring road safety.

Roads should be designed in a manner that minimizes the likelihood of traffic crashes, whereas inadequate geometric design may contribute to an increase in accident frequency (Monnet, Hare and Lucet, 2020; Gaikawad and Ghodmare, 2020; Gangwa & Deulkar, 2020).

According to previous research, the following relationships can be identified:

- accident frequency generally decreases as the horizontal curve radius increases;
- the relationship between horizontal curve length and accident frequency is relatively complex;
- longer vertical curves are generally associated with lower accident rates;
- accident frequency tends to increase as the algebraic difference between successive longitudinal grades increases.

Road design is based on the integrated design of the horizontal alignment, vertical alignment, and cross-sectional elements.

In general, roads are designed to accommodate the anticipated traffic demand. Consequently, the primary objective of the designer is to ensure an efficient traffic flow while maintaining the highest possible level of safety. Achieving this objective requires balancing safety requirements with economic constraints, anticipated traffic demand, and the characteristics of the vehicle fleet.

Numerous factors influence roadway design and, consequently, road safety. These include vehicle speed, vehicle performance, and human factors. Infrastructure-related characteristics, such as pavement type, skid resistance, roadway width, and available sight distance, also play a significant role in accident occurrence.

Road crashes exhibit hourly, daily, and seasonal variations that generally reflect traffic demand. Consequently, accident frequency tends to increase with traffic volume. Therefore, a high number of crashes occurring on a particular road section does not necessarily indicate a hazardous location, but may simply reflect a higher traffic exposure.

Meaningful comparisons between different roadway sections require comparable traffic conditions. Since this is rarely possible, accident analyses generally rely on accident rates that relate the number of crashes to traffic volume.

A commonly used measure is the accident rate expressed as the number of crashes per million vehicles, which relates the number of crashes occurring at a given location to the traffic volume passing that location over a specified period. For analytical purposes, a "location" may represent any road section with relatively constant traffic volume.

Mathewson and Brenner recommended the use of volume-based accident rates that are independent of road section length for engineering analyses.

Smith and Hurd reported that accident rates decrease as roadway width increases.

For two-lane roads, the most influential cross-sectional parameters are opposing traffic volume and shoulder width.

Greater lateral clearance reduces the probability of head-on collisions and impacts with roadside obstacles.

Raff concluded that roadway width and shoulder width have little influence on accident rates along tangent sections; however, both contribute significantly to accident reduction on horizontal curves of two-lane roads.

The Ohio Study (Ref. 6) reported that shoulder widths smaller than 1.20 m increase the likelihood of driver errors that may result in road crashes.

Studies conducted in several countries indicate that roadway width and the number of lanes have little influence on accident occurrence provided that:

- the carriageway width is at least 7.00 m; and
- the shoulder width is 1.20 m or greater.

The horizontal curve radius is one of the most influential geometric design parameters affecting road safety. In general, the smaller the curve radius, the greater the probability of accident occurrence.

Zhang determined the average radius for each curve category included in the study and correlated these values with the corresponding average accident rates. The results confirmed previous findings, demonstrating a strong relationship between curve radius and accident frequency.

Similarly, a study conducted by the UK Department of Transport (1984) reported a significant increase in accident rates as horizontal curve radius decreases.

Other researchers have shown that accident frequency increases substantially on roads with horizontal curve radii smaller than 200 m.

Glennon et al. (1985), Glennon (1987), and Zegeer et al. (1991) demonstrated that sharp horizontal curves are associated with considerably higher accident rates than flatter curves. Likewise, Ali Aram reported that horizontal curves experience a greater number of crashes—including rollovers and collisions—than other roadway elements. OECD (1976) suggested that a critical horizontal curve radius of approximately 430 m represents a threshold beyond which accident severity tends to decrease, concluding that most crashes occurring on curves are closely related to vehicle dynamics.

Conversely, Glennon et al. (1985) suggested that excessively large curve radii may also contribute to increased accident frequency and associated costs, indicating that road safety may deteriorate when the horizontal curve radius exceeds approximately 400 m.

Overall, previous studies consistently demonstrate the significant influence of horizontal curve radius on road safety. Although smaller radii are generally associated with higher accident frequency and severity, different researchers have proposed different threshold values for the optimum curve radius.

Longitudinal grade is another important geometric design parameter that significantly influences accident occurrence.

Several studies have shown that steeper grades are generally associated with higher accident rates. Based on a Swedish study, Hedman (1990) reported that a 2.5% longitudinal grade may increase accident frequency by approximately 5%, whereas a 4% grade may increase accident frequency by approximately 20% compared with nearly level road sections.

Similarly, Glennon et al. (1987) concluded that road sections with steeper grades experience higher accident rates than relatively flat sections.

Therefore, longitudinal grade should be regarded as an important factor affecting road safety.

Superelevation is introduced to counteract the centrifugal force acting on vehicles travelling through horizontal curves while simultaneously improving vehicle stability and driver comfort.

Ali Aram reported that sharp horizontal curves substantially increase accident frequency on two-lane roads. This phenomenon is mainly attributed to sudden changes in horizontal alignment, which reduce driver expectancy and increase the likelihood of driving errors. To mitigate this effect, several researchers recommend maintaining a consistent design speed throughout the roadway alignment in order to improve driver expectancy.

Numerous studies have also demonstrated that the number of traffic lanes influences accident occurrence (Deo and Chimba, 2004).

Similarly, Abdel-Aty et al. (2000) observed that increasing the number of lanes on urban highways is associated with higher accident rates. Comparable conclusions were reached by Noland and Oh (2004).

Although wider lanes generally reduce driver-related errors, this benefit may be partially offset by higher operating speeds.

Most researchers recommend an optimum lane width ranging between 3.5 m and 3.6 m.

Nevertheless, cross-sectional design should be evaluated considering all geometric elements rather than lane width alone.

Similarly, NCHRP Report 197 (1978) reported lower accident rates for lane widths of 3.35 m and 3.65 m.

Sight distance, together with operating speed, represents one of the fundamental control parameters in highway geometric design. The safe and efficient operation of roads and highways largely depends on providing adequate visibility conditions.

Although roads are generally perceived as linear infrastructure elements, they are inherently three-dimensional. Consequently, sight distance and its influence on driving performance should be evaluated within a three-dimensional design environment.

Both the AASHTO Green Book (2011) and the Swiss Standard VSS (1991) recommend coordinating horizontal and vertical alignments by overlapping the alignment bisectors in plan and profile (Figure 1a). This design approach creates a smooth three-dimensional S-shaped visual appearance, which improves the aesthetic quality of the roadway while enhancing driver perception (Figure 1b).

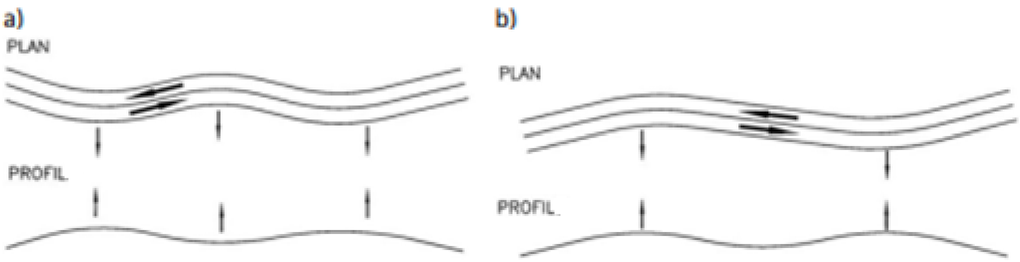


Figure 1. Correlation between horizontal alignment and longitudinal profile

Regarding the AASHTO design criterion, Moreno et al. (2014) demonstrated that the minimum Available Sight Distance (ASD) can be maximized when horizontal curves and crest vertical curves are properly coordinated, provided that the offset between their vertices falls within a specific range (Figure 2) [5].

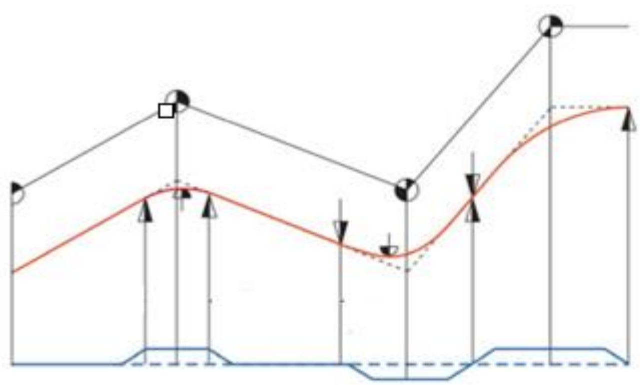


Figure 2. Correlation between horizontal alignment and longitudinal profile [6]

Figure 3 illustrates the longitudinal profiles for rolling terrain and flat terrain.

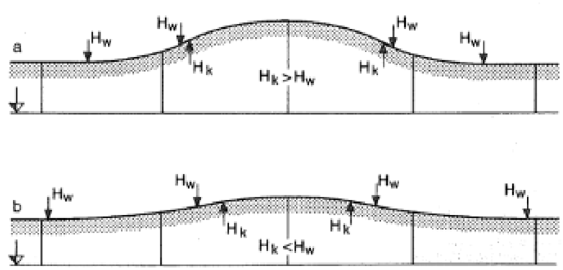
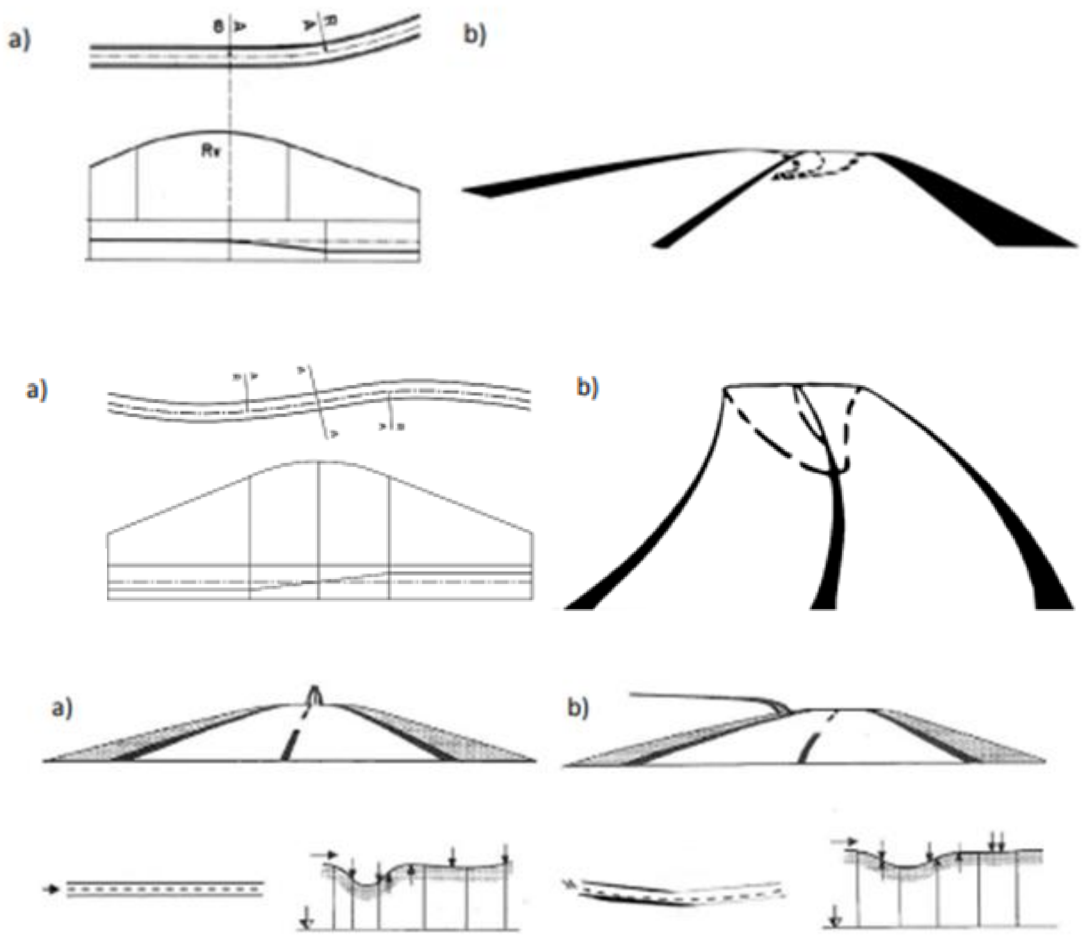


Figure 3. Longitudinal profile for rolling terrain and flat terrain [7]

When the beginning of a horizontal curve is located near the crest of a crest vertical curve, drivers may have difficulty recognizing the change in roadway direction in sufficient time [8]. This difficulty in perceiving the spatial coordination between the horizontal and vertical alignments becomes even more pronounced under nighttime conditions [9].

Drivers should be able to recognize the presence of the horizontal curve and reduce their speed at a comfortable rate before entering the curve. Therefore, a sufficiently long portion of the curve should remain visible to allow drivers to correctly perceive the change in horizontal alignment.

Figure 4 illustrates examples of the coordination between horizontal alignment and longitudinal profile.



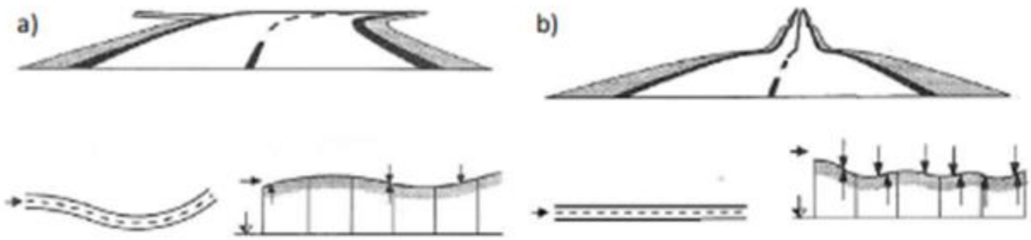


Figure 4. Examples of overlap between horizontal alignment and longitudinal profile [11]

Figure 5a illustrates the perspective view of a sag vertical curve preceding a left-hand horizontal curve, whereas Figure 5b illustrates the perspective view of a sag vertical curve preceding a right-hand horizontal curve.

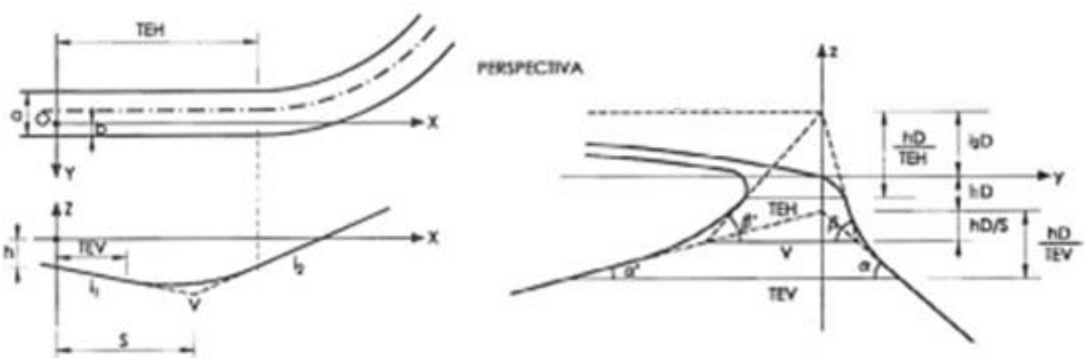


Figure 5a. Perspective of a sag vertical curve preceding a left horizontal curve [13]

When a vertical curve and a horizontal curve are superimposed, drivers may perceive the horizontal curve radius to be larger than it actually is [8], [14]. This misperception may lead drivers to negotiate the curve at an inappropriate speed.

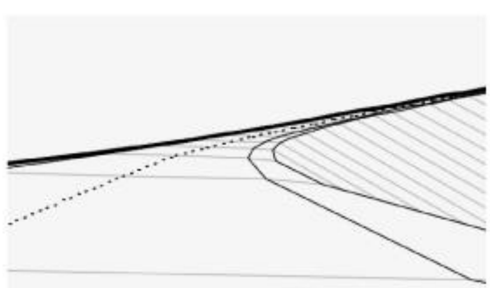


Figure 5b. Perspective of a sag vertical curve preceding a right horizontal curve [8]

Another example of inadequate geometric design occurs when the point of inflection—that is, the location where the horizontal alignment changes direction—is situated within a sag vertical curve [10], [15]. This configuration creates the visual illusion of a narrowing roadway (Figure 6), which may mislead drivers and adversely affect their perception of the roadway alignment.

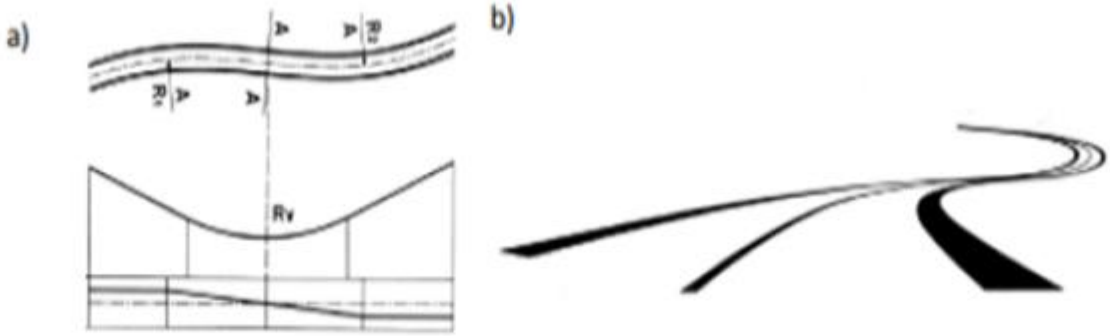


Figure 6. Apparent narrowing of the roadway: (a) horizontal alignment and longitudinal profile, and (b) perspective [15]

Figure 7 illustrates a horizontal curve with a small radius in both plan view and longitudinal profile.

With regard to their impact on road safety, small-radius horizontal curves are considered critical geometric elements. According to geometric design principles, these locations present an increased safety risk because drivers typically reach relatively high operating speeds along long tangent sections, requiring a substantial speed reduction when approaching the curve [16].

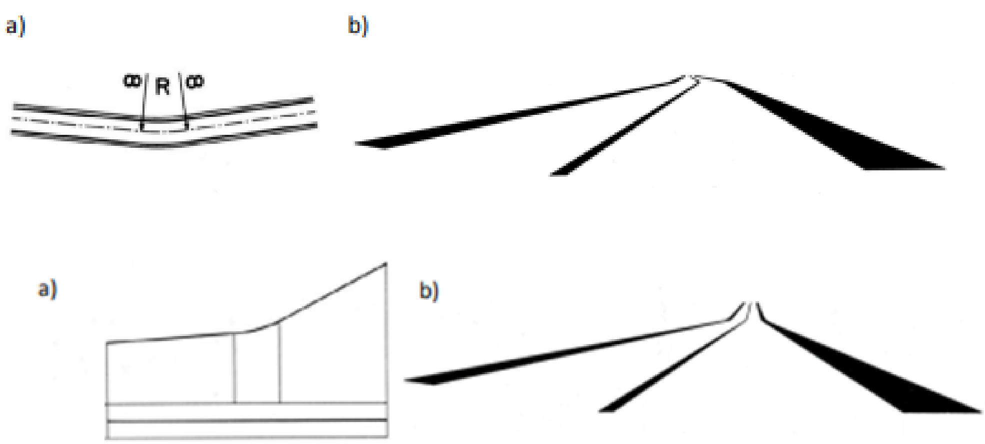


Figure 7. Small-radius curve in horizontal alignment and longitudinal profile [15]

Figure 8 illustrates a critical roadway configuration according to the German design standard.

If the horizontal alignment cannot be entirely divided into a sequence of Successive Speed Environments (SSE), and modifying its configuration is not feasible, designers should verify that no hidden curve entry is present. A hidden curve entry is defined as a horizontal curve in which a deflection angle of 3.5 gon cannot be perceived from a distance of at least 75 m before the beginning of the curve. If such a condition is identified, the overlap between the horizontal and vertical alignments should be redesigned. Subsequently, the revised alignment should be assessed to ensure that no aesthetic deficiencies are introduced.

Because redesigning the horizontal alignment often requires additional land acquisition, the recommendations favour increasing the radii of vertical curves and reducing longitudinal grades while maintaining a balanced earthwork volume.

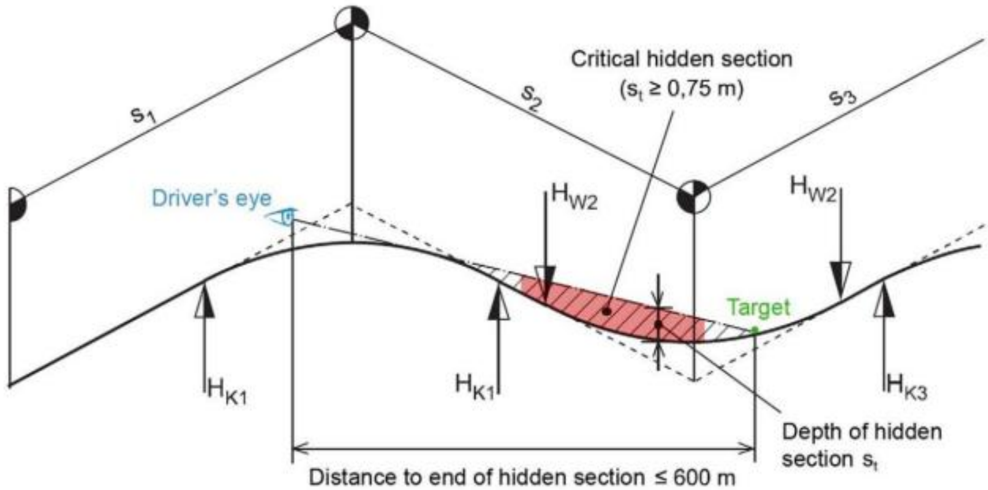


Figure 8. Hidden critical zone according to the German standard [6]

Reaction time contributes directly to the Stopping Sight Distance (SSD); therefore, longer reaction times result in longer minimum stopping distances. The AASHTO design value for driver perception–reaction time is 2.5 s, and this value has remained unchanged since 1954 (AASHTO, 2018).

Most studies reported in the literature suggest that a perception–reaction time of 2.5 s or less is sufficient to represent the behaviour of the majority of drivers [17], [18]. Early investigations, together with numerous subsequent studies, demonstrated that this value adequately represents the capabilities of approximately 90–95% of drivers. Nevertheless, the AASHTO design value is more conservative than those adopted in many other countries. Several European countries use a perception–reaction time of 2.0 s, while the United Kingdom, Ireland, and Greece adopt the same value but permit a reaction time of 1.5 s on lower-speed roads.

Although the perception–reaction time adopted by AASHTO remains conservative compared with international practice, substantial changes in driver behaviour have occurred over recent decades. In particular, driver distraction—both inside and outside the vehicle—has become increasingly common.

Numerous studies have identified additional factors affecting perception–reaction time, including vehicle speed, visibility conditions [17], [19], and the type of obstacle encountered [20]. More recent findings from naturalistic driving studies indicate considerably longer reaction times, with much of this increase being attributed to driver distraction.

Figure 9 presents the distribution of driver reaction times obtained from the SHRP2 Naturalistic Driving Study (Strategic Highway Research Program 2) for crash and near-crash events. The results indicate that a substantial proportion of drivers exhibit reaction times exceeding the 2.5 s design value adopted in the AASHTO Green Book (2018) [21]. These findings are particularly important because previous research [22] demonstrated that mobile phone use increases the likelihood of involvement in a road traffic crash by approximately four times.

The increasing prevalence of distracted driving and its effect on driver reaction time highlights the need to re-evaluate the perception–reaction time currently adopted in the AASHTO Green Book (2018).

More complex driving environments, such as dense urban areas or complex intersections, may require longer perception–reaction times. Under these conditions, the Decision Sight Distance (DSD) may provide a more appropriate design criterion than the Stopping Sight Distance (SSD). Conversely, shorter reaction times have been observed in less demanding driving environments characterized by low traffic congestion and favourable weather conditions [21].

Forward Collision Warning (FCW) and Automatic Emergency Braking (AEB) systems have the potential to reduce the perception–reaction component considered in stopping distance calculations. These technologies can alert drivers to imminent hazards and, when necessary, automatically initiate braking.

However, the availability of these systems and the thresholds at which they intervene vary considerably among vehicle models. Consequently, future geometric design recommendations should remain conservative and should not rely on these technologies when defining perception–reaction time values. It is estimated that such technologies will not be available in at least 85% of the vehicle fleet before 2035 [23]. Furthermore, since these systems are primarily intended for emergency situations, roadway design should continue to be based on the capabilities of drivers rather than on the performance of vehicle assistance systems.

Figure 9 illustrates the distribution of driver perception–reaction times obtained from the SHRP2 Naturalistic Driving Study.

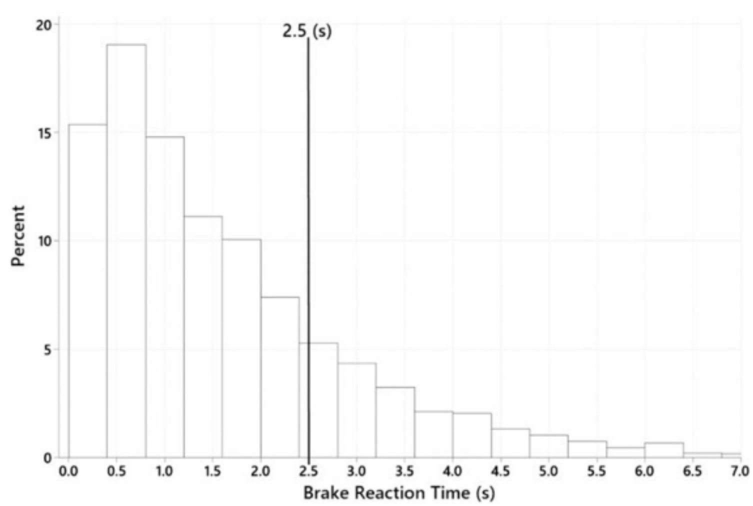


Figure 9. Distribution of reaction time according to SHRP2 [21]

Design speed has long been used as the primary criterion for estimating the Stopping Sight Distance (SSD) required for a particular roadway. However, editions of the AASHTO Green Book published before 2001 included two alternative models for calculating SSD. One model assumed lower operating speeds under wet pavement conditions, whereas the other, which was less conservative, based the design directly on the roadway design speed (AASHTO, 1984; 1990; 1994).

Beginning with the 2001 edition, the Green Book provides SSD values based exclusively on design speed (AASHTO, 2021). Although this approach results in a more conservative design, field studies have shown that operating speeds frequently exceed the design speed, in some cases by a considerable margin (Fitzpatrick et al., 2003).

Because vehicle speed influences both the distance travelled during the driver's perception–reaction time and the braking distance, underestimating operating speed may result in insufficient available sight distance under a wide range of roadway conditions.

The design speed of a roadway is determined by factors such as the functional classification of the road, surrounding land use, and other design considerations. However, field data reported in NCHRP Report 504 indicate that operating speeds may exceed the design speed under certain conditions [24]. Consequently, vehicles travelling faster than the design speed may not have sufficient stopping distance, which becomes a significant safety concern when a substantial proportion of traffic exceeds the intended design speed.

The 2001 edition of the Green Book was also the first to introduce deceleration rate as an explicit parameter in the SSD model (AASHTO, 2001).

Prior to this revision, the SSD model relied on the coefficient of longitudinal friction (f), which represents the friction developed between the tires and the pavement surface. This coefficient is influenced by several factors, including vehicle speed, pavement surface condition, tire characteristics, and other operating conditions.

Historically, stopping-distance calculations assumed a passenger car braking on a wet pavement surface with locked wheels throughout the braking manoeuvre [17]. The widespread introduction of Anti-lock Braking Systems (ABS) has largely eliminated the uncertainty associated with choosing between locked-wheel braking and controlled braking, the latter producing substantially longer braking distances [25].

Following the 2001 revision of the Green Book (AASHTO, 2001), several countries—including Canada, Germany, Ireland, Mexico, and the United Kingdom—updated their geometric design methodologies by replacing the friction coefficient with the deceleration rate [26]. In contrast, other countries, including Australia, India, New Zealand, Norway, and South Africa, continue to use design procedures based on friction coefficients (Austroads, 2020; Indian Roads Congress, 2018; Norwegian Public Roads Administration, 2014).

Braking tests have demonstrated that modern vehicles are capable of achieving deceleration rates exceeding 32.2 ft/s^2 (1.0 g) on dry pavements in good condition. Nevertheless, design values must accommodate the needs of nearly all drivers under a wide range of roadway conditions, while accounting for pavement deterioration and the reduction in skid resistance under wet pavement conditions [17].

The AASHTO Green Book (2018) recommends a design deceleration rate of 11.2 ft/s² (0.35 g) because approximately 90% of drivers are capable of exceeding this value. Modern vehicle braking systems, together with the available tire–pavement friction, generally allow considerably higher deceleration rates to be achieved on most wet pavement surfaces [17].

When drivers must stop to avoid an unexpected hazard or an emergency occurring within their travel lane, deceleration rates greater than 0.46 g (14.8 ft/s²) are generally achievable (AASHTO, 2018). In this context, future research examining braking performance under different roadway conditions could provide valuable additional information. Further studies investigating the relationship between deceleration rate and driver perception–reaction time would also be beneficial.

The deceleration rate has a direct influence on the required stopping distance: as the deceleration rate increases, the stopping distance decreases. However, roadway design should be based on a comfortable level of deceleration, since drivers should not be required to brake aggressively in order to compensate for inadequate sight distance.

Early attempts to define a comfortable deceleration rate, based on driver assessments together with driver and passenger responses during high-speed braking tests, suggested values ranging between 8.5 and 9.0 ft/s² [27]. The AASHTO Green Book (2018) recommends a design value of 11.2 ft/s² (0.35 g) for SSD calculations, which is considered comfortable for the majority of drivers according to the conclusions of NCHRP Report 400 [17].

The available literature also summarizes measured deceleration rates obtained both from controlled driving experiments and from naturalistic driving studies [21], [28], [29], [30].

Longitudinal grade also affects stopping distance. Upgrade sections are generally associated with shorter stopping distances, whereas downgrade sections require longer stopping distances.

Figure 10 presents the frequency distributions of maximum deceleration rates recorded during crash and near-crash events in the SHRP2 Naturalistic Driving Study (NDS).

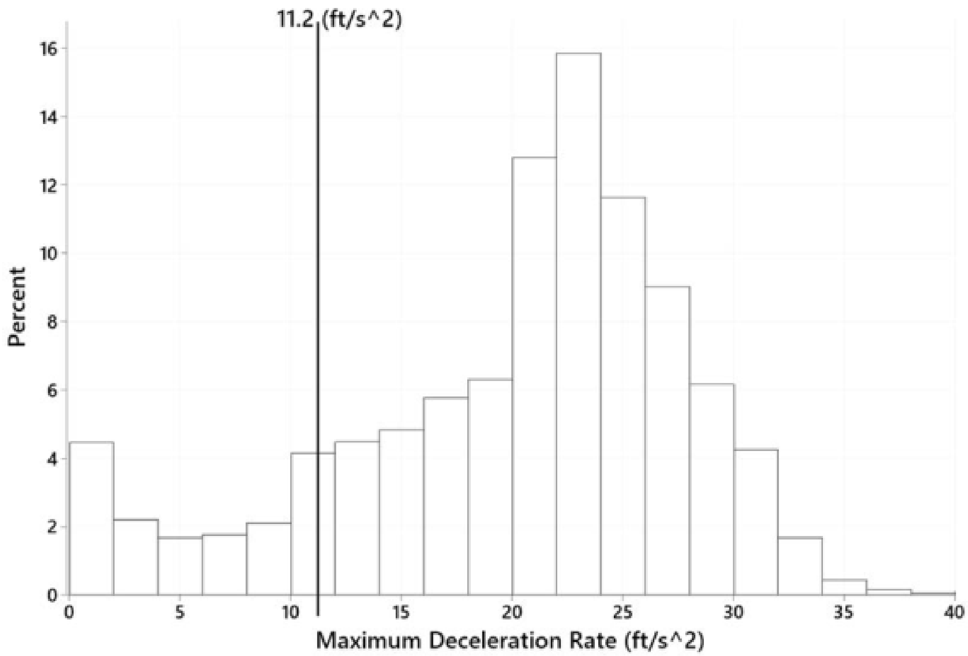


Figure 10. Frequency distributions of maximum deceleration rates for crash and near-crash events from SHRP2 NDS [21]

Driver eye height is a key parameter in Available Sight Distance (ASD) calculations governing the design of crest vertical curves. A higher driver eye height increases the available sight distance, allowing shorter crest vertical curves to satisfy the required visibility criteria.

Driver eye height was first introduced as a geometric design parameter in the 1920s, when a value of 5.5 ft was adopted [17]. It was subsequently reduced to 4.5 ft (AASHO, 1940), 3.75 ft (AASHTO, 1965), and 3.5 ft (AASHTO, 1984) to reflect changes in the composition of the vehicle fleet. The current AASHTO design values are 3.5 ft for passenger cars and 7.6 ft for trucks. These values are based on NCHRP Report 400, which concluded that approximately 90% of passenger-car drivers have an eye height greater than 3.5 ft [17].

Studies conducted between 2012 and 2020 [31], [32], [33] reported mean driver eye heights ranging from 4.07 to 4.16 ft for passenger cars, vans, and pickup trucks, while the corresponding 15th-percentile values ranged between 3.75 and 4.06 ft. These findings differ from those reported in studies conducted between 1978 and 1997 [17], [34], [35], which indicated mean eye heights ranging from 3.69 to 3.77 ft and 15th-percentile values between 3.49 and 3.59 ft.

Internationally, driver eye heights used for geometric design vary from approximately 1.0 m (3.3 ft) to 2.5 m (8.2 ft). Rather than adopting a single design value, several countries—including Australia, Switzerland, and the United Kingdom—use different eye-height values depending on the roadway context (Department of Transport, 2007; Austroads, 2020).

Studies published after NCHRP Report 400 (1997) [31], [32], [33] consistently report higher average and 15th-percentile driver eye heights, primarily due to the increasing proportion of larger vehicles, particularly Sport Utility Vehicles (SUVs). Since the late 1990s, the distribution of driver eye heights has gradually increased as the composition of the vehicle fleet has changed [29]. This trend has continued with the growing share of SUVs and pickup trucks in the national vehicle fleet.

Historically, adopting driver eye-height values based on passenger cars was justified because passenger cars represented the majority of vehicles in traffic. Today, however, a significant proportion of the vehicle fleet consists of SUVs and pickup trucks, which position drivers higher above the pavement surface and consequently increase the representative driver eye height.

Figure 11 illustrates the distribution of vehicle types between 1983 and 2019.

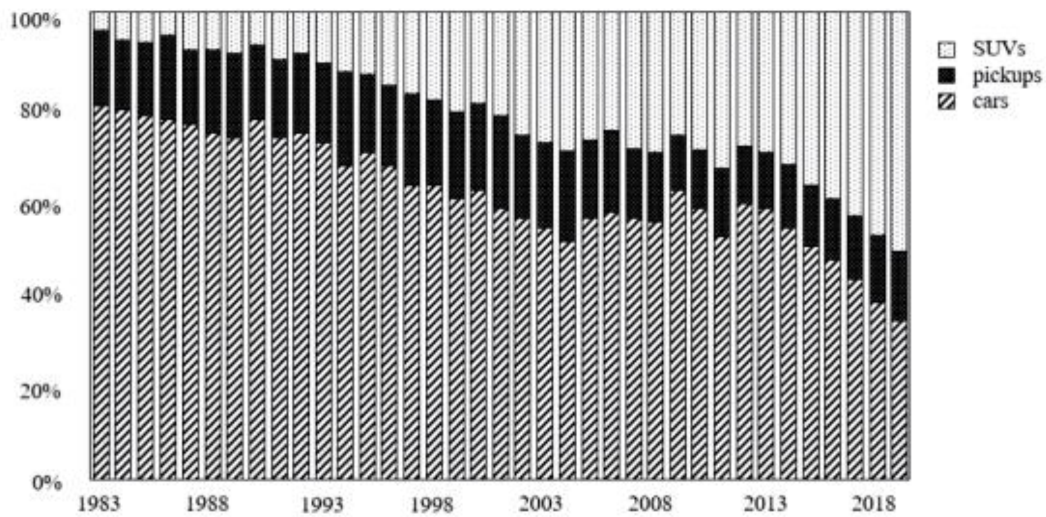


Figure 11. Distribution of vehicles by type, 1983–2019

Object height is another key parameter in Available Sight Distance (ASD) calculations governing the design of crest vertical curves. As the object height increases, the minimum crest vertical curve length required to provide adequate Available Sight Distance (ASD) decreases.

Over time, the AASHTO design value for object height has increased from 0.33 ft (AASHO, 1940) to 0.5 ft (AASHO, 1965), and subsequently to 2.0 ft (AASHTO, 2001).

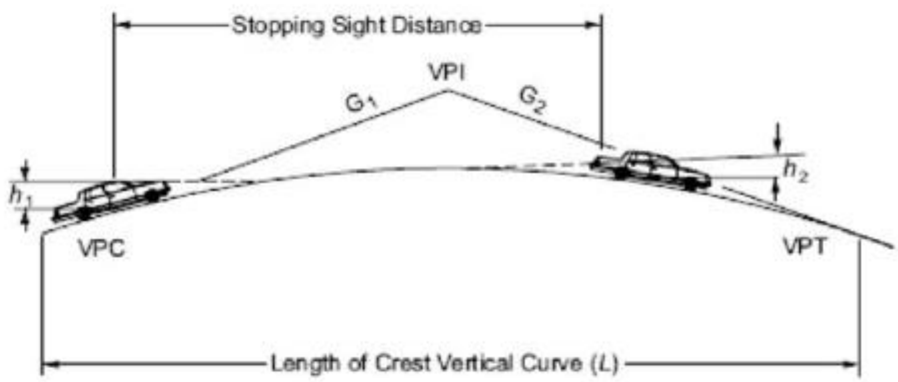
Beginning with the 2001 edition of the Green Book, the design object height was increased from 0.5 ft to 2.0 ft, based on the findings of NCHRP Report 400, which concluded that objects lower than 2.0 ft are difficult to detect at, or beyond, the minimum Stopping Sight Distance (SSD) values recommended by AASHTO (AASHTO, 2001) [17]. Furthermore, objects of this size are unlikely to constitute a significant crash hazard [17].

The objects most commonly involved in crashes related to stopping sight distance are other vehicles. Research has shown that, in 95% of passenger vehicles, the rear lamps are positioned at a height greater than 1.5 m above the pavement surface, while in 90% of vehicles the headlamps are mounted above the same height [17]. Although changes in the composition of the vehicle fleet have likely increased the average mounting height of rear lamps and headlamps, the 10th-percentile values have probably remained relatively unchanged. In addition, drivers of taller vehicles are even less likely to collide with an object having a height of 2.0 ft.

The minimum length of a crest vertical curve is an important parameter in highway geometric design. It depends primarily on two variables: driver eye height and object height. The current assumptions adopted in the AASHTO Green Book (2018) for these two parameters are based on studies conducted more than five decades before the research performed under NCHRP Project 15-75. Since then, both vehicle design and the composition of the vehicle fleet have changed considerably, potentially affecting the validity of the current design assumptions.

The evaluation of the minimum crest vertical curve length using a probabilistic (reliability-based) analysis considered two input variables: driver eye height and object height. Figure 12 illustrates the variables used to determine the minimum crest vertical curve length required to provide adequate Stopping Sight Distance (SSD). According to AASHTO, the design values adopted for driver eye height and object height above the pavement surface are 3.5 ft and 2.0 ft, respectively.

The K-values (defined as the vertical curve length required for a 1% change in grade) used in the analysis were obtained from the AASHTO Green Book (2018).

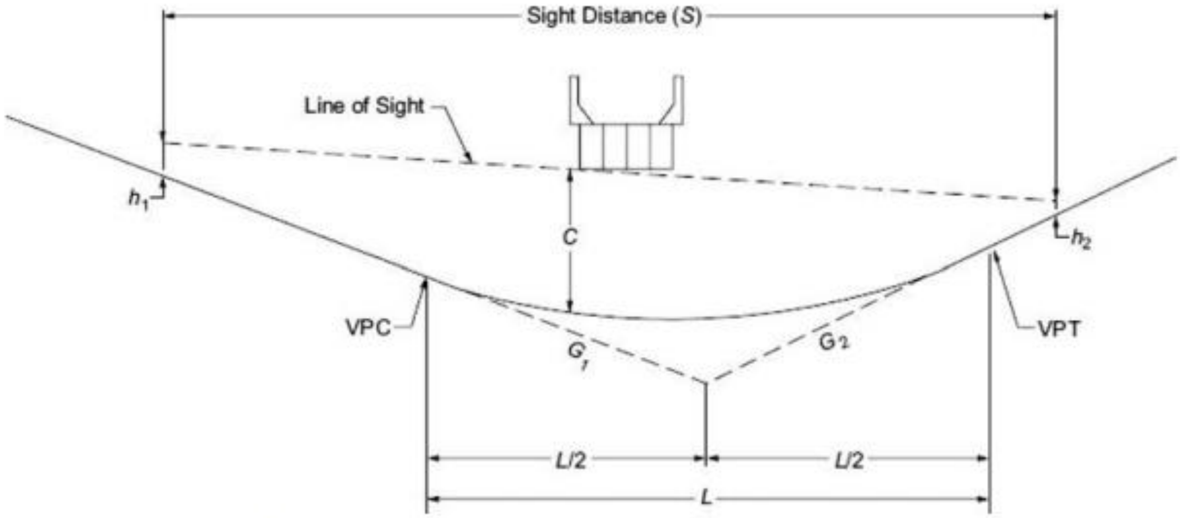


Source: *A Policy on Geometric Design of Highways and Streets* (2018) by AASHTO, Washington, DC. Used with permission.

Figure 12. Parameters considered in determining the length of a crest vertical curve to ensure sight distance

Figure 13 illustrates the variables used to determine the minimum length of a sag vertical curve. The length of a sag vertical curve can be calculated using Equations 3-7 and 3-8 (AASHTO, 2018), depending on the relationship between the available sight distance and the length of the vertical curve.

According to AASHTO (2018), the design values adopted for truck driver eye height and object height are 8.0 ft and 2.0 ft, respectively. For the vertical clearance (C), the minimum value recommended by AASHTO (2018) is 14 ft.



Source: *A Policy on Geometric Design of Highways and Streets* (2018) by AASHTO Washington, DC. Used with permission.

Figure 13. Parameters considered in determining the length of a sag vertical curve at an underpass to ensure sight distance

To ensure safe and efficient roadway operation, adequate sight distance must be provided so that drivers can perceive and respond appropriately to potential hazards. Although the available sight distance should be maximized wherever possible, it is often limited by crest vertical curves and by line-of-sight obstructions located along horizontal curves.

Consequently, roadway designers must consider all these factors when developing both the horizontal and vertical alignment of a road.

The concept of sight distance provides a measurable design parameter that can be quantified and directly related to roadway geometry.

This concept is based on a number of simplifying assumptions regarding both the characteristics of potential hazards and the expected behaviour of drivers. It is assumed that the hazard consists of an object of sufficient size to require the driver to take evasive action once it becomes visible within the driver's field of view.

The longitudinal profile of a roadway consists of a sequence of grades connected by vertical curves. It is designed by considering both the configuration of the natural terrain and the need to achieve a balanced earthwork distribution.

Several types of curves can be used to provide vertical alignment transitions. Traditionally, the parabola has been the preferred solution because of the simplicity of its mathematical formulation and the ease of manual calculations.

Figure 14 illustrates the different types of vertical curves.

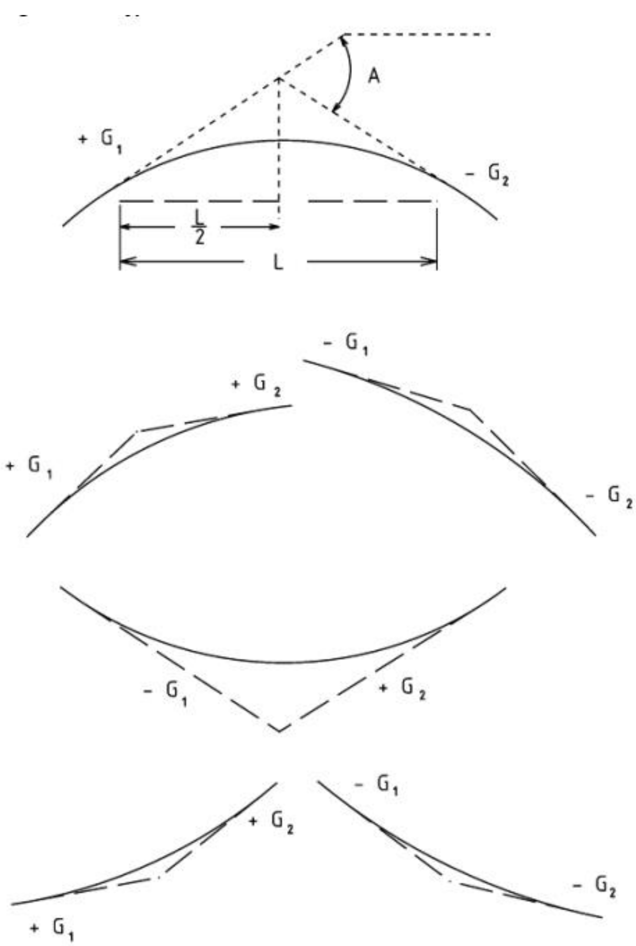


Figure 14. Types of vertical curves

When the Available Sight Distance (ASD) is shorter than the Passing Sight Distance (PSD), increasing the length of the vertical curve may extend the passing zones on either side of the crest, thereby facilitating overtaking manoeuvres in the vicinity of the crest.

The aesthetic appearance of the roadway alignment is important for both small and large changes in longitudinal grade, as is the case for crest vertical curves.

Sag vertical curves are generally designed to satisfy the comfort criterion. However, on unlit rural roads and urban roads, the design of sag vertical curves should also satisfy the headlight sight distance criterion, since nighttime visibility is governed by the illumination provided by vehicle headlights.

Several types of sight distance are considered in highway geometric design, including Stopping Sight Distance (SSD), Passing Sight Distance (PSD), and Available Sight Distance (ASD).

At every point along a roadway, the Available Sight Distance (ASD) should be greater than or equal to the Stopping Sight Distance (SSD). Furthermore, to achieve an appropriate Level of Service (LOS), the ASD should exceed the Passing Sight Distance

(PSD) over a specified proportion of the roadway length (Highway Capacity Manual, 2010).

After detecting a potential hazard—such as another vehicle, a pedestrian, or any other obstacle—the driver requires a finite period to initiate an appropriate response, such as braking or performing an evasive manoeuvre. This interval is referred to as the driver perception–reaction time.

During this period, the driver perceives the hazard, identifies the relevant information, evaluates the situation, decides on the appropriate response, and initiates the corresponding action, while the vehicle continues to travel at its operating speed, covering a considerable distance.

The driver perception–reaction time is typically assumed to be approximately 2 s [36]. Braking begins only after this interval has elapsed. Bringing the vehicle from its operating speed to a complete stop requires an additional braking distance.

The equations presented in Figure 15 are based on the vehicle speed, V, expressed in km/h, while all distances are expressed in metres. The braking forces are generated by the combined effects of longitudinal tire–pavement friction (represented by the **longitudinal friction coefficient, f **) and rolling resistance, which is generally assumed to be 2% (0.02) of the vehicle's gross weight. The longitudinal friction coefficient depends on vehicle speed, decreasing from approximately 0.44 at 40 km/h to 0.27 at 130 km/h [37].

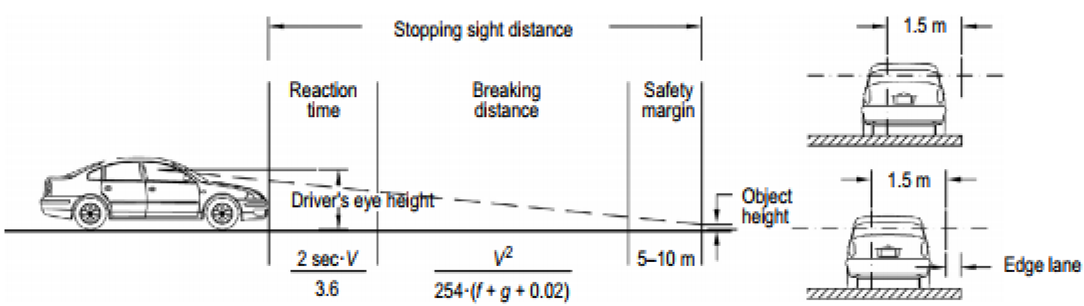


Figure 15. Calculation of sight distance

In practice, as a vehicle decelerates from its initial speed, V, to a complete stop, the longitudinal friction coefficient (f) increases, changing from relatively low values at higher speeds to higher values as the vehicle speed approaches 0 km/h. Upgrades reduce the required braking distance, whereas downgrades have the opposite effect. Finally, a safety margin of 5 to 10 m is added to obtain the total Stopping Sight Distance (SSD) [37].

When evaluating whether the line of sight is obstructed by roadside features—such as cut slopes, vegetation, or the pavement surface along a crest vertical curve—the driver's eye is assumed to be located 1.1 m above the pavement surface and 1.5 m from the right-hand edge of the traffic lane.

The line of sight terminates at an object located on the pavement surface with a height of 0.10 m.

To perform a safe overtaking manoeuvre on a two-lane roadway, the driver must ensure that no opposing vehicle is approaching within a distance equal to or greater than the required Passing Sight Distance (PSD). During the manoeuvre, the overtaking vehicle travels at a speed ΔV higher than that of the overtaken vehicle, while both the overtaken vehicle and the opposing vehicle are assumed to travel at the design speed, V. The entire overtaking manoeuvre is completed within a time interval Δt.

Figure 16 illustrates the calculation of the Passing Sight Distance (PSD).

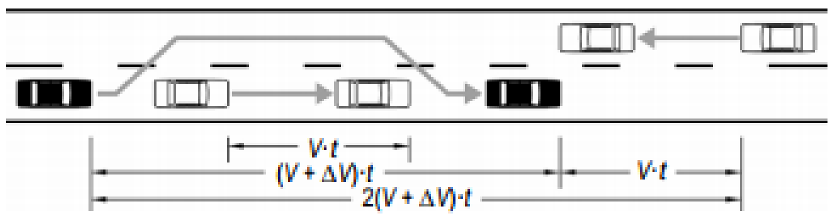


Figure 16. Calculation of passing sight distance

While the Stopping Sight Distance (SSD) must be provided at every point along the roadway, the Passing Sight Distance (PSD) is required only on selected roadway sections.

Even in countries recognized for high levels of driver discipline [38], vehicle speeds on rural roads are influenced more by the geometric characteristics of the roadway than by the posted speed limits.

The minimum horizontal curve radius is established according to the specified design speed. In practice, this minimum radius is generally applied only at critical locations, whereas larger radii are used along the remaining sections of the roadway. Consequently, it is reasonable to assume that drivers negotiate minimum-radius curves at speeds close to the design speed, while travelling at higher speeds on curves with larger radii.

The relationship between horizontal curve radius and operating speed is illustrated in Figure 17. It is assumed that vehicles negotiate each curve at the operating speed determined from this relationship, regardless of the roadway design speed.

Figure 18 presents the relationship between longitudinal grade and operating speed. Passenger-car operating speed is assumed to remain unaffected by grade values ranging from −5% (downgrade) to +4% (upgrade).

Based on the assumptions described above, the variation of operating speed along the roadway can be determined and represented by means of an operating speed profile (Figure 19). In general, the operating speed profile is obtained by combining two separate speed profiles: one derived from the horizontal alignment and the other from the vertical alignment.

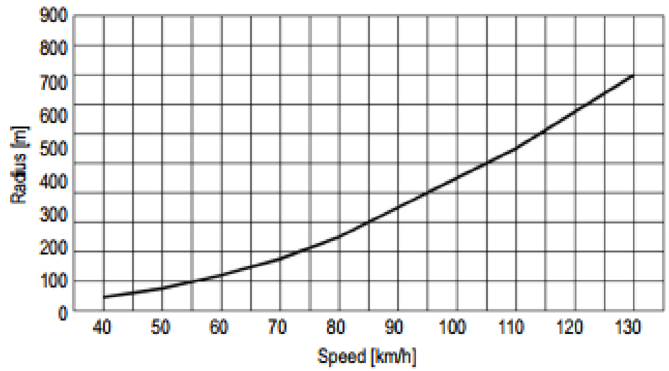


Figure 17. Relationship between horizontal curve radius and speed [37]

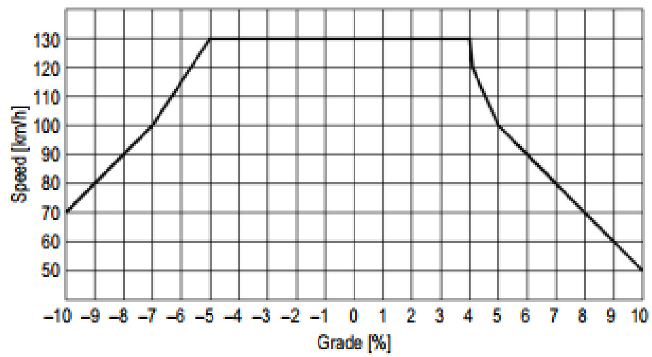


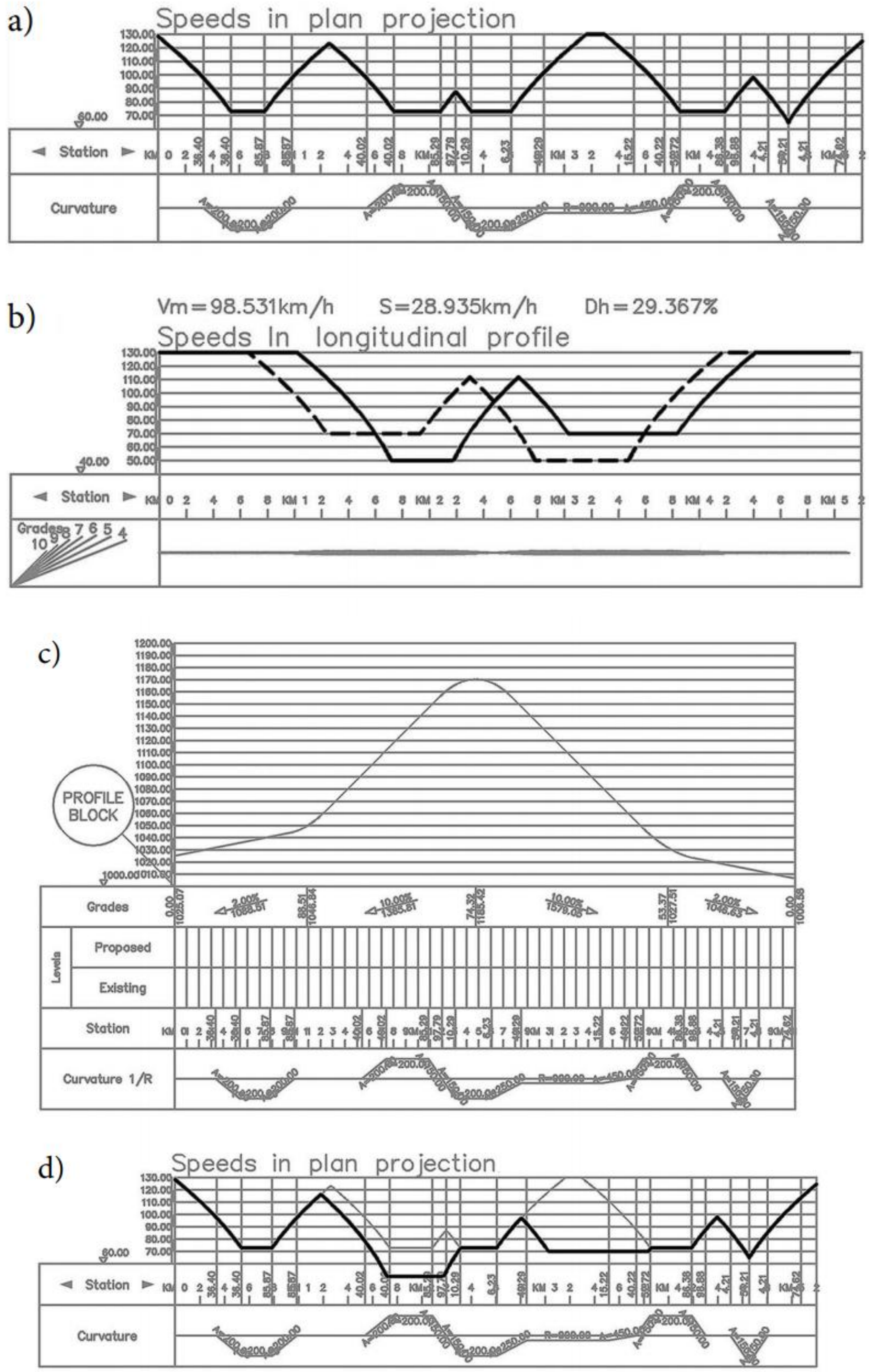
Figure 18. Relationship between longitudinal grade and speed [37]

Figure 19a illustrates how operating speed varies as a function of the horizontal alignment. Within each horizontal curve (ARC), the operating speed is assumed to be equal to the maximum speed corresponding to the curve radius, as defined by the relationship shown in Figure 17. As a vehicle travels along the tangent section between two successive curves—whether reverse curves or curves in the same direction—it initially accelerates and, after reaching its maximum operating speed, decelerates to the speed required to negotiate the next curve safely. Both the acceleration and deceleration rates are assumed to be 0.8 m/s^2 [36], [37].

Figures 19b and 19c illustrate the influence of the vertical alignment on operating speed. Figure 19c shows a longitudinal profile consisting of a crest vertical curve connected to relatively steep grades on both sides. The operating speeds presented in Figure 19b are determined using the speed–grade relationship shown in Figure 18.

Under these conditions, the operating speed profiles differ for the two directions of travel. The solid line represents the operating speed of a vehicle travelling in the forward direction (to the right), whereas the dashed line represents the operating speed of a vehicle travelling in the opposite direction (to the left). The solid line shown in Figure 19d illustrates the reduction in operating speed caused by the characteristics of the vertical alignment for vehicles travelling in the forward direction.

Similarly, the dashed line in Figure 19e represents the overall operating speed profile for vehicles travelling in the opposite direction. Consequently, the final operating speed profiles illustrated in Figures 19d and 19e are established for both directions of travel. These two operating speed profiles are subsequently used to calculate the Required Sight Distance (RSD) for each direction of travel.



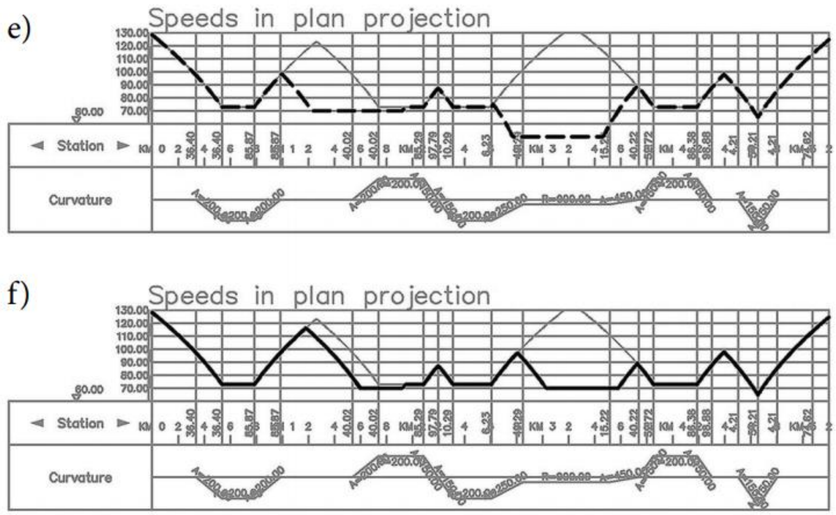


Figure 19. Calculation of operating speed levels

At any point along the roadway, the cross slope of the pavement is identical for both sides of the roadway and must satisfy the highest operating speed resulting from traffic travelling in the two opposing directions. Consequently, the maximum operating speed profile for both directions of travel must first be established.

The Available Sight Distance (ASD) is defined as the length of roadway visible to the driver. At every point along the roadway, the ASD must be greater than the Required Sight Distance (RSD). Furthermore, to provide an adequate Level of Service (LOS), the ASD should exceed the Passing Sight Distance (PSD) over a specified proportion of the roadway length.

A 3D CAD environment provides the most effective and, in many cases, the only practical method for determining the Available Sight Distance (ASD). As illustrated in Figure 20, ASD values are extracted from the triangulated three-dimensional roadway model. A virtual vehicle, representing the driver's eye, travels along the roadway. The driver's eye is positioned 1.1 m above the pavement surface and 1.5 m from the right-hand edge of the traffic lane.

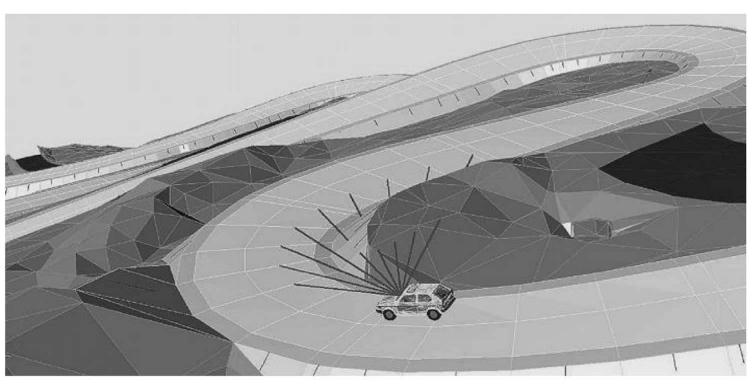


Figure 20. Available Sight Distance (ASD) in software

As the virtual vehicle progresses along the roadway, lines of sight are generated successively from each driver's eye position toward potential obstacles. While the driver's eye remains fixed at a given location, successive lines of sight are traced to objects positioned on the pavement surface at predefined intervals ahead of the vehicle. These objects are typically assumed to have a height of 0.10 m and are located 1.5 m from the right-hand edge of the traffic lane.

Keeping the driver's eye at the same location, the analysis begins with the object positioned closest to the vehicle and proceeds successively toward more distant objects. For each line of sight, the software checks whether it intersects any of the triangles composing the triangulated three-dimensional roadway model.

When an intersection is detected, the analysis is terminated for that driver's eye position. The length of the last unobstructed line of sight is recorded as the Available Sight Distance (ASD), after which the driver's eye is moved to the next calculation position and the procedure is repeated.

Figure 21 illustrates the three-dimensional roadway model used for the determination of the Available Sight Distance (ASD).

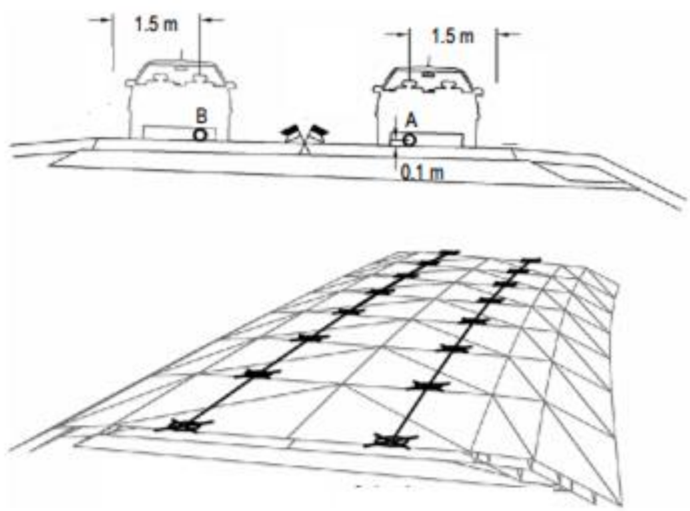


Figure 21. 3D modeling for Available Sight Distance (ASD)

The Serbian highway design guidelines introduce the concept of operating speed and relate the optical evaluation of roadway geometry to this parameter. Unlike the Stopping Sight Distance (SSD), which remains constant along the roadway because it is based on a constant design speed, the newly introduced parameter, Required Sight Distance (RSD), varies continuously along the roadway.

The Required Sight Distance (RSD) is conceptually equivalent to the Stopping Sight Distance (SSD) but is calculated using a more realistic operating speed, which varies according to the roadway geometry. Operating speed increases on sections with larger horizontal curve radii, tangent sections, and reverse curves, while decreasing to approximately the design speed only on critical curves with the minimum allowable radius.

Several studies have investigated methods for improving the estimation of realistic operating speed profiles, both in Serbia (Fric, 2014) and in other countries [39], [40]. On horizontal curves with relatively small deflection angles, considerable differences may exist between the radius of the roadway centreline and the actual radius of the vehicle trajectory. On gentle curves, drivers may follow a path with a larger radius than the centreline while remaining entirely within their traffic lane. Consequently, vehicles negotiate these curves at speeds higher than those associated with the nominal centreline radius.

Current research therefore focuses on determining actual vehicle trajectories and realistic operating speeds, particularly on gentle horizontal curves. The results of these studies are expected to improve the estimation of operating speed profiles and, consequently, enhance the accuracy of Required Sight Distance (RSD) analyses.

Horizontal curves represent the geometric element associated with the highest crash risk. According to the Fatality Analysis Reporting System (FARS), since 2005 approximately 5,000 fatalities per year have resulted from single-vehicle crashes occurring on horizontal curves along rural two-lane highways in the United States (National Highway Traffic Safety Administration, 2011). These statistics are generally attributed to drivers' misperception of roadway alignment, which may lead them to adopt speeds or driving behaviours that are inconsistent with the actual roadway geometry.

Numerous studies have shown that the likelihood of driver misperception increases with the complexity of the roadway alignment and becomes particularly significant when horizontal curves are combined with vertical curves.

In particular, Smith and Lamm (1994) hypothesized that the presence of an overlapping crest vertical curve may cause a horizontal curve to appear sharper than it actually is, whereas an overlapping sag vertical curve may cause the same horizontal curve to appear flatter than its true geometry (the driver perception hypothesis) [41]. Under these conditions, drivers may select lower or higher operating speeds, respectively, than they would if no vertical curve were present. Consequently, the misperception of horizontal curve geometry may be especially critical when a horizontal curve is combined with a sag vertical curve, where drivers may perceive a sharp curve as being considerably less severe than it actually is.

Highway geometric design guides in several countries, including Italy, Spain, and the United States (Ministero delle Infrastrutture e dei Trasporti, 2001; Ministerio de Fomento, 2001; AASHTO, 2011), recommend avoiding, whenever possible, the combination of horizontal curves with sag vertical curves. When such a combination cannot be avoided, the recommended practice is to align the bisectors of the two curves and to design the horizontal and vertical curves with comparable lengths (hereinafter referred to as the recommended curve combination). The guidelines also discourage the configuration in which a sag vertical curve is located immediately before a horizontal curve, referred to hereafter as the critical sag configuration, because this arrangement produces undesirable visual effects.

These recommendations originate primarily from studies based on perspective representations of roadway alignments. However, this approach has important limitations because it cannot reproduce the dynamic visual perspective experienced by drivers while travelling along the roadway. Consequently, numerous studies conducted during the past decade have investigated roadway perception using advanced computer animation and visualization techniques [42]–[44]. Nevertheless, these visualization methods are generally non-interactive and therefore cannot assess drivers' behavioural responses to the perceived roadway environment.

One of the primary objectives of highway geometric design is to provide clear and unambiguous visual cues that enable drivers to make appropriate and timely decisions. Even when such visual cues are present, however, drivers may still experience optical illusions that lead to an incorrect perception of the roadway alignment. These perceptual errors may substantially increase the risk of a crash.

The perception of horizontal curves is of particular importance because crash frequencies on curved sections are significantly higher than on tangent sections. According to the OECD (1999), the number of crashes occurring on horizontal curves is approximately three times greater than on tangent sections, while the rate of single-vehicle run-off-road crashes on rural roads is approximately four times higher on curves. Furthermore, crash frequency increases with curve severity, with the degree of curvature being the geometric parameter that best explains variations in crash rates. More recent studies [44] have shown that the risk becomes even greater when horizontal and vertical curves overlap.

Because driver perception directly influences driving decisions and manoeuvre selection, an inaccurate perception of horizontal curve geometry may significantly increase crash risk.

The most influential factor affecting driver perception is the Available Sight Distance (ASD). This explains the higher probability of perceptual errors associated with sag vertical curves, which generally provide greater sight distance than crest vertical curves. In addition, the available sight distance increases almost linearly with increasing horizontal curve radius, thereby increasing the likelihood of driver misperception.

Some geometric parameters, such as superelevation rate and curve direction, were found to have no statistically significant influence on the perception of horizontal curve radius.

In addition to the type of overlapping horizontal curve, the perception of horizontal curvature also depends on the characteristics of the vertical curve. In general, the greater the algebraic difference in grades, or the sharper the vertical curve, the higher the proportion of drivers who misperceive the horizontal curvature. This trend can be explained by the increasingly pronounced vertical alignment, which differs substantially from the visual appearance of a horizontal curve superimposed on a constant grade.

Figure 22 illustrates the relationship between the horizontal alignment and the longitudinal profile.

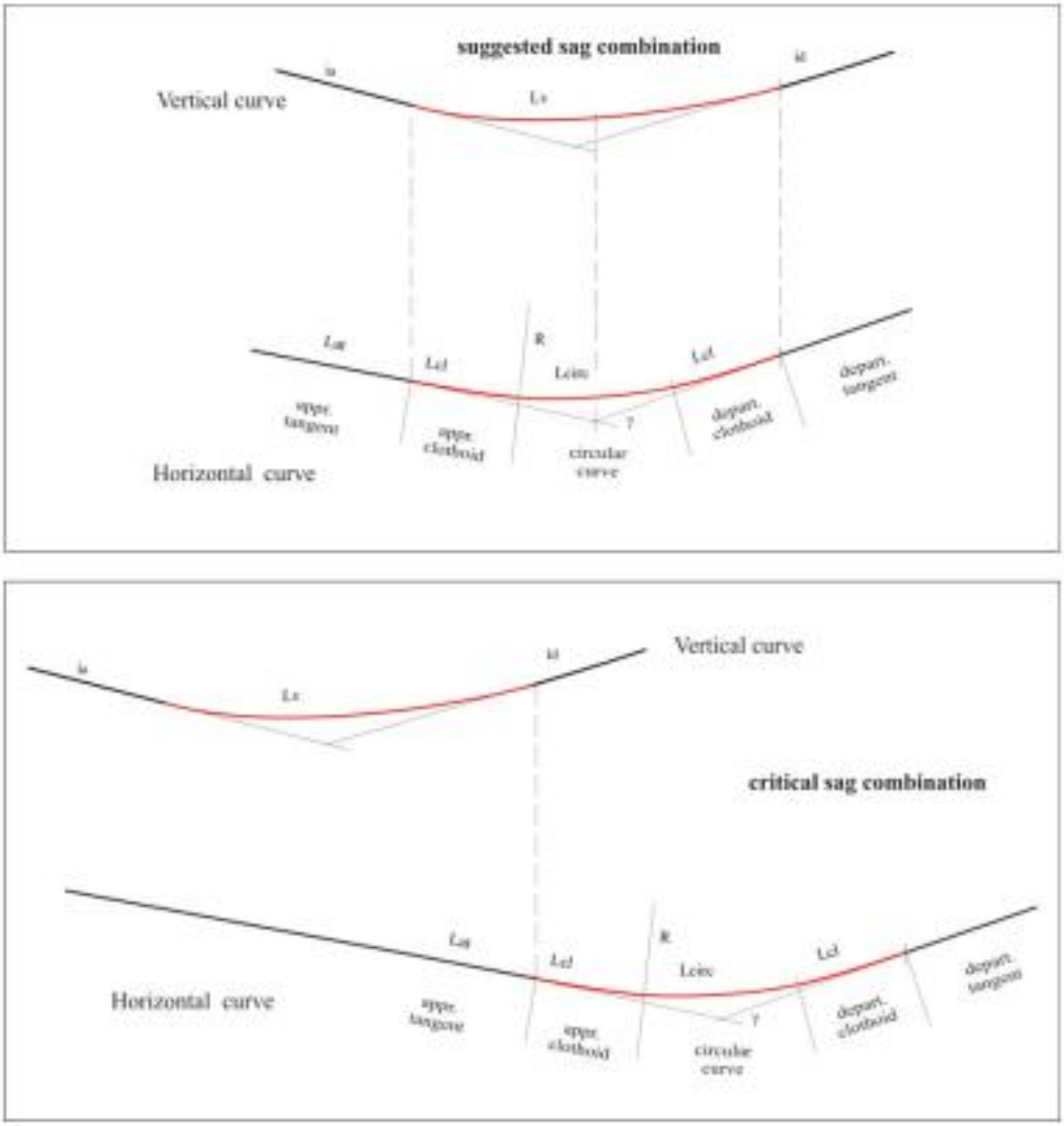


Figure 22. Correlations between horizontal alignment and longitudinal profile

Freeway exit areas exhibit the highest crash rates within the entire freeway system and therefore represent critical locations from a road safety perspective. According to statistical studies conducted in the United States, crashes occurring within diverge areas account for approximately 44% of all crashes associated with freeway interchanges. In one study, researchers analysed 1,150 crashes occurring at interchanges in Northern Virginia and found that 48% occurred within exit ramp areas, whereas 36% occurred near entrance ramps. Similarly, approximately 2,400 crashes involving heavy vehicles were recorded on freeways in the state of Colorado between 1993 and 1995, of which nearly 30% occurred within interchange ramp areas [45].

Driver behaviour is closely related to road safety, and safety within diverge areas is influenced by numerous factors. Traffic operations in these locations are inherently complex. Driving manoeuvres such as lane keeping, deceleration, merging, and lane changing in the vicinity of exit ramps have a significant influence on crash occurrence. Consequently, considerable research has been devoted to identifying the factors contributing to crashes in these areas. Most studies have focused on the relationship between acceleration and deceleration lanes and crashes occurring at freeway entrances and exits, as well as on the influence of exit ramp configuration on crash frequency. Other studies have investigated the effects of guide signs and pavement markings, showing that crash frequency is strongly influenced by Available Sight Distance (ASD), shoulder width, and traffic guidance devices.

Numerous studies have examined the relationship between Decision Sight Distance (DSD) and roadway geometry; however, relatively few have explicitly investigated the influence of horizontal curve radius on DSD. In 1979, DSD was related to specific roadway types, design speeds, and traffic operating conditions through the development of a model describing the driver's hazard-avoidance process. This approach established the relationship between Decision Sight Distance (DSD) and roadway geometric alignment. Most subsequent studies have focused primarily on refining the parameters used in DSD and Stopping Sight Distance (SSD) calculation models [45].

The AASHTO Green Book establishes the fundamental principles governing the geometric design of highways and streets. Stopping Sight Distance (SSD) is defined as the length of roadway visible ahead that allows a driver travelling at, or near, the design speed to stop safely before reaching a stationary object on the roadway. Decision Sight Distance (DSD) represents the distance required for a driver to detect and interpret an unexpected or difficult-to-perceive situation within a visually complex roadway environment. It is intended to provide drivers with sufficient time to recognize the situation, evaluate the available options, and make an appropriate decision.

Because Decision Sight Distance (DSD) provides drivers with sufficient distance to perform a lane-change manoeuvre within a diverge area, it should, at a minimum, ensure that a driver travelling in the second lane (the lane adjacent to the outside lane) can identify the separation of the mainline from the exit ramp in sufficient time to observe the guide signs, confirm the intended exit, and move safely into the deceleration lane. Therefore, to provide an adequate level of safety within the diverge area, the downstream limit of the Decision Sight Distance (DSD) should coincide with the beginning of the deceleration lane transition (Figure 23). This enables drivers to recognize the exit before entering the deceleration lane, thereby improving operational safety within the diverge area.

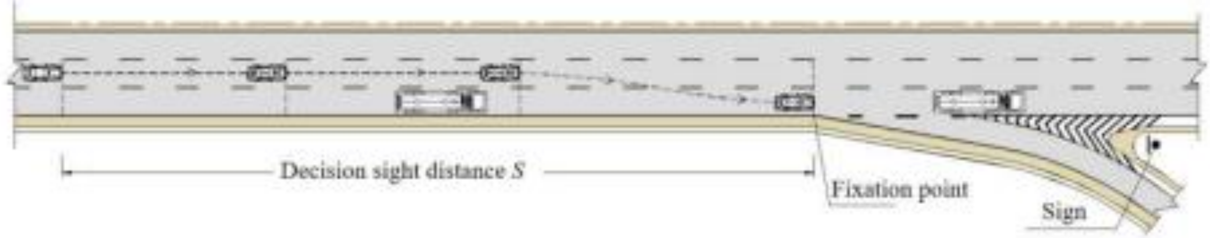


Figure 23. Sight distance in an exit area [45]

When the mainline alignment within a diverge area consists of a left-hand horizontal curve, it is assumed that the vehicle intending to leave the mainline is travelling in the second traffic lane.

Under these conditions, median barriers and anti-glare screens installed within the median may restrict the driver's field of view when the horizontal curve radius is insufficient. Consequently, inadequate Decision Sight Distance (DSD) may prevent the driver from identifying the exit in sufficient time, thereby adversely affecting both the decision-making process and the execution of the required driving manoeuvres.

The driver's line of sight is illustrated in Figure 24. In this figure, SP denotes the vehicle trajectory, whereas TP represents the driver's fixation point. Based on this concept, the determination of the minimum radius of a left-hand horizontal curve on the mainline within a diverge area can be simplified using the geometric model illustrated in Figure 24.

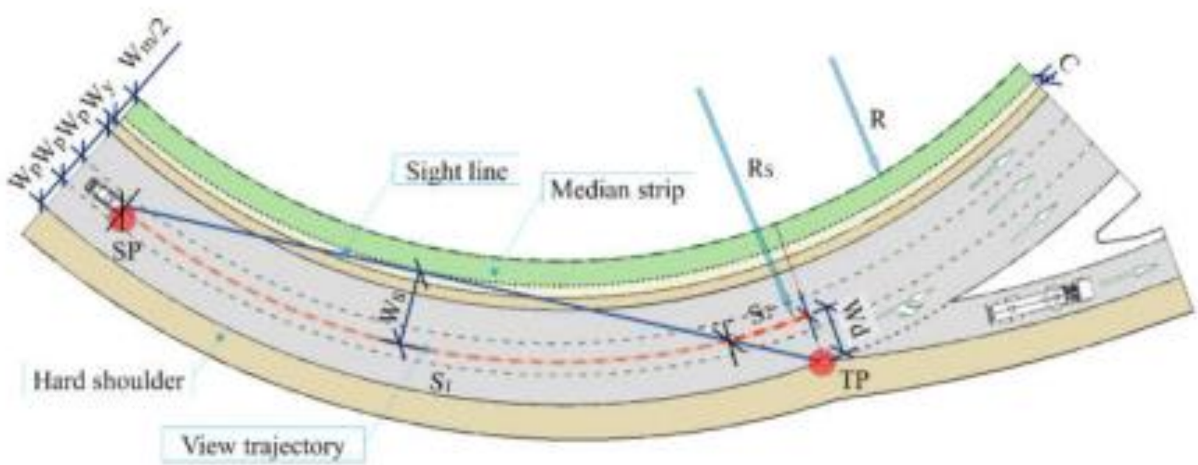


Figure 24. Schematic for the minimum radius of a left circular curve [45]

3. CASE STUDIES

I. Motorway – Two Sections

I.1 Study 1

In the present study, sight distance was analyzed on motorways with two lanes per direction, for design speeds of 100 km/h, 120 km/h, and 140 km/h.

For each speed, the driver eye height was varied between 1.00 m and 1.35 m.

The study was conducted considering an object height lower than the median barrier height, since for greater heights the sight distance is typically satisfied.

According to the Romanian standard, the minimum sight distance is:

- 150 m for 100 km/h
- 200 m for 120 km/h
- 325 m for 140 km/h

The study was performed only for a motorway segment and not for other road categories.

It was not possible to measure sight distance in cases where it exceeded the values recommended by Romanian standards for the respective speeds.

The graphical representations highlight:

- the horizontal curve section, where sight distance requirements were not satisfied (km 16+350 – km 17+050)
- the horizontal tangent section, in plan view
- the crest vertical curve, in longitudinal profile

The study was conducted on a 3.15 km motorway section (km 14+200 – km 17+350), consisting of:

- a left horizontal curve (km 16+223.24 – km 17+325.87)
- a horizontal tangent of 2.023 km length

The analysis was carried out using Civil Site Design software (road design software), as illustrated in Figure 25.

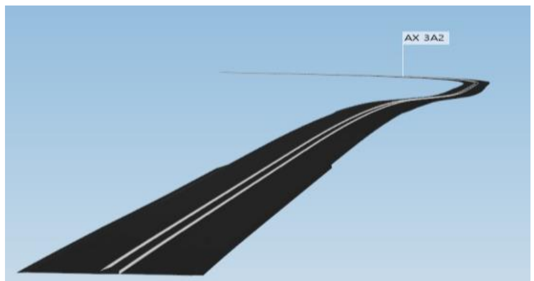


Figure 25. Route studied in perspective (km 14+200 - km 17+350)

A schematic drawing of the transverse profile of the studied motorway section is shown in Figure 2 and the measurement of the sight distance according to the CIVIL SITE DESIGN software is shown in Figure 3.

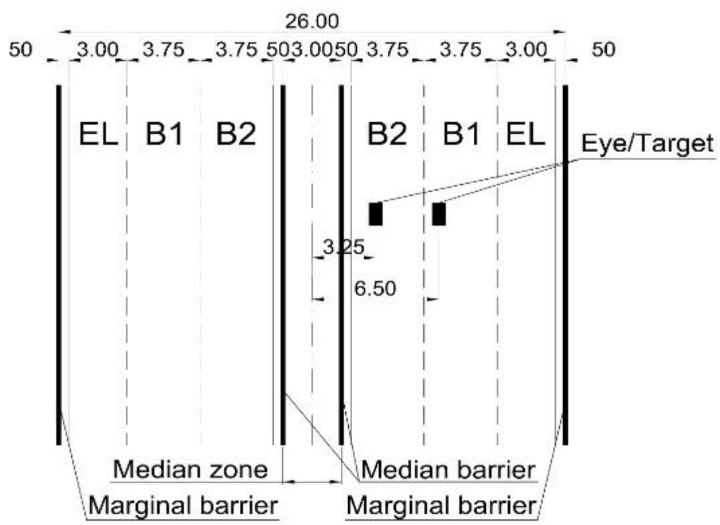


Figure 26. Highway transversal section - schematic drawing

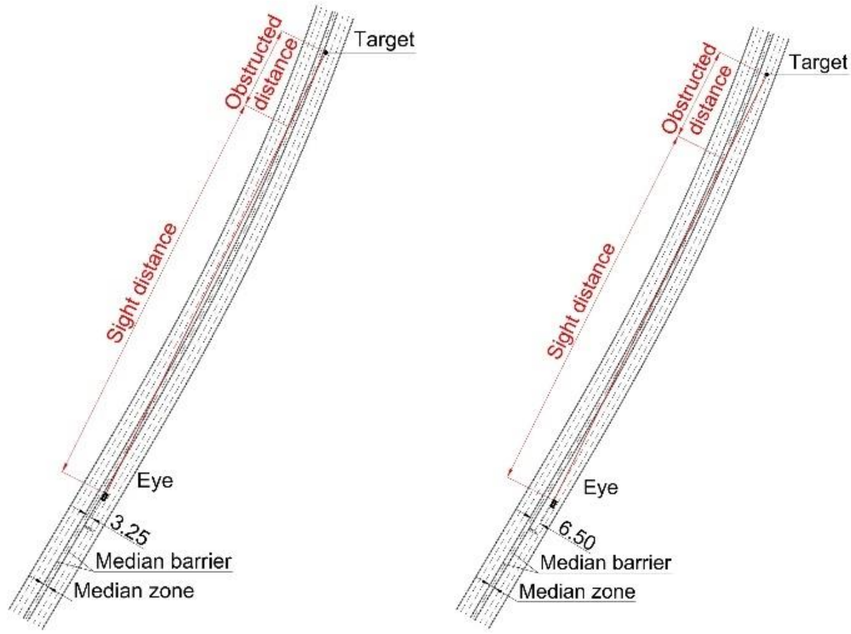


Figure 27. Sight distance measurement according to CIVIL SITE DESIGN software for traffic lane B1 and traffic lane B2 respectively

The curve in the situation plane is made up of: a clothoid (L = 200 m), a curve (C = 700 m) and a clothoid (L = 200 m). On the curve area (from the situation plan) there is a 1% slope, and on the alignment area (from the situation plan) there is a convex vertical curve with a radius of 10000 m and a concave vertical curve with a radius of 20000 m (the route was designed for a speed of 120km/h, according to Romanian standards), (Figure 4). On the vertical alignment the visibility problems are on the convex vertical curve area, which is studied. On the studied route, there is a median barrier with a height of 0.75 m.

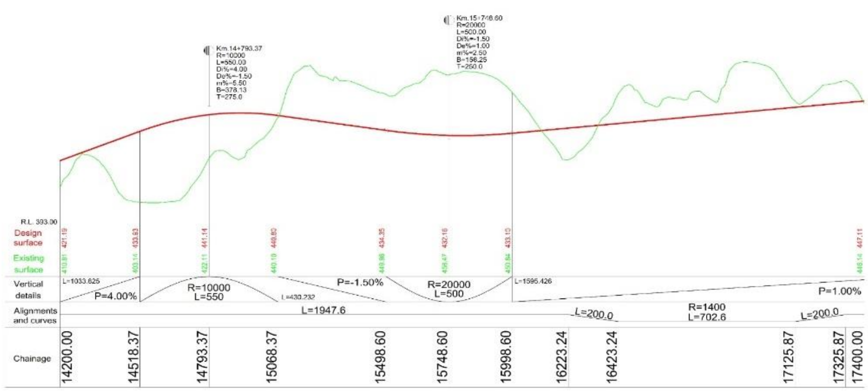


Figure 28. Longitudinal profile of the studied route (km 14+200 - km 17+350)

In Figure 5, Figure 6, Figure 7 and Figure 8 the studies are shown only for traffic lane B2, but for traffic lane B1 the graphs are similar. Sight distance as a function of kilometre position and driver eye height, for V = 100 km/h, in traffic lane B2, $h_{obstacle}$ = 0.0 m, for the horizontal curve is shown in Figure 5.

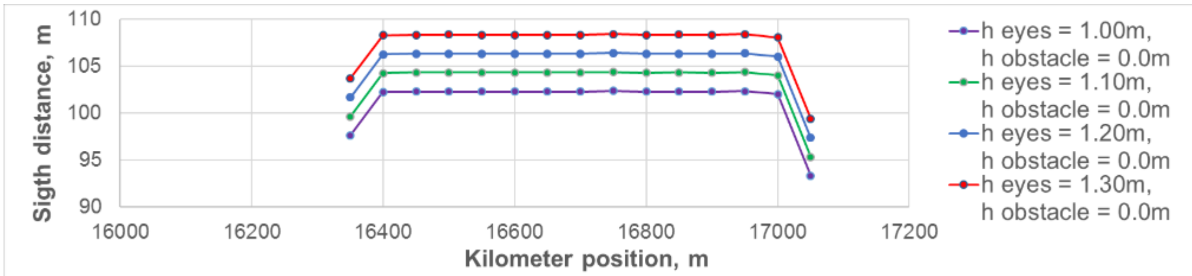


Figure 29. Sight distance as a function of kilometre position, for V = 100 km/h, traffic lane B2, h $_{obstacle}$ = 0.00 m - horizontal curve

Between km 16+350 and km 17+050, for h obstacle = 0.00m, the sight distance increases with the height of the driver's eye by 2%-7% for V=100 km/h.

Sight distance as a function of kilometre position and driver eye height, for V = 120 km/h, in traffic lane B2, h $_{obstacle}$ = 0.00 m, for the horizontal curve is shown in Figure 6.

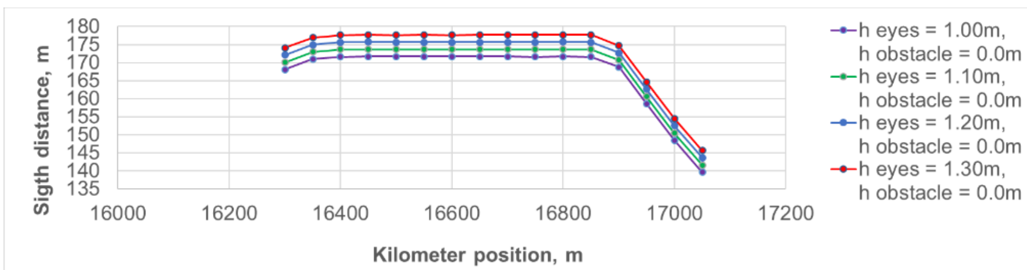


Figure 30. Sight distance as a function of kilometre position, for V = 120 km/h, traffic lane B2, h $_{obstacle}$ = 0.0 m - horizontal curve

Between km 16+350 and km 17+050, for h obstacle = 0.00m, the sight distance increases with the height of the driver's eye by 1%-5% for V= 120 km/h.
Sight distance as a function of kilometric position and driver's eye height, for V = 140 km/h, in traffic lane B2, h $_{obstacle}$ = 0.00 m, for the horizontal curve is shown in Figure 7.

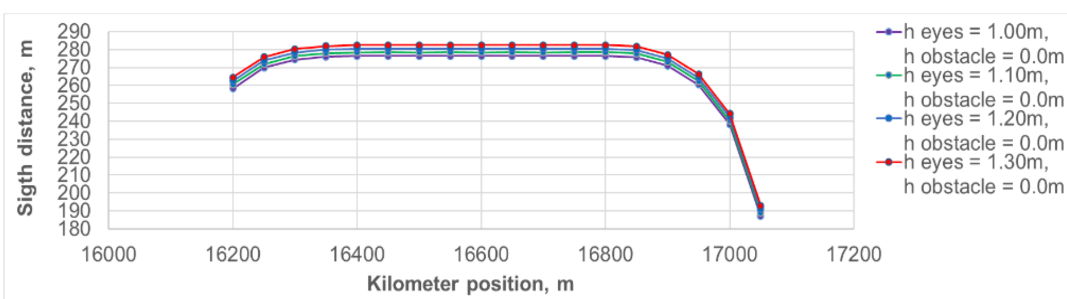


Figure 31. Sight distance as a function of kilometre position, for V = 140 km/h, traffic lane B2, h $_{obstacle}$ = 0.00m - horizontal curve

Between km 16+350 and km 17+050, for h obstacle = 0.00m, the sight distance increases with the height of the driver's eye by 1%-4% for V=140 km/h.

The sight distance as a function of kilometre position and position on the highway, respective traffic lane, V = 140 km/h, for $h_{obstacle}$ = 0.00m is shown in Figure 9, and for $h_{obstacle}$ = 0.40m is shown in Figure 10.

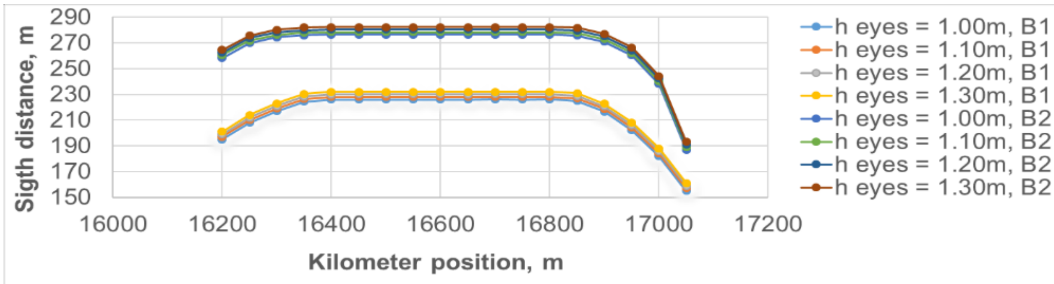


Figure 32. Sight distance as a function of kilometre position and traffic lane, for V = 140 km/h, $h_{obstacle}$ = 0.00m - horizontal curve

The sight distance for V = 140 km/h is 17%-19% less in traffic lane B1 than in traffic lane B2 for $h_{obstacle}$ = 0.00m.

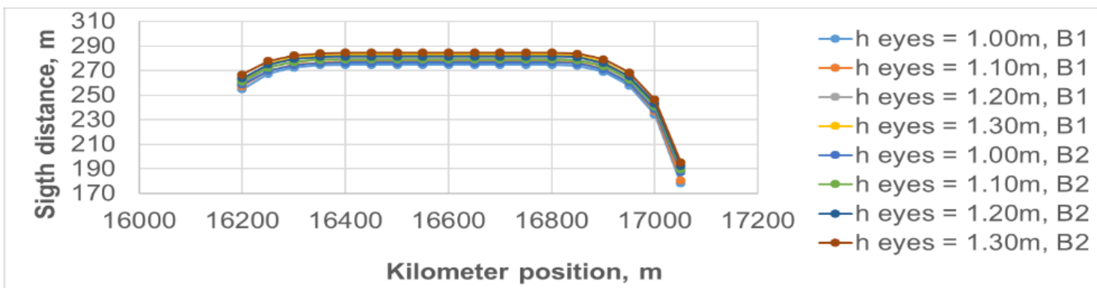


Figure 33. Sight distance as a function of kilometre position, for speed 140 km/h, $h_{obstacle}$ = 0.40m - horizontal curve

The sight distance for V = 140 km/h is 1%-2% less in traffic lane B1 than in traffic lane B2 for $h_{obstacle}$ = 0.40m.

The sight distance as a function of the kilometric position and the height of the driver's eye, for V = 120 km/h and $h_{obstacle}$ = 0.00m, on the vertical convex curve - horizontal alignment is shown in Figure 11.

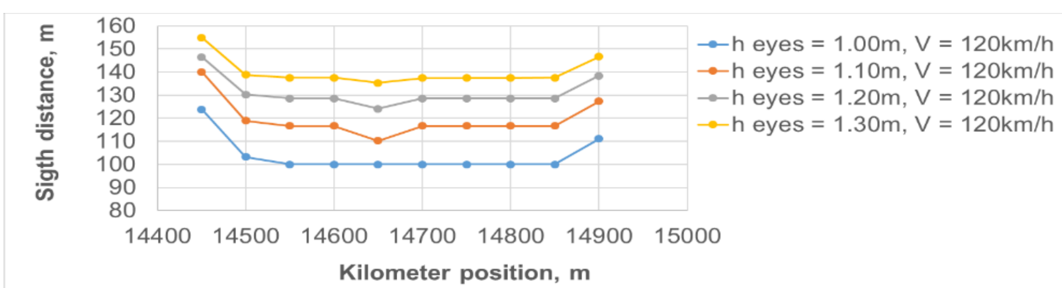


Figure 34. Sight distance as a function of kilometric position, for speed 120 km/h and $h_{obstacle}$ = 0.00m, on vertical convex curve area – horizontal alignment

Sight distance increases by 8% - 15% with the height of the driver's eye in the area of the convex vertical curve for V = 120 km/h.
The sight distance (expressed in percentages according to the minimum sight distance according to Romanian standards) according to the kilometric position and height of the driver's eye, for V = 120 km/h and V = 140 km/h, $h_{obstacle}$ = 0.00m, on the area of the vertical convex curve - horizontal alignment is shown in Figure 12.

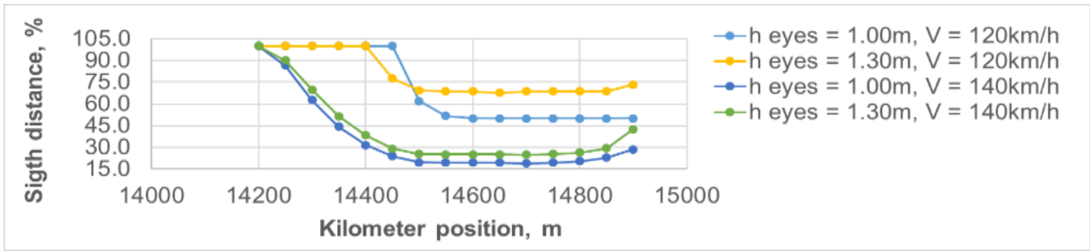


Figure 35. Sight distance as a function of kilometric position, for $h_{obstacle}$ = 0.00m, on the vertical convex curve area - horizontal alignment

The sight distance increases by approximately 19% with the height of the driver's eye in the area of the vertically convex curve for V = 120 km/h and by approximately 9% with the height of the driver's eye in the area of the vertically convex curve for V = 140 km/h. Sight distance increases by approximately 30% with speed, on the vertical convex curve area, for h_{eyes} = 1.00m and by approximately 45% with speed, on the vertical convex curve area, for h_{eyes} = 1.30m.

Sight distance as a function of kilometric position and radius of the vertical convex curve, for $h_{obstacle}$ = 0.00m and V = 120 km/h - horizontal alignment is shown in Figure 13.

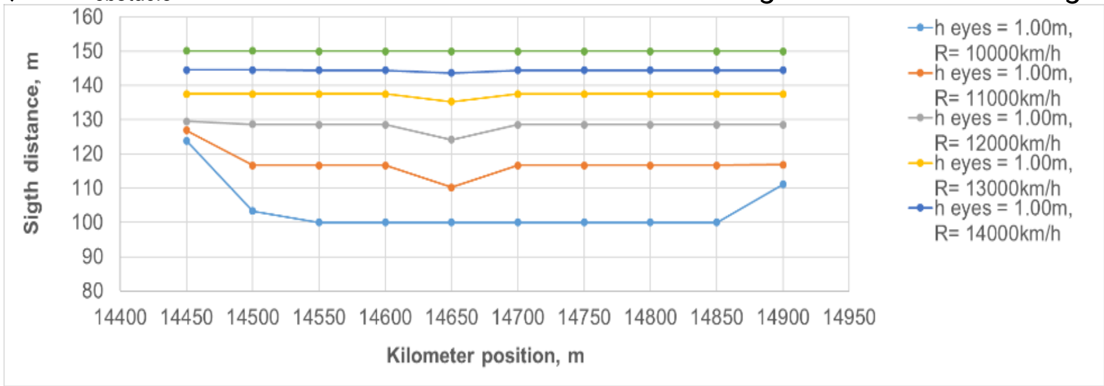


Figure 36. Sight distance as a function of kilometric position, for $h_{obstacle}$ =0.00m and different values of vertical convex curve radius

Sight distance depending on kilometric position increases with radius of the vertical curve by 5% - 17%, for $h_{obstacle}$ = 0.00m.

I.2 Study 2

In the present study, an 11 km motorway section was analyzed.

The initial design was developed in 2007, based on the standards in force at that time, for a design speed of 120 km/h.

The geometric elements, both in horizontal alignment and longitudinal profile, complied with the standards; however, sight distance requirements were not considered.

According to current standards, the radii of vertical curve transitions in the longitudinal profile no longer comply with the requirements.

Therefore, these elements were updated, and the alignment was revised to ensure compliance with sight distance criteria.

According to Order No. 26/2020, amending Annex No. 1 of the Technical Standards for the design, construction, and modernization of roads, approved by Order No. 1296/2017, the positioning of the median barrier was modified.

The alignment in plan and longitudinal profile is illustrated in Figure 37 and Figure 39.

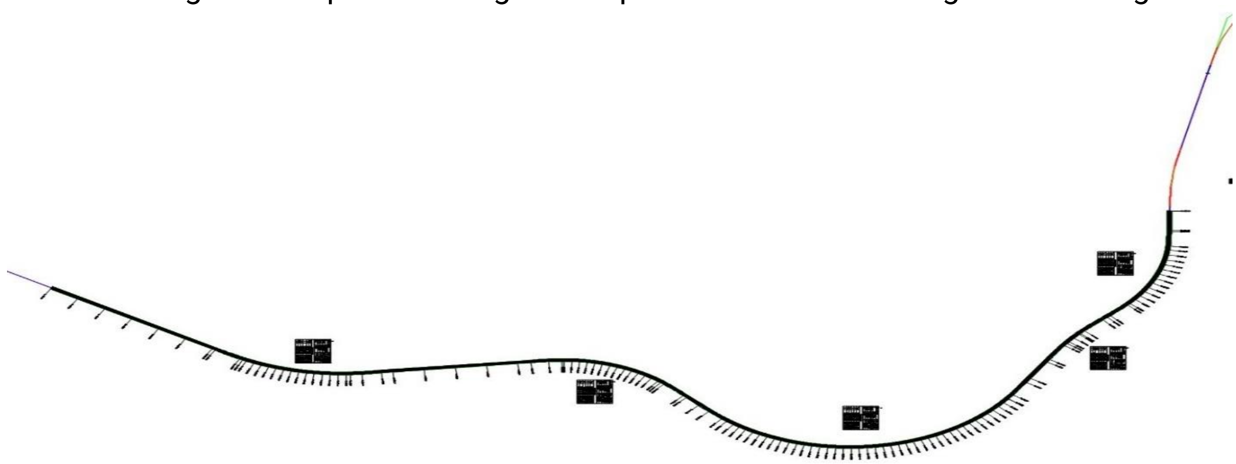


Figure 37. Motorway alignment in plan view

In the Figure 38. is motorway alignment in perspective view.

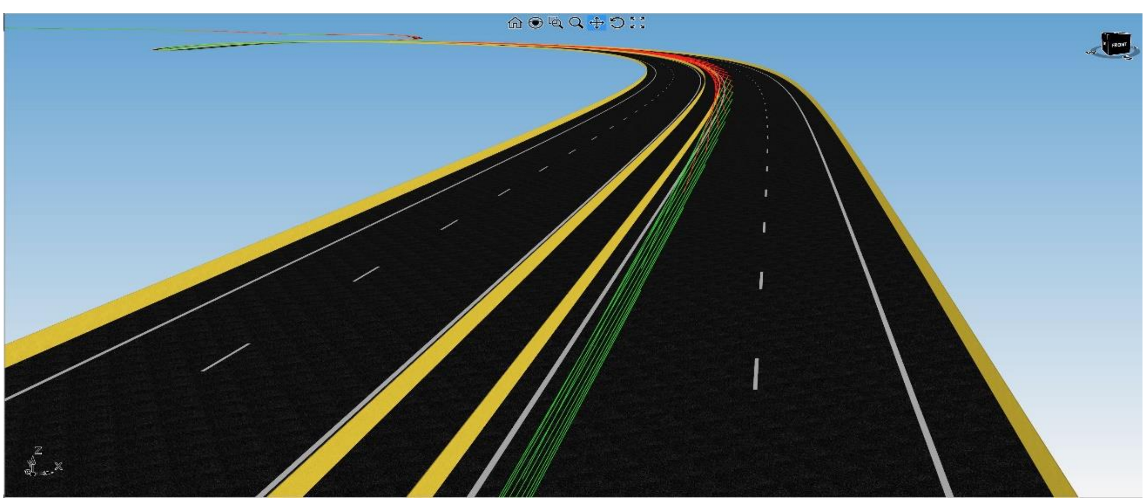


Figure 38. Motorway alignment in perspective view

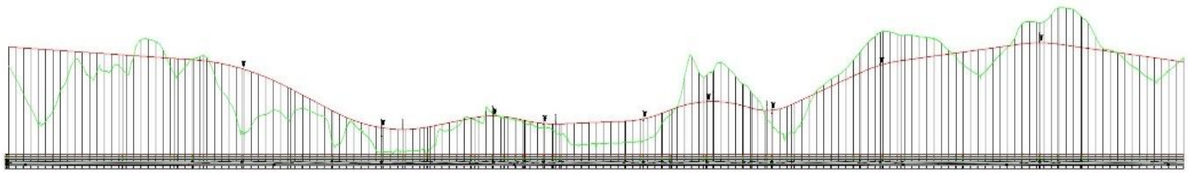


Figure 39. Motorway alignment in longitudinal profile

Table 1 presents the radii of horizontal curves in the existing configuration and in the updated configuration according to the current standards.

Table 1. Horizontal curve radii in plan view

No.	**Existing radius** [m]	Curve type	**Updated radius** [m]
1	1400	Left	2900
2	1005	**Right**	1005
3	1260	Left	1260
4	1300	**Right**	1300
5	1005	Left	1005

Table 2 presents the radii of vertical curves in the existing configuration and in the updated configuration according to the current standards.

Table 2. Vertical curve radii in longitudinal profile

No.	Existing radius [m]	Vertical curve type	Updated radius [m]
1	20000	Crest (convex)	20000
2	12500	Sag (concave)	12500
3	10000	Crest (convex)	15000
4	13000	Sag (concave)	13000
5	10000	Sag (concave)	10000
6	10000	Crest (convex)	15000
7	5000	Sag (concave)	6000

8	12000	Crest (convex)	15000
9	12000	Crest (convex)	15000

Efforts were made to improve the alignment visibility both in horizontal alignment and in longitudinal and cross-sectional profiles.

In horizontal alignment, some curve radii could not be modified due to site constraints; however, it was possible to increase the radius of the first curve.

The influence of horizontal curve radius on sight distance is illustrated in Figure 40.

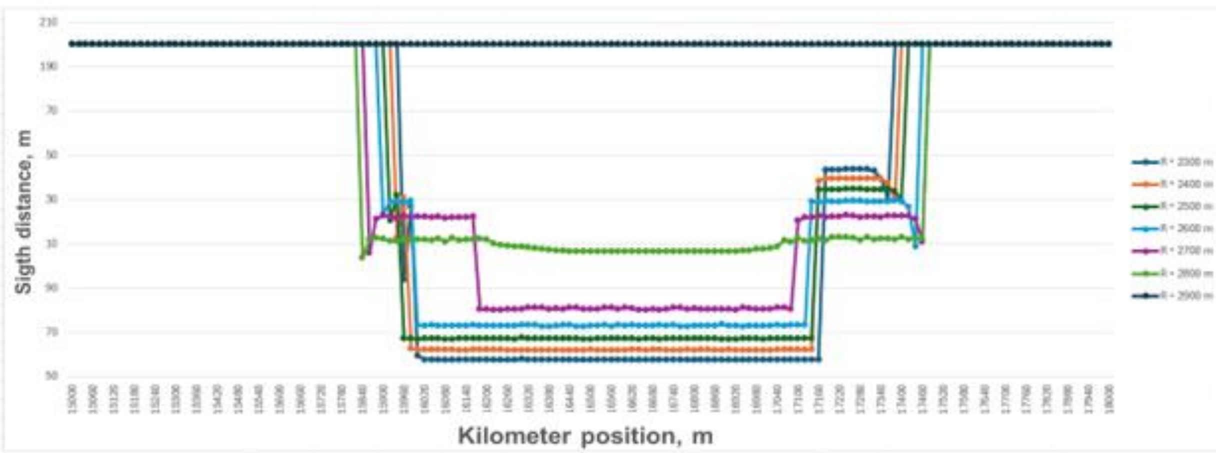


Figure 40. Influence of horizontal curve radius on sight distance

It can be observed that increasing the horizontal curve radius leads to an increase in sight distance.

A 26% increase in radius results in approximately a 50% increase in sight distance, and for a radius value of 2900 m, the sight distance requirement is satisfied.

The influence of vertical curve radii in the longitudinal profile on sight distance is illustrated in Figure 41.

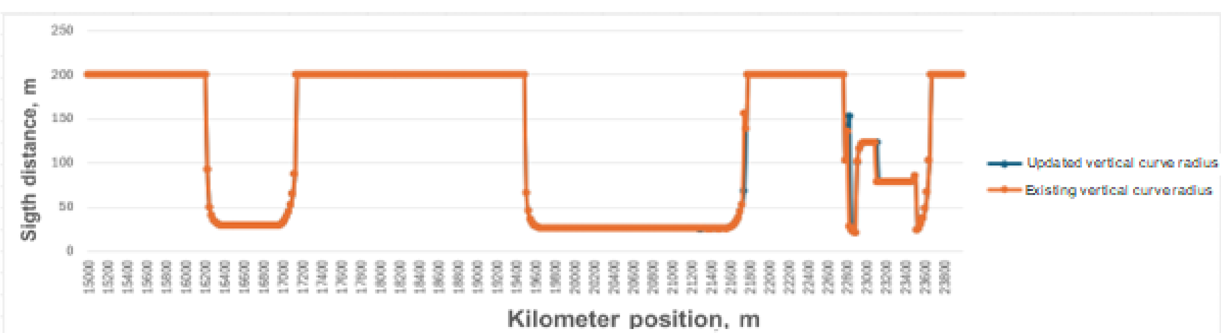


Figure 41. Influence of vertical curve radii on sight distance

It can be observed that increasing the radii of vertical curves does not significantly affect sight distance.

The influence of median barrier positioning on sight distance is illustrated in Figure 42.

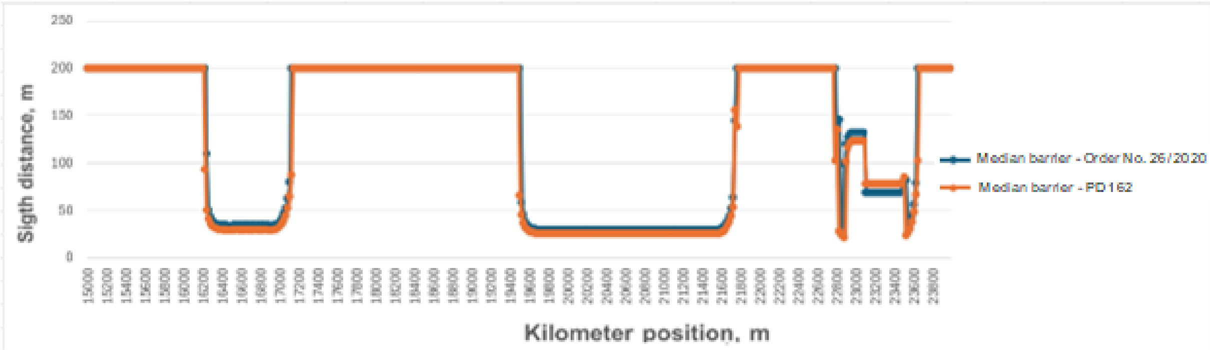


Figure 42. Influence of median barrier positioning on sight distance

It can be observed that positioning the median barrier in accordance with Order No. 26/2020 leads to an increase in sight distance.

For the updated median barrier positioning in accordance with Order No. 26/2020, sight distance increases by approximately 20%.

II. Road

The CIVIL SITE DESIGN application was used for the case studies as an extension of the AutoCAD. The Civil Site Design application is developed by Civil Survey Solutions Australia and works on top of BricsCAD, AutoCAD, AutoCAD Civil 3D platforms and provides advanced functionality for the design and rehabilitation of roads to Romanian standards. It includes basic commands for drawing road geometric elements (plan and vertical), automatic intersection curve, automatic generation of longitudinal and transverse profiles and calculation of related backfill and excavation volumes.

The Civil Site Design application is used in Romania, being one of the most powerful and dynamic software solutions for the design and rehabilitation of roads. From route geometrization and automatic curves arrangement according to the standards in force (STAS 863-85, PD 162-2002, forestry, etc.), to the extraction of quantity lists and reporting in files of the designed elements, to the automatic printing of the execution drawings in AutoCAD format, ARD is an indispensable tool for any designing engineer.

According to STAS 863-65, the minimum sight distance for a speed of 80 km/h is 230 m and for a speed of 60 km/h is 140 m. The studied road section consists of two alignments, the first one from km 19+200 to 20+258.602, the second one from km 20+926.092 to km 21+200, joined by an arched clothoid to the right, Figure 43.

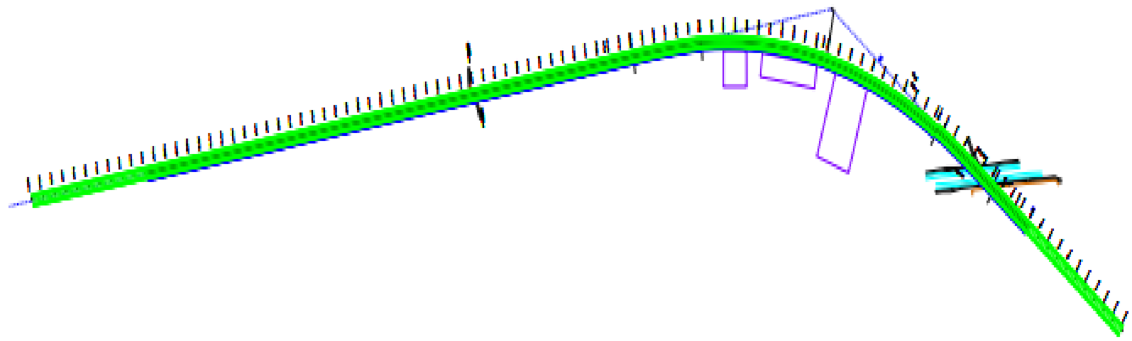


Figure 43. Route studied in situation plan

Design line, from the longitudinal profile consists of two gradients and a crest vertical curve, between km 19+200 and km 19+800.88 there is a 4.50% gradient followed by the crest vertical curve between km 19+800.88 and km 20+093.38 and a -2.00% gradient between km 20+093.38 and km 21+200, Figure 44.

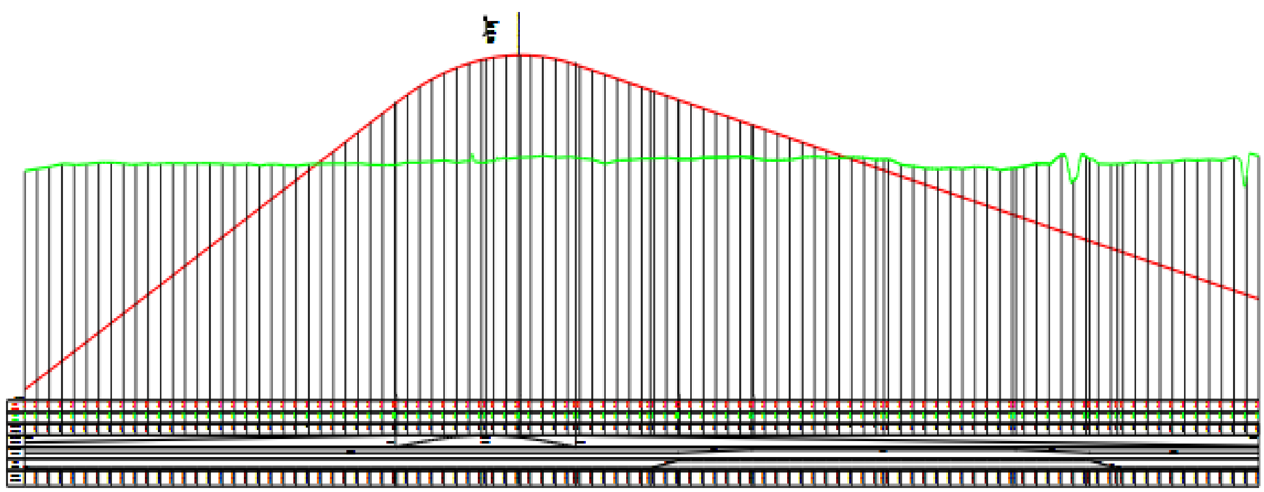


Figure 44. Route studied in longitudinal profile

In Figure 45. it is a representation of the sight distance, on the curve in the situation plane, in perspective.

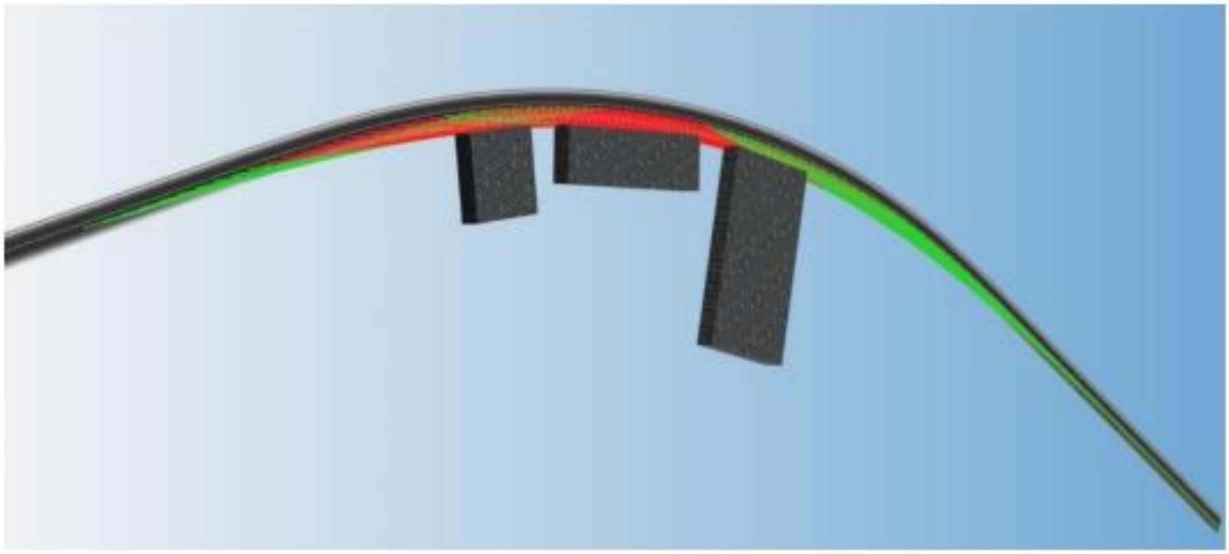


Figure 45. Sight distance on the curve of the situation plan, in perspective

Figure 46. shows the sight distance, in percentages depending on minimum sight distance, for driver eye height between 1.00-1.30 m and object height between 0.20 - 1.00m.

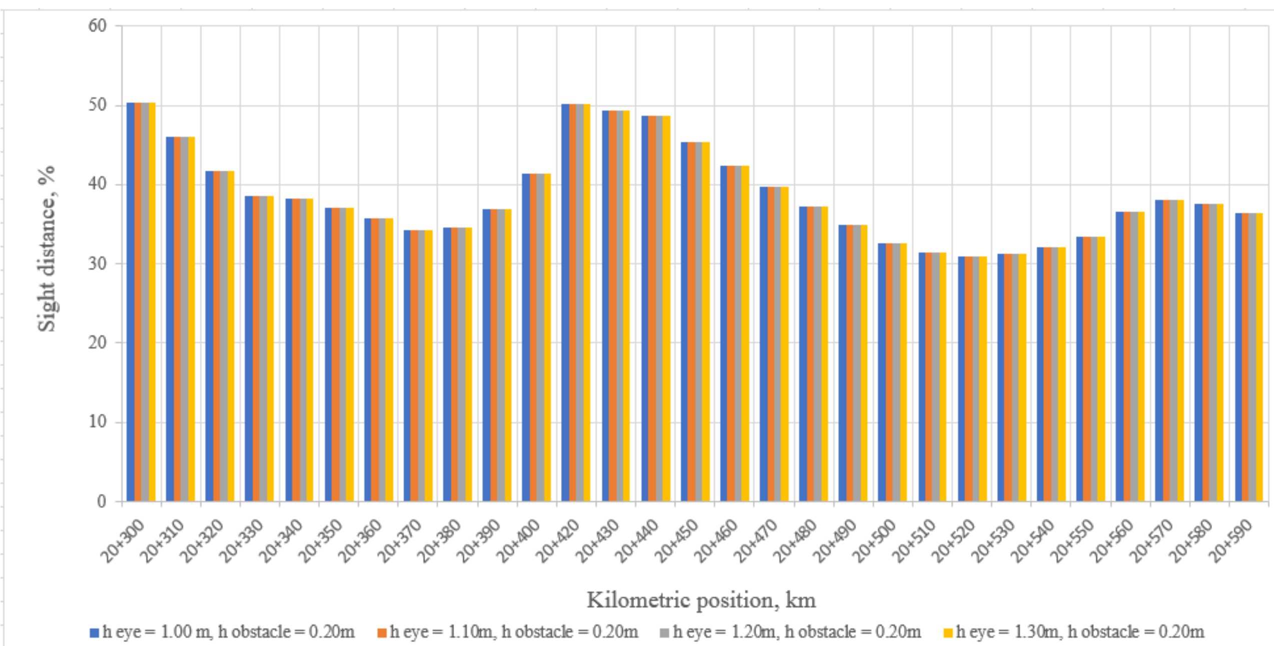


Figure 46. Sight distance, in percentages depending on minimum sight distance, for driver eye height between 1.00-1.30 m and object height between 0.20 m

Figure 47. shows the sight distance, in percentages depending on minimum sight distance, in longitudinal profile for driver eye height between 1.00-1.30 m, object height 0.20 m and speed 80 km/h.

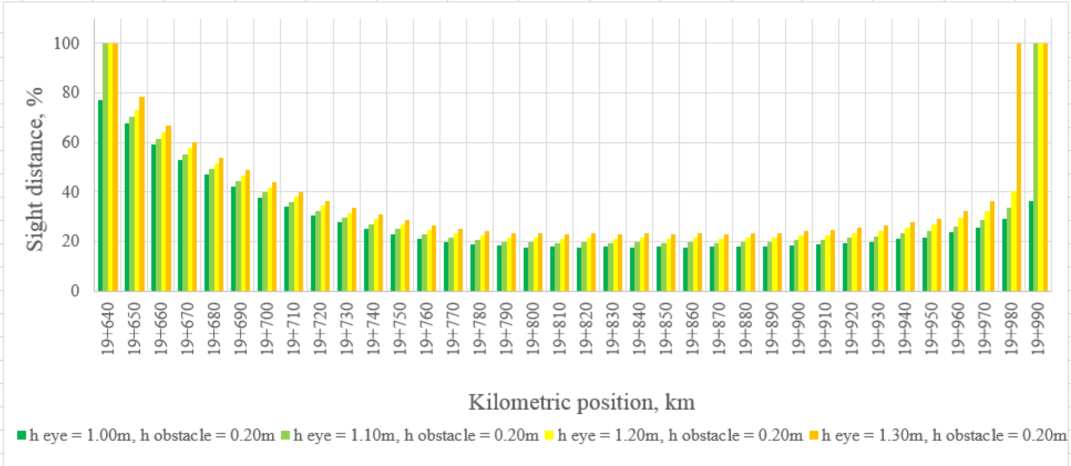


Figure 47. Sight distance, in percentages depending on minimum sight distance, for driver eye height between 1.00-1.30 m and object height of 0.20 m

The influence of the crest vertical curve on the sight distance is important in the horizontal alignment. Between km 19+640 and km 19+990, for h object = 0,20 m, the sight distance is increases with driver eye height by 4%-22% for V = 80 km/h.

For an object height of 0.20 m, depending on the driver's eye height, the sight distance varies between 23% - 100% of the minimum sight distance, for a driver eye height of 1.30 m and between 18% - 77% of 230 m, for a driver eye height of 1.00 m. From kilometre position 19+640 for driver's eye height of 1.00m the minimum sight distance is no longer respected, whereas for h eye = 1.10m - 1.30m the lack of sight distance starts 10m later, i.e. at kilometre 19+650. At kilometre 19+990, when h eye = 1.00 m, the sight distance is 36% of the minimum sight distance and for higher driver eye heights the minimum sight distance is ensured. As the height of the driver's eye increases, the sight distance increases by 4 - 64%.

Figure 48. shows the sight distance, in percentages depending on minimum sight distance, in longitudinal profile for driver eye height 1.00-1.30 m, object height 1.00 m and speed 80 km/h.

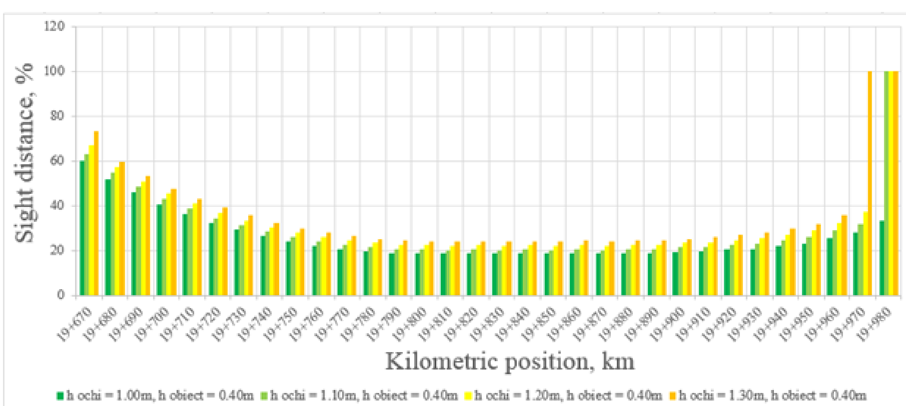


Figure 48. Sight distance for a driver's eye height between 1.00 –1.30 m and an object height of 0.40 m

Figure 49 shows the sight distance in the longitudinal profile for a driver's eye height between 1.00–1.30 m, an object height of 0.60 m, and a speed of 80 km/h.

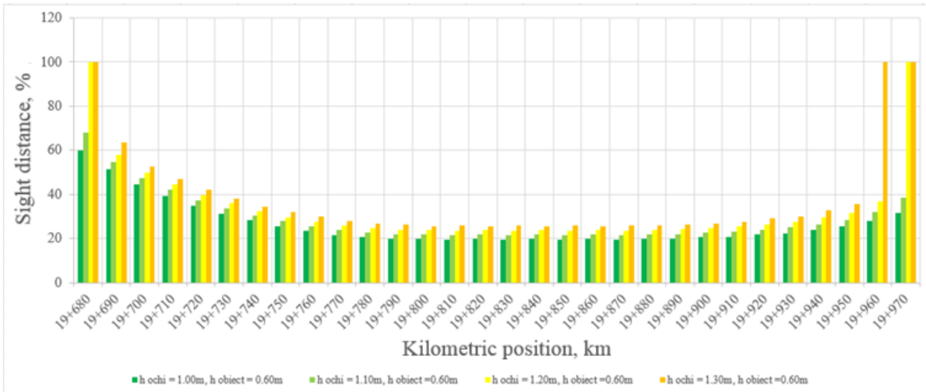


Figure 49. Sight distance for a driver's eye height between 1.00–1.30 m and an object height of 0.60 m

Figure 50 shows the sight distance in the longitudinal profile for a driver's eye height between 1.00–1.30 m, an object height of 0.80 m, and a speed of 80 km/h.

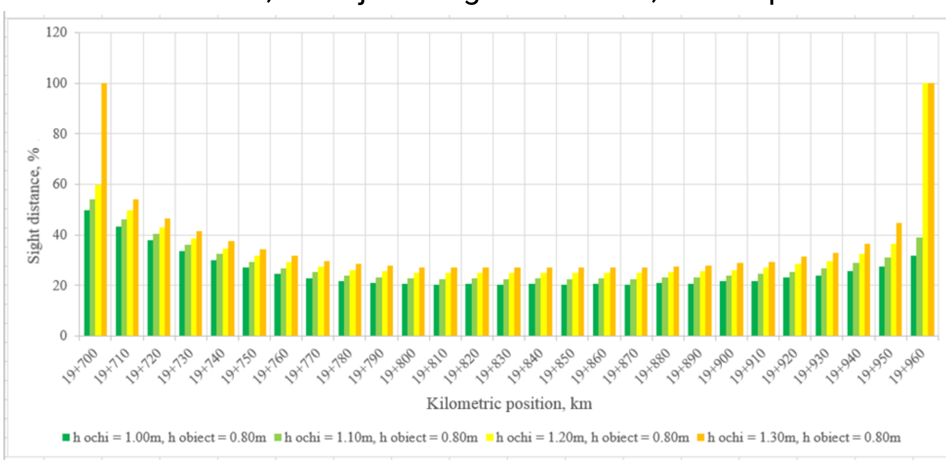


Figure 50. Sight distance for a driver's eye height between 1.00–1.30 m and an object height of 0.80 m

Figure 51 shows the sight distance in the longitudinal profile for a driver's eye height between 1.00–1.30 m, an object height of 1.00 m, and a speed of 80 km/h.

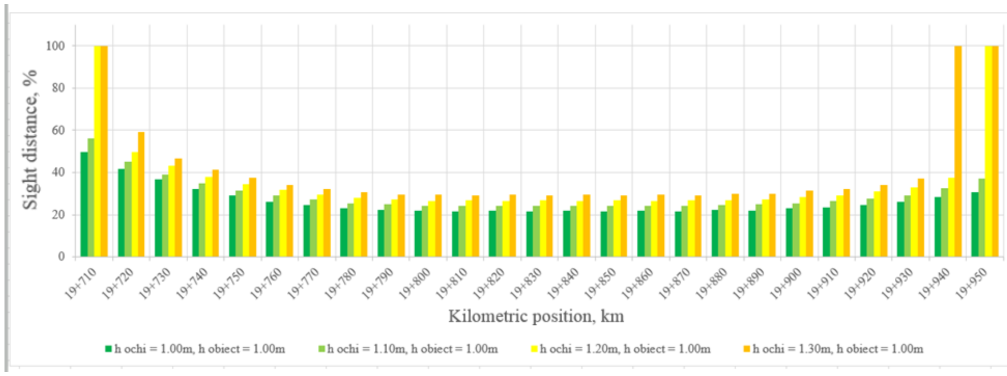


Figure 51. Sight distance for a driver's eye height between 1.00–1.30 m and an object height of 1.00 m

At chainage 19+710, for a driver's eye height of 1.00–1.10 m, the sight distance is less than 230 m, while for eye heights of 1.20–1.30 m, the sight distance requirement is satisfied. Sight distance increases with the driver's eye height by approximately 8%–63%.

Figure 52 shows the sight distance in the longitudinal profile for a driver's eye height of 1.00 m, an object height between 0.20–1.00 m, and a speed of 80 km/h.

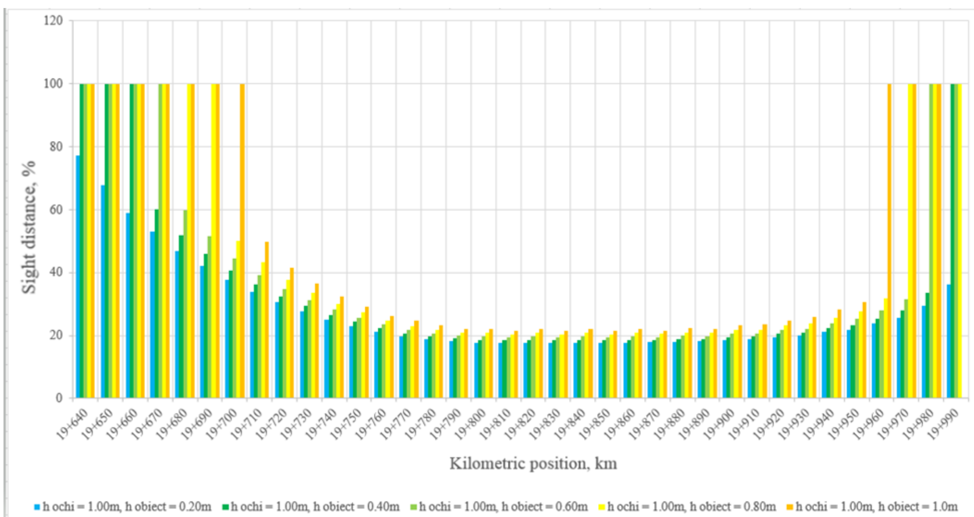


Figure 52. Sight distance for a driver's eye height of 1.00 m and an object height between 0.20–1.00 m

From chainage 19+640 to 19+660, for an object height of 0.20 m, the sight distance varies between 59% and 77%, while for other object heights the minimum sight distance requirement is satisfied. Sight distance increases with the driver's eye height by 5%–64%.

Figure 53 shows the sight distance in the longitudinal profile for a driver's eye height of 1.10 m, an object height between 0.20–1.00 m, and a speed of 80 km/h.

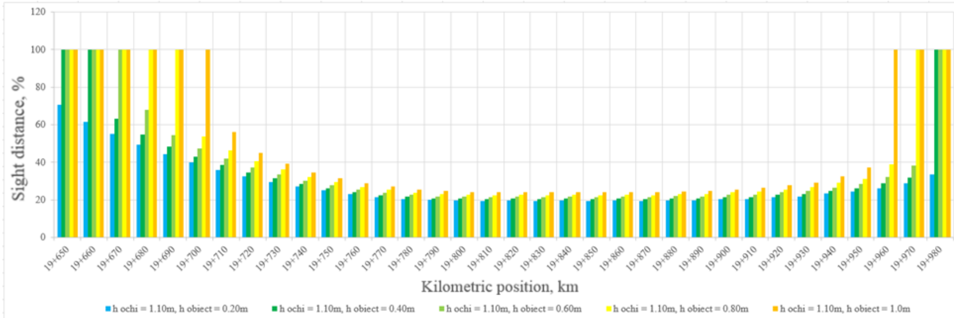


Figure 53. Sight distance for a driver's eye height of 1.10 m and an object height between 0.20–1.00 m

Figure 54 shows the sight distance in the longitudinal profile for a driver's eye height of 1.20 m, an object height between 0.20–1.00 m, and a speed of 80 km/h.

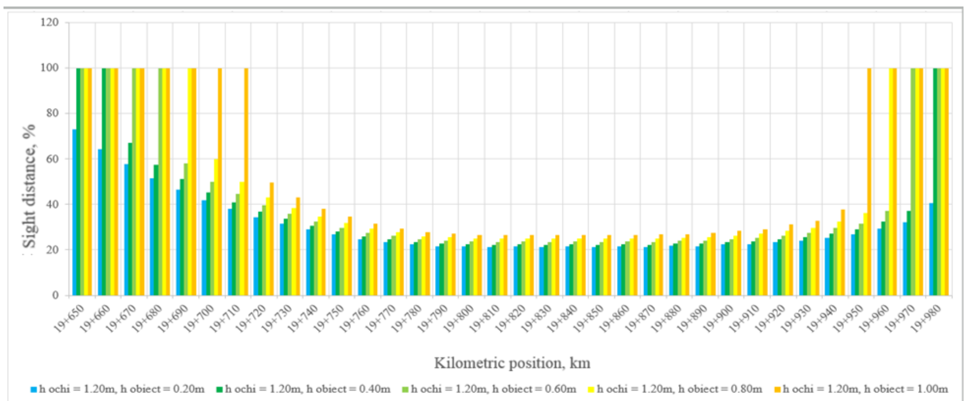


Figure 54. Sight distance for a driver's eye height of 1.20 m and an object height between 0.20–1.00 m

Figure 55 shows the sight distance in the longitudinal profile for a driver's eye height of 1.30 m, an object height between 0.20–1.00 m, and a speed of 80 km/h.

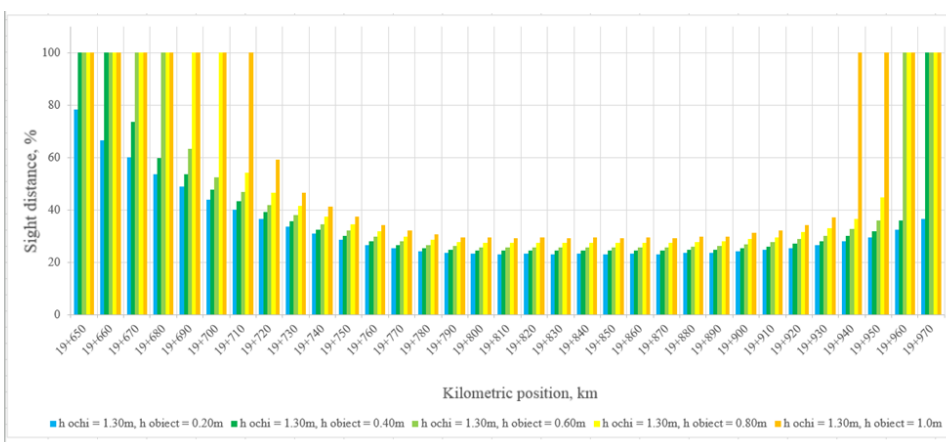


Figure 55. Sight distance for a driver's eye height of 1.30 m and an object height between 0.20–1.00 m

Sight distance for an object height of 0.20 m at chainage 19+650–19+660 varies between 66%–78% for a driver's eye height of 1.00 m, while for object heights greater than 0.20 m the sight distance requirement is satisfied. Sight distance increases with object height by 7%–54%.

Figure 56 shows the sight distance in the longitudinal profile for a driver's eye height between 1.00–1.30 m, an object height of 0.00 m, and a speed of 60 km/h.

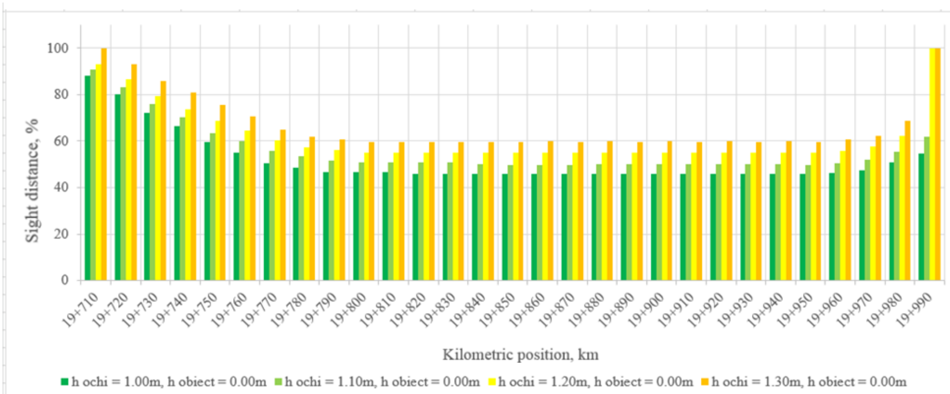


Figure 56. Sight distance for a driver's eye height between 1.00–1.30 m and an object height of 0.00 m

Sight distance increases by approximately 3%–39% with increasing eye height, from a driver's eye height of 1.00 m to 1.30 m. Sight distance varies between 46%–88% for a driver's eye height of 1.00 m and between 60%–100% for a driver's eye height of 1.30 m. At chainage 19+990, for eye heights of 1.20–1.30 m, the sight distance requirement is satisfied, while for eye heights of 1.00–1.10 m it is 38%–45% lower.

Figure 57 shows the sight distance in the longitudinal profile for a driver's eye height between 1.00–1.30 m, an object height of 0.10 m, and a speed of 60 km/h.

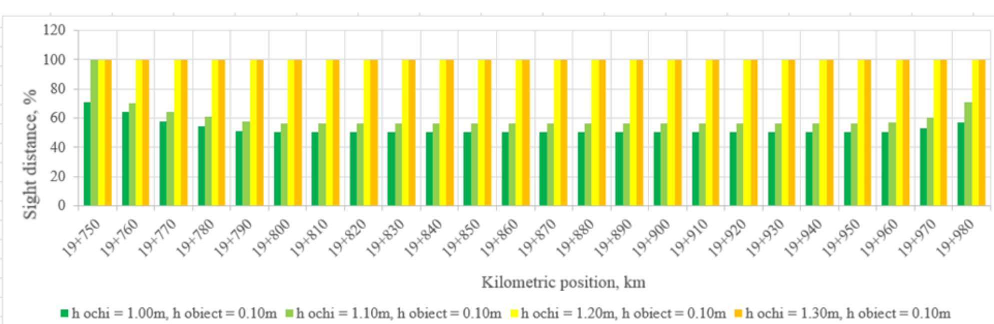


Figure 57. Sight distance for a driver's eye height between 1.00–1.30 m and an object height of 0.10 m

Figure 58 shows the sight distance in the longitudinal profile for a driver's eye height between 1.00–1.30 m, an object height of 0.20 m, and a speed of 60 km/h. For driver's eye heights greater than 1.00 m, the sight distance requirement is satisfied.

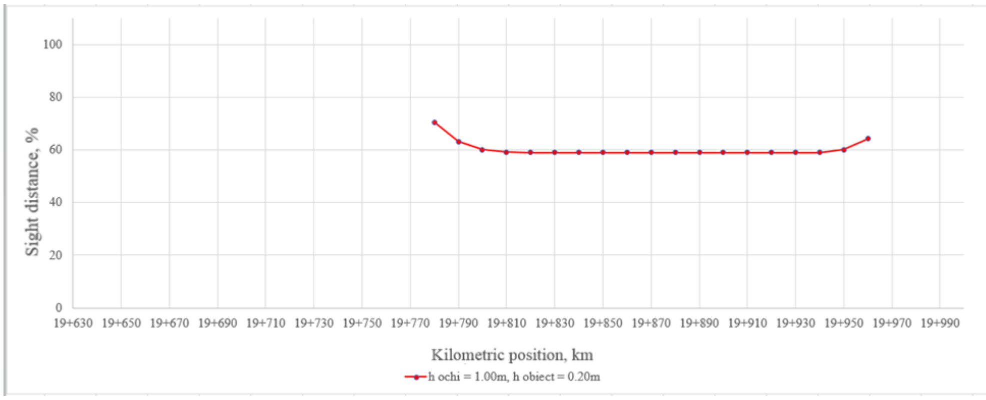


Figure 58. Sight distance for a driver's eye height between 1.00–1.30 m and an object height of 0.20 m

Figure 59 shows the sight distance in the longitudinal profile for a driver's eye height of 1.00 m, an object height between 0.00–0.20 m, and a speed of 60 km/h. For object heights greater than 0.20 m, the sight distance requirement is satisfied.

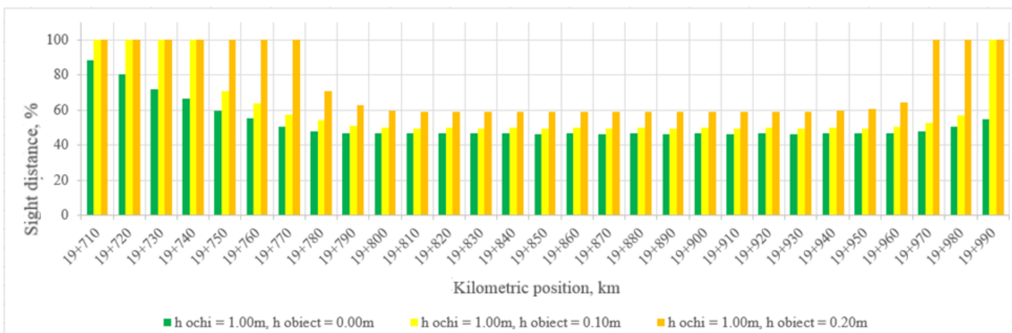


Figure 59. Sight distance for a driver's eye height of 1.00 m and an object height between 0.00–0.20 m

Between chainage 19+710 and 19+740, for an object height of 0.00 m, the sight distance is 21%–33% lower than the value specified in STAS 863-65, while for object heights of 0.10–0.20 m the sight distance requirement is satisfied. From chainage 19+750 to 19+770, for an object height of 0.10 m, the minimum sight distance is 29%–36% lower than the value specified in STAS 863-65 (140 m), while for an object height of 0.20 m it is satisfied.

For an object height of 1.30 m, the sight distance required by the standard is not satisfied between chainage 19+780 and 19+960, being approximately 40% lower. The sight distance, for a driver's eye height of 1.00 m, increases with object height by values ranging between 6%–46%.

Figure 60 shows the sight distance in the longitudinal profile for a driver's eye height of 1.10 m, an object height between 0.00–0.10 m, and a speed of 60 km/h. For object heights greater than 0.10 m, the sight distance requirement is satisfied.

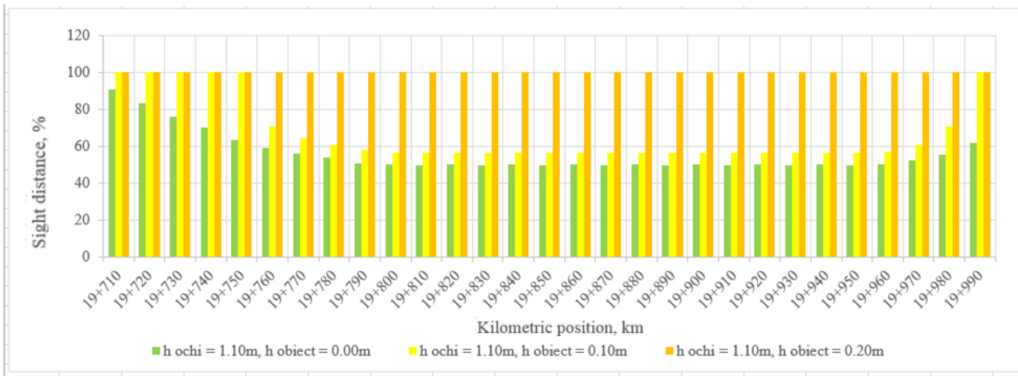


Figure 60. Sight distance for a driver's eye height of 1.10 m and an object height between 0.00–0.20 m

Figure 61 shows the sight distance in the longitudinal profile for a driver's eye height of 1.20 m, an object height between 0.00–0.10 m, and a speed of 60 km/h. For object heights greater than 0.10 m, the sight distance requirement is satisfied.

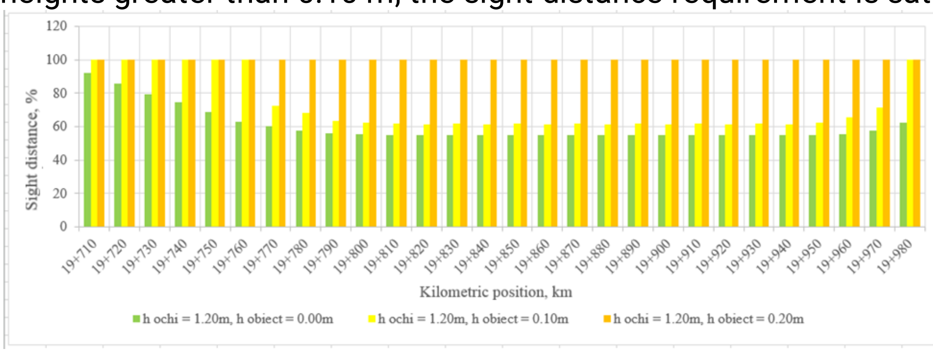


Figure 61. Sight distance for a driver's eye height of 1.20 m and an object height between 0.00–0.20 m

Figure 62 shows the sight distance in the longitudinal profile for a driver's eye height of 1.30 m, an object height between 0.00–0.10 m, and a speed of 60 km/h. For object heights greater than 0.10 m, the sight distance requirement is satisfied.

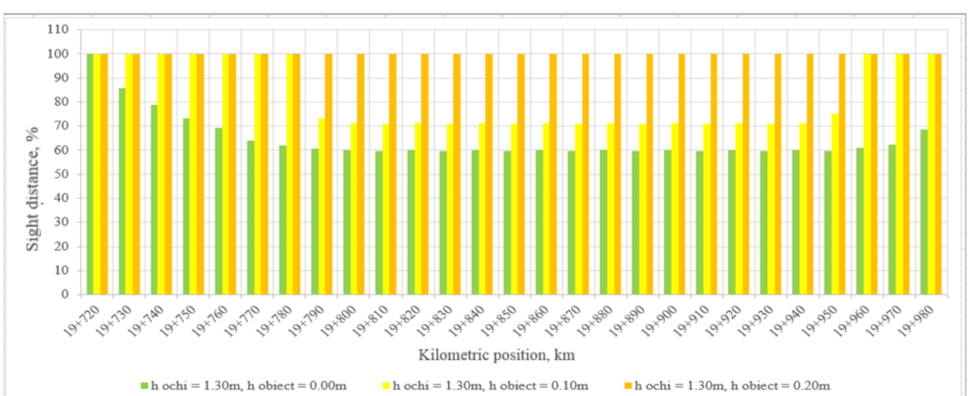


Figure 62. Sight distance for a driver's eye height of 1.30 m and an object height between 0.00–0.20 m

For an object height of 0.20 m, the minimum sight distance is satisfied. The values range between 71%–100% from chainage 19+790 to 19+950 for an object height of 0.10 m, while for an object height of 0.00 m they vary between 60%–100% from chainage 19+720 to 19+980.

Figure 63 shows the sight distance, expressed as a percentage of the minimum sight distance, in the longitudinal profile for a driver's eye height of 1.00 m, an object height of 0.20 m, and speeds of 60 km/h and 80 km/h, respectively.

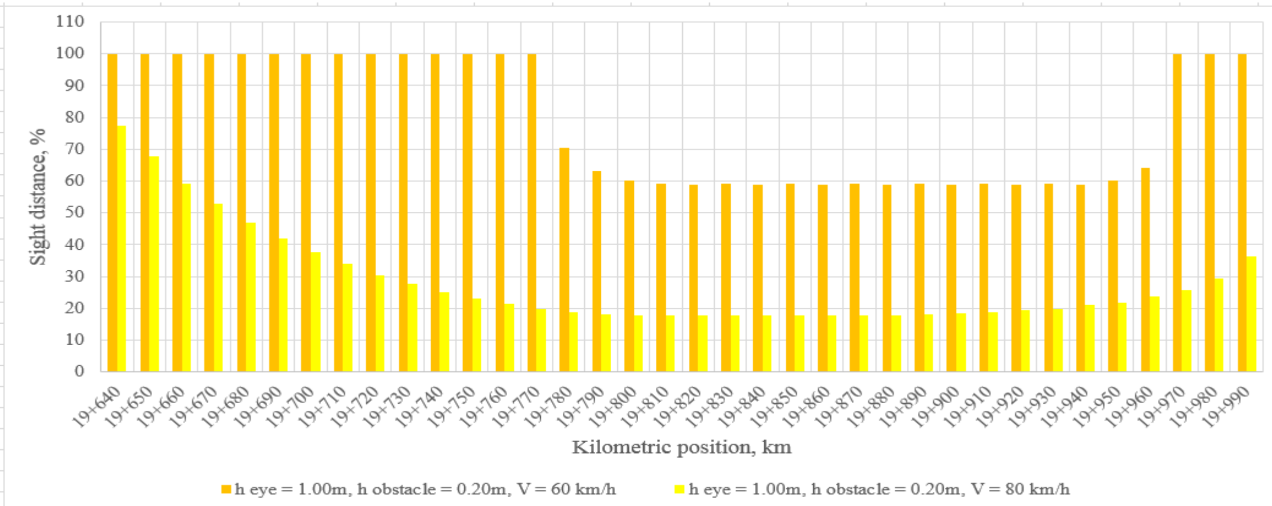


Figura 63. Sight distance, in percentages depending on minimum sight distance, for driver eye height of 1.00 and object height of 0.20 m

The sight distance is about 23%-80% less at 80 km/h than at 60 km/h, the sight distance being calculated as a percentage of the minimum sight distances in STAS 863-65.

III. Intersection

By analyzing the literature and identifying gaps in current knowledge, the research provides a solid foundation for the development of new theories and predictive models to explain how various variables, such as intersection geometric characteristics, the presence of visual obstructions, and environmental conditions, influences the visibility distance.

To carry out this case study, the intersection was analyzed taking into account the starting and approaching visibility triangle in accordance with AND 600. The intersection is located on DN 22 national road at km 131+962, at the intersection with the access road to Quarry Revarsarea. In the plan, there is a curve with a radius of 115m on the main DN 22 road. The connecting radius of the secondary road with DN 22 is 12m. The width of the traffic lanes, both the current ones of DN 22, as well as the width of the left turn lane is 3.50m. Figure 64 shows the intersection studied.

In longitudinal profile, the studied route is designed according to STAS 863-65. Figure 65 shows the longitudinal profile on the DN 22 national road where the slopes are between 0.5% and 5.50%. Near the intersection, at approximately 120m, there is a convex vertical connecting curve designed with a radius of 800m. Figure 66 shows the longitudinal profile of the access road to Quarry Revarsarea, with two slopes, namely in the intersection area it is 0.5%, and after the vertical connecting curve the slope is 10.5%.

Figure 64. Intersection general layout

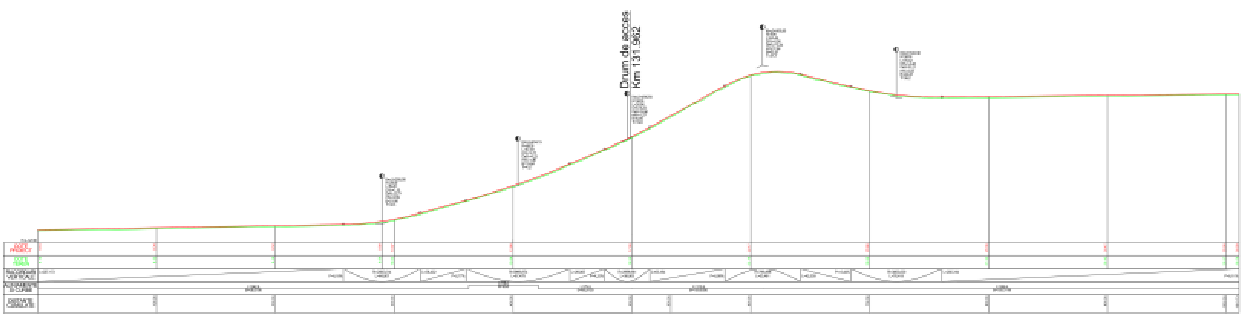


Figure 65. Longitudinal profile DN 22

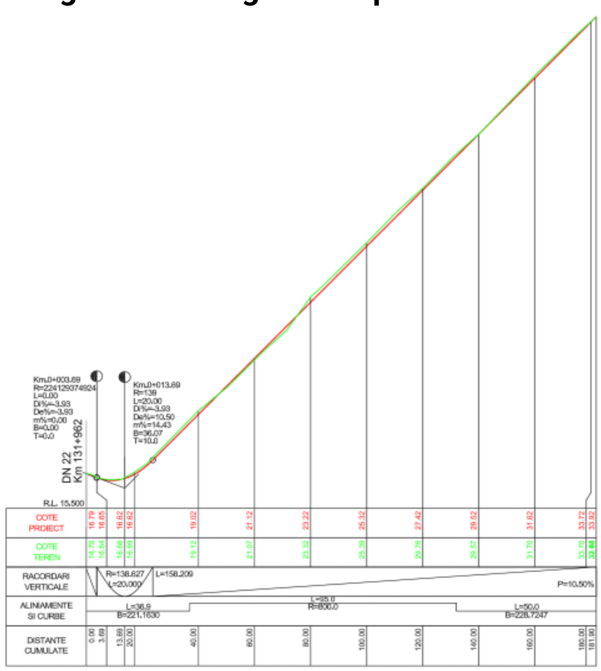


Figure 66. Longitudinal profile for the access road to Revărsarea quarry

Figure 67 shows a perspective view of the studied intersection.

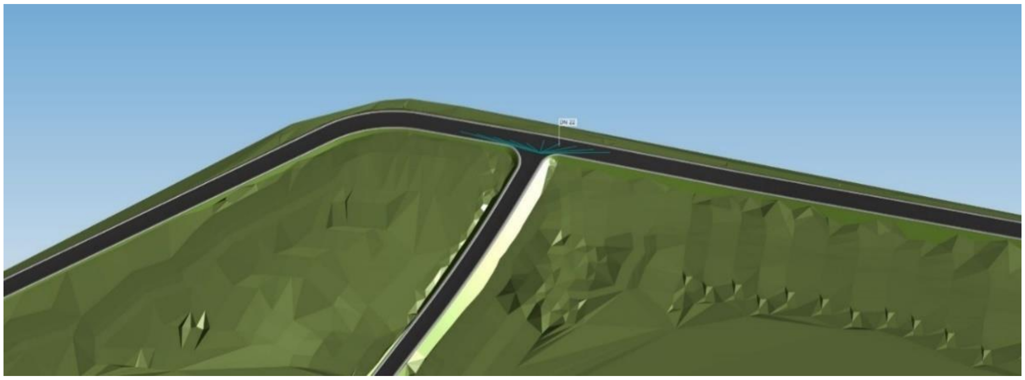


Figure 67. Perspective view of the studied intersection

The sight triangle (Figure 68) is defined as the spatial area formed by the paths of the vehicle travelling along the major road and the vehicle travelling along the intersecting minor road, leading to a potential conflict point. The area of the sight triangle depends on the required sight distances, which must be ensured according to the design speeds of the conflicting traffic movements.

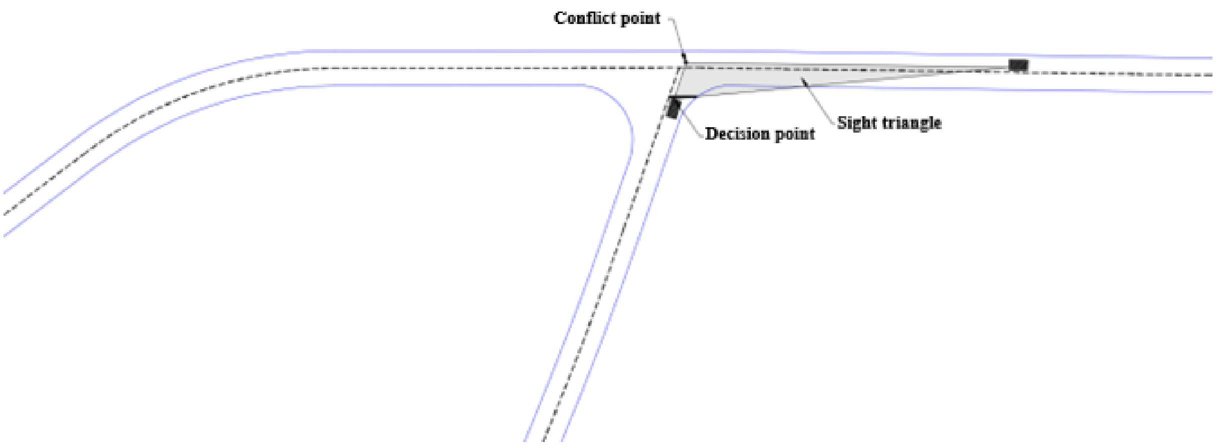


Figure 68. Sight triangle for entering the major road

Figure 69 presents the sight triangle for stopping and manoeuvring.

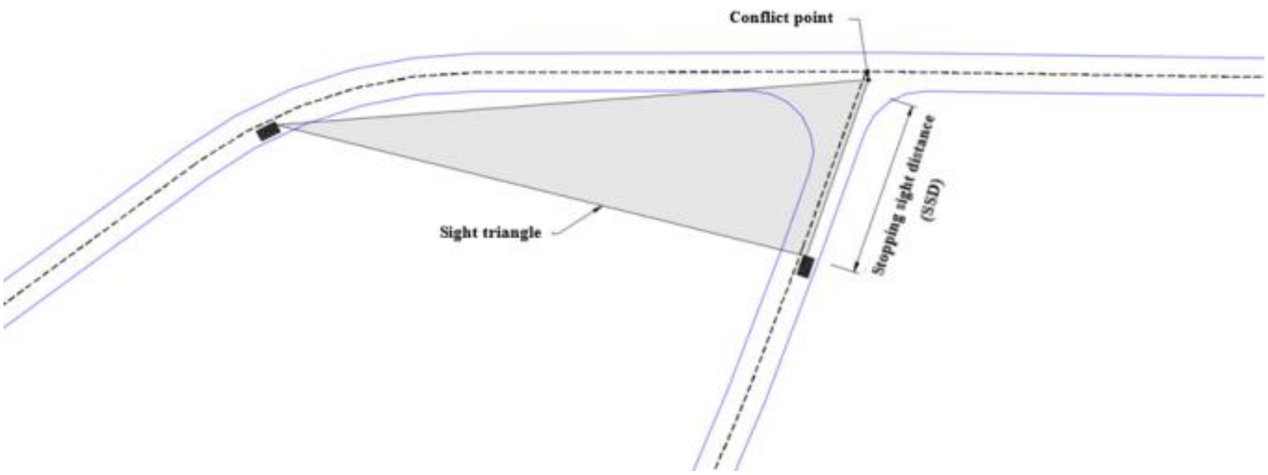


Figure 69. Sight triangle for stopping and manoeuvring

In this three-dimensional analysis, the sight distance was evaluated at the intersection between National Road DN22 and the access road to the Revărsarea Quarry, configured as a T-intersection.

Criterion - STOP at a speed of 60 km/h

The visibility distance is composed of two distances, a decision distance and a stopping distance, according to AND 600. The stopping visibility distance for the speed of 60 km/h is 85m, the decision visibility distance for the speed of 60 km/h is 195m. The required visibility distance in the intersection for the speed of 60 km/h, on the main road, is 280m.

Figure 70 shows the visibility distance (% of the visibility distance according to AND 600) depending on the kilometer position and the slope of the slope, on the left side of the intersection. It is observed that for the slope of 1:4 the visibility distance is greater than for the slope of 1:2 and increases with the kilometer position, and for the last 2-kilometer positions this is satisfied.

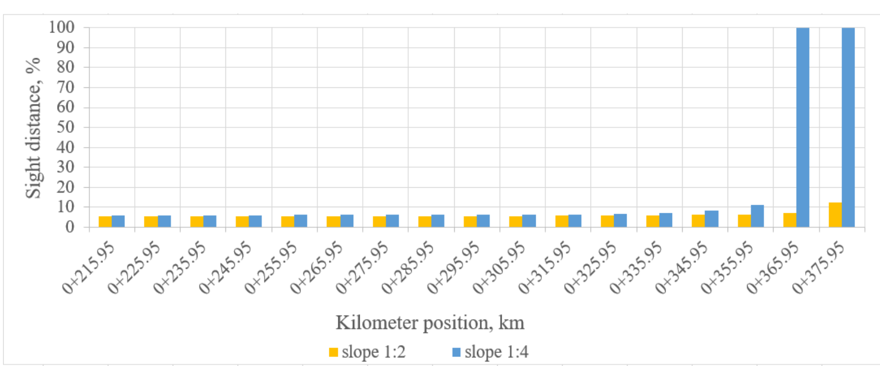


Figure 70. Sight distance as a function of slope on the left side

A 3D model of the studied intersection is shown in Figure 71 and the sight distances for the slope of 1:2 for both sides is plotted.

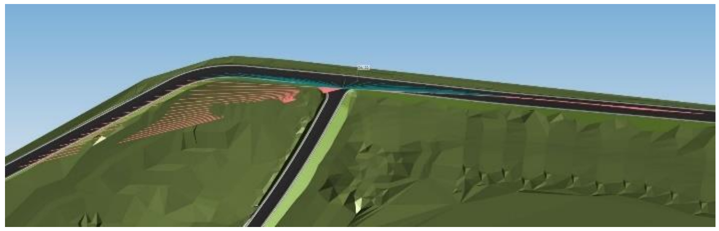


Figure 71. Sight distance perspective for 1:2 slope

Figure 72 shows a perspective of the studied intersection, but this time with a slope of 1:4. Compared to the other perspective, from Figure 5 an increase in the visibility distance on the left side is observed.

Figure 72. Sight distance perspective for 1:4 slope

In Figure 73 the visibility distance is represented on the right side, where we notice that the visibility distances coincide regardless of the slope, in this case we will refer to the longitudinal profile in Figure 65 where a convex connection on the main road DN 22 is observed which obstructs the visibility on the right at this intersection. Because of this, the visibility distance does not vary according to the slope of the slope.

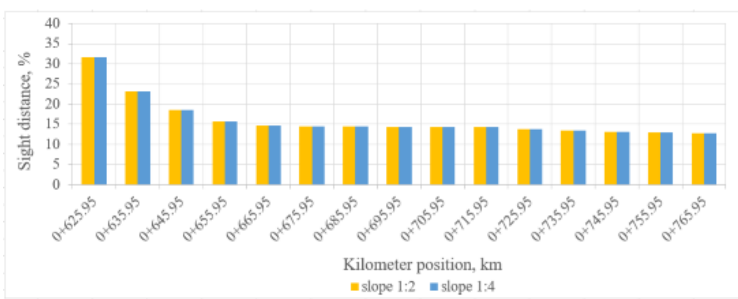


Figure 73. Sight distance as a function of slope on the right side

Criterion - STOP at a speed of 50 km/h

The stopping visibility distance for the speed of 50 km/h is 65m, the decision visibility distance for the speed of 50 km/h is 155m. The required visibility distance in the intersection for the speed of 50 km/h on the main road is 220m. Figure 74 shows a sight distance according to the shape of the slope on the left side

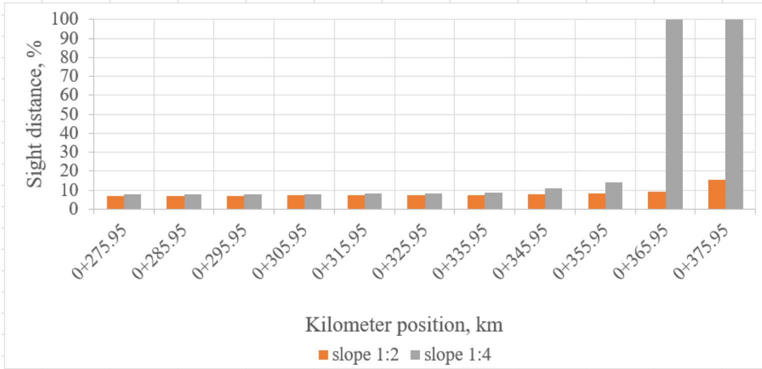


Figure 74. Sight distance according to the shape of the slope on the left side

Figure 75 shows a perspective of the studied intersection, but this time with a slope of 1:2.

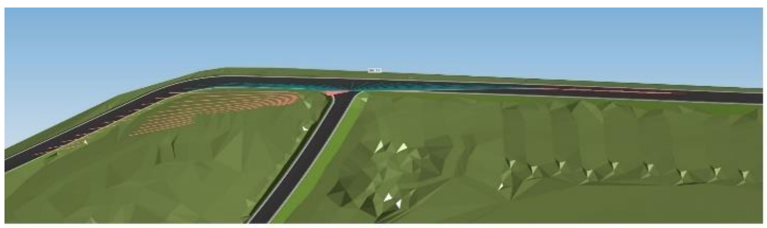


Figure 75. Sight distance perspective for 1:2 slope

Figure 76 shows a perspective of the studied intersection, but this time with a slope of 1:4. Compared to the other perspective, from Figure 64 an increase in the visibility distance is observed on the left side.

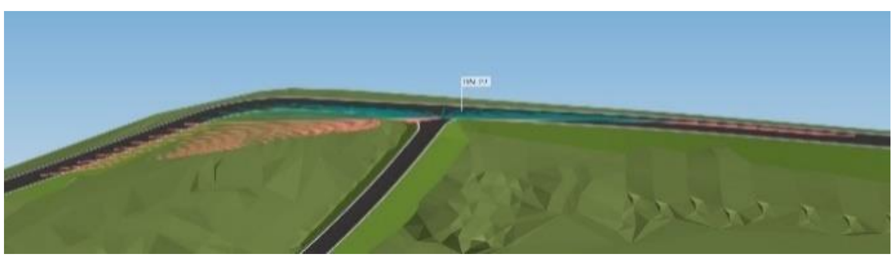


Figure 76. Sight distance perspective for 1:4 slope

In Figure 77 the visibility distance, on the right side, can be seen to be identical for the 1:2 slope and the 1:4 slope. In this case we will refer to the longitudinal profile on the main road where it is observed that the convex connection between the slopes on DN A obstructs the visibility on the right side in this intersection. Because of this, the visibility distance does not vary according to the slope of the slope.

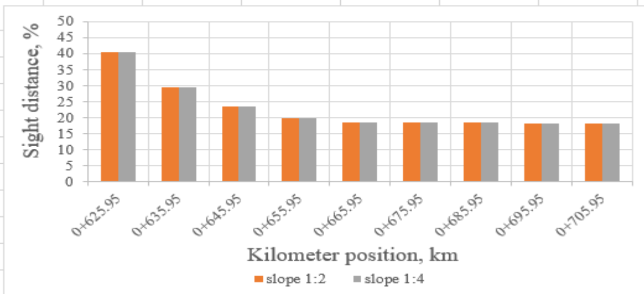


Figure 77. Sight distance as a function of slope on the right side

Criterion - STOP at a speed of 40 km/h

The visibility distance when stopping for a speed of 40 km/h is 50m. The sight distance of 50m is required in the intersection for the speed of 40 km/h on the main road.

It is necessary to specify – according to AND 600 for speeds lower than 50 km/h there is no decision visibility distance, so the STOP 40 km/h criterion is no longer composed of the sum of the two visibilities prescribed and used in the previous criteria.

Figure 78 shows the sight perspective at the intersection for a speed of 40 km/h.

Figure 79 shows the variation of visibility as a function of speed and the shape of the slope in the intersection on the left side.

Figure 80 shows the variation of visibility as a function of speed and the shape of the slope in the intersection on the right side.

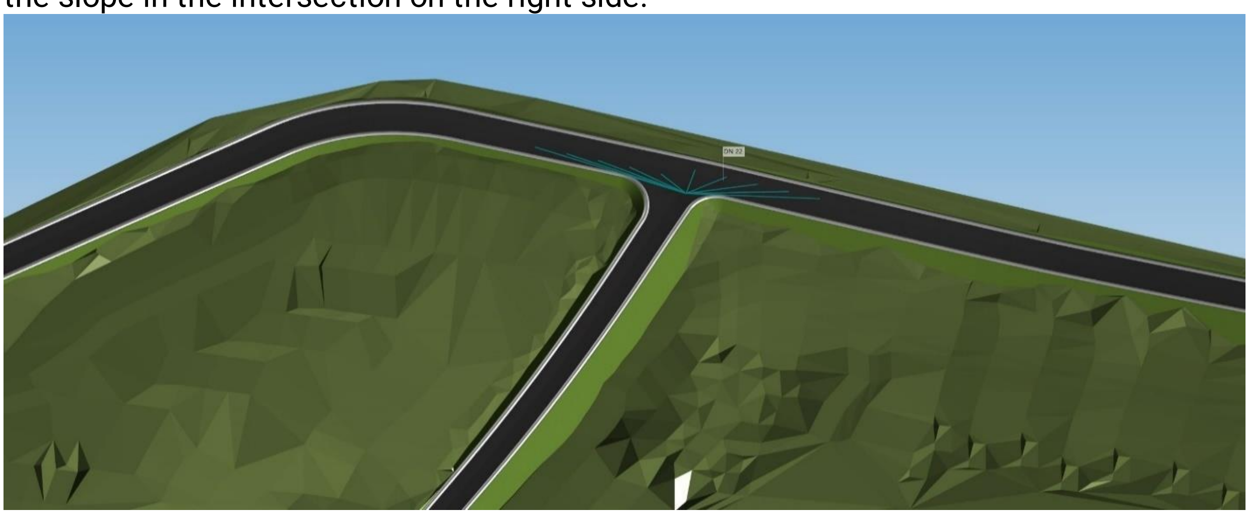


Figure 78. Sight perspective at the intersection for a speed of 40 km/h

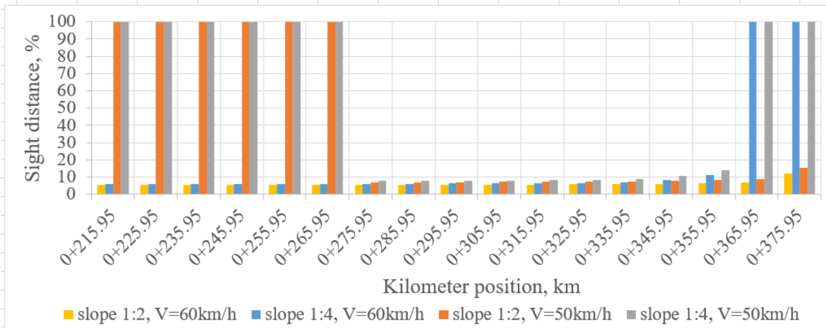


Figure 79. Sight distance as a function of speed and slope shape, on the left side

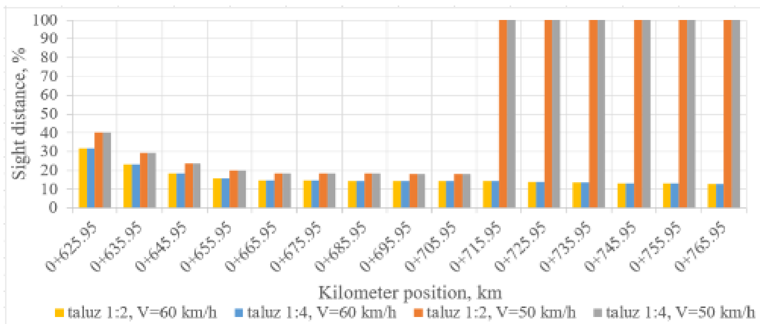


Figure 80. Sight distance as a function of speed and slope shape, on the right side

Criterion – Maneuver at a speed of 60 km/h

The study continues with the check of visibility when stopping and maneuvering. This criterion checks the non-traffic intersection signaled with the Give way sign.

The criterion considers that both participants are in motion and their trajectories meet in one of the conflict points of the intersection. The position of the participant on the secondary road is for the case where the minimum stopping visibility distance of 35m is respected, according to AND 600 – the speed on that section is 30km/h.

In the software this check criterion is identified as RO-AND_600-INTERS-NSMF_MANEVRA, the speeds at which these checks were made are 60km/h, 50km/h, 40 km/h and 30 km/h.

The criterion is composed of two visibility distances, one for stopping and one for maneuvering, according to AND 600. The decision visibility distance for stopping at a speed of 60 km/h is 85m, the decision visibility distance for maneuvering at a speed of 60 km/h is 235m. The required visibility distance in the intersection for the speed of 60 km/h, on the main road, is 320m.

In Figure 81 we can see the improvements in the drivers' field of vision due to the variation in the shape of the slope in the intersection, on the left side. It is observed that for the intersection with slope of 1:4, the visibility increases and for the last kilometer position the visibility distance is satisfied.

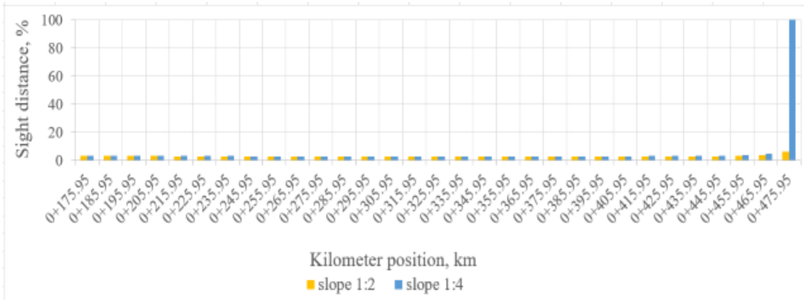


Figure 81. Sight distance according to the shape of the slope on the left side

Figure 82 shows a perspective of the studied intersection, but this time with a slope of 1:4.

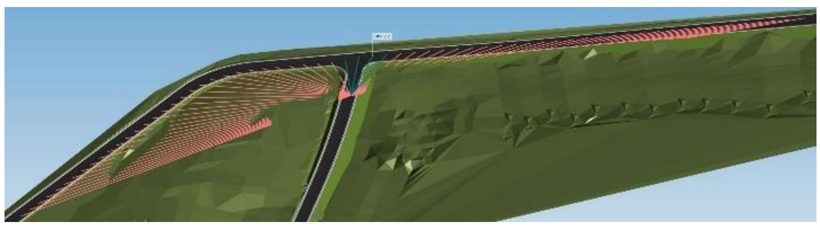


Figure 82. Sight distance perspective for 1:2 slope

In Figure 83 the visibility distance is represented on the right side.

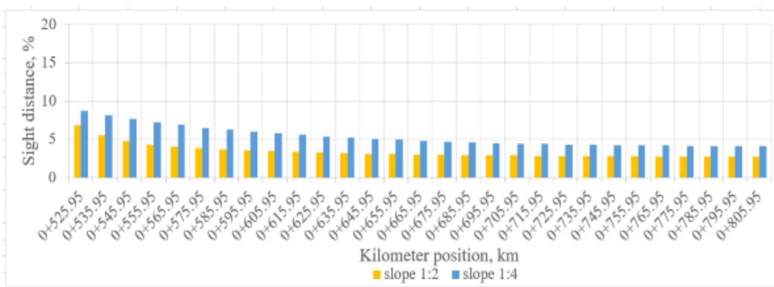


Figure 83. Sight distance according to the shape of the slope on the right side

Figure 84 shows the visibility perspective when the slope of the slope is 1:4. Compared to the other perspective, from Figure 81 an increase in the visibility distance on the left side is observed.

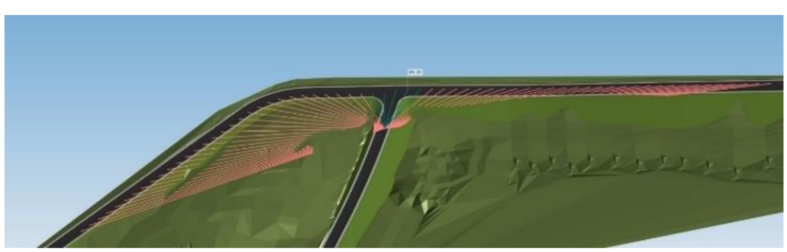


Figure 84. Sight distance perspective for 1:4 slope

Criterion – Maneuver at a speed of 50 km/h

In Figure 85, the visibility distance is represented on the left side where we observe the variation depending on the slope.

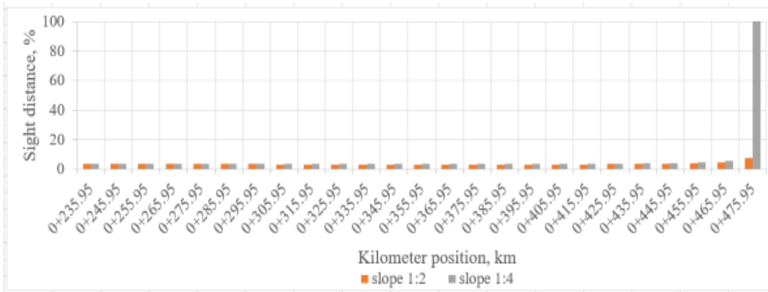


Figure 85. Sight distance according to the shape of the slope on the left side

According to the perspective in Figure 86 of the sight distance for the model with a slope of 1:2 it is observed that inside the visibility triangle the red lines signal that the visibility distance is obstructed by the slope and different forms of the land near the intersection.

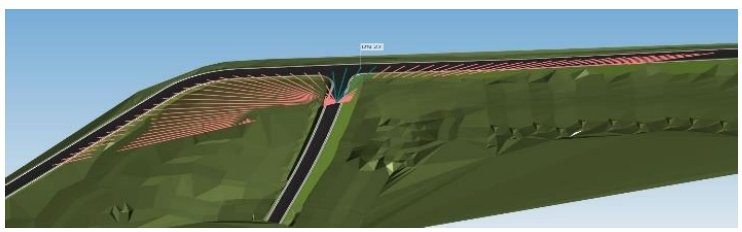


Figure 86. Sight distance perspective for 1:2 slope

In Figure 87, the visibility distance is represented depending on the inclination of the slope on the right side.

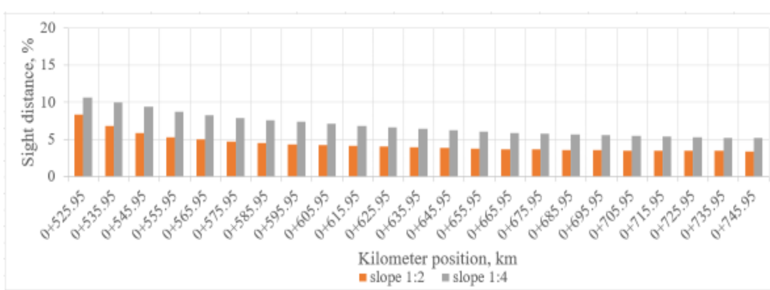


Figure 87. Sight distance according to the shape of the slope on the right side

Figure 88 shows a perspective of the studied intersection, but this time with a slope of 1:4.

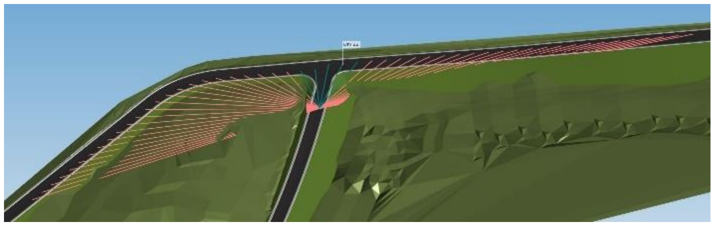


Figure 88. Sight distance perspective for 1:4 slope

Criterion – Maneuver at a speed of 40 km/h

Criterion The 40 km/h maneuver is based on the stopping visibility distance presented by AND 600. The stopping visibility distance for the speed of 40 km/h is 50m.

For this criterion - in the standard, the decision visibility distance disappears, as a result the visibility distance is no longer made up of two components, it is considered as the minimum visibility distance when stopping. Figure 89 show in sight distance depending on the shape of the slope in the intersection.

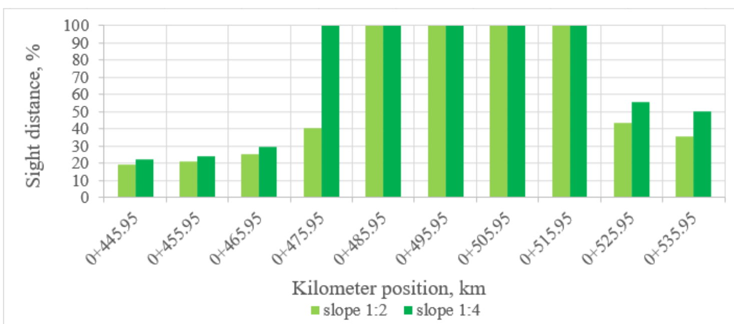


Figure 89. Sight distance depending on the shape of the slope in the intersection

In Figure 90. is present the perspective of the intersection with a slope of 1:2 compared to Figure 90, where the perspective of the intersection with the shape of the slope 1:4 is found.

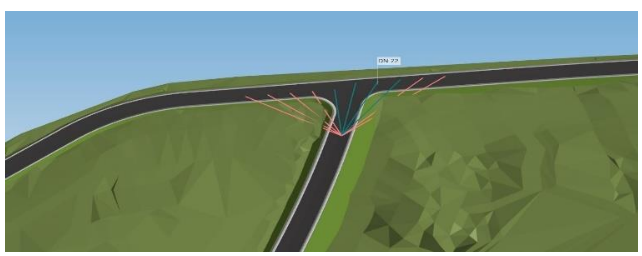


Figure 90. Sight distance perspective for 1:2 slope

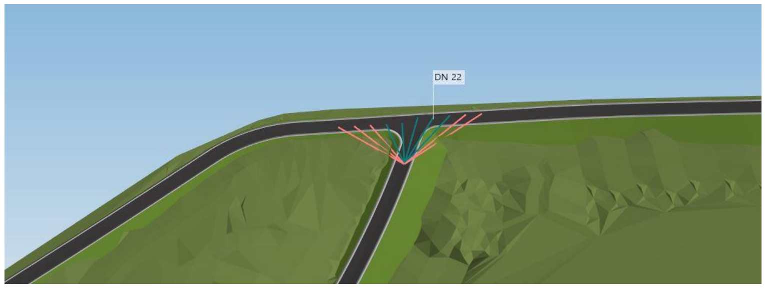


Figure 91. Sight distance perspective for 1:4 slope

Criterion – Maneuver at a speed of 30 km/h

The criterion of the 30 km/h maneuver is based on the stopping visibility distance presented by AND 600. The stopping visibility distance for the speed of 30 km/h is 35m.

In this criterion we specify that the speed of all participants on the main and secondary road is 30 km/h and the minimum stopping distances are the same for all 3 participants considered in this intersection.

In Figure 92, the visibility distance is shown depending on the shape of the slope for both parts in the intersection.

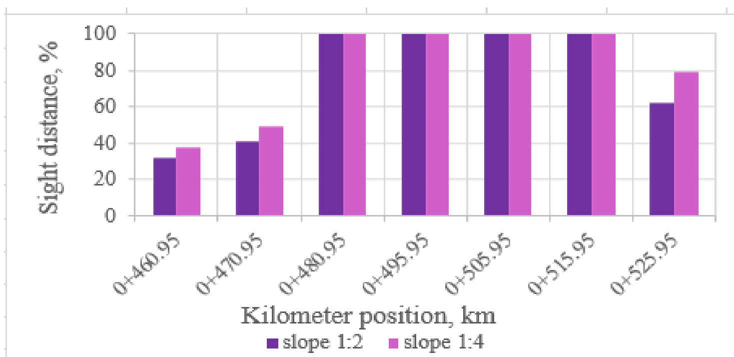


Figure 92. Sight distance depending on the shape of the slope in the intersection

Figure 93 shows the intersection perspective with side slopes of 1:2.

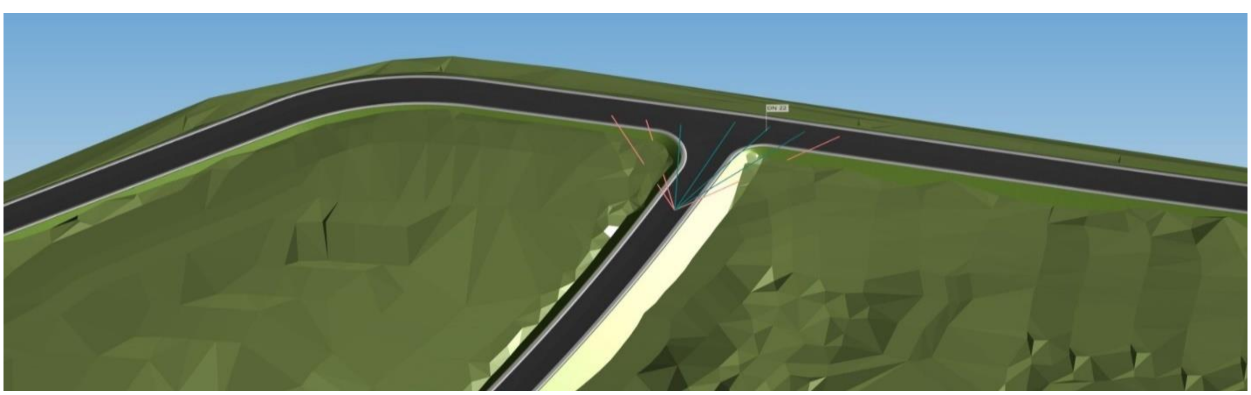


Figure 93. Sight distance perspective for a 1:2 side slope

Figure 94 shows the intersection perspective with side slopes of 1:4.

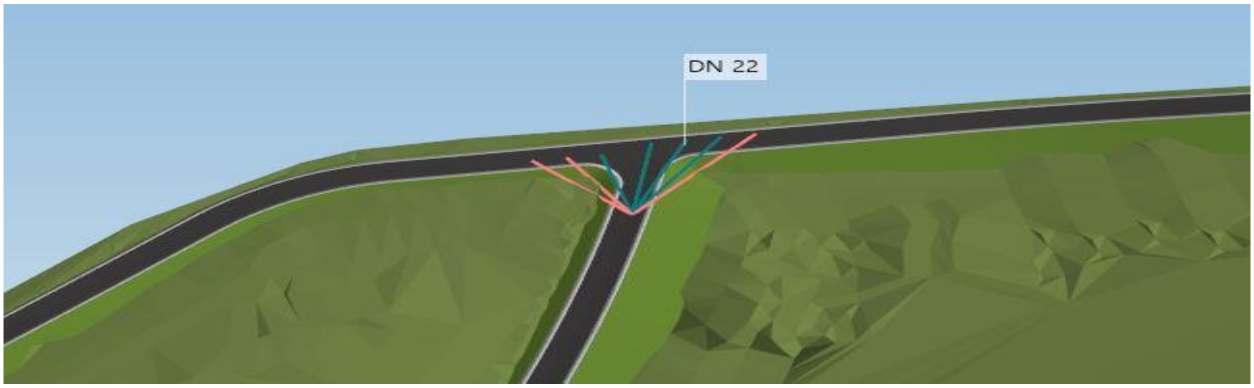


Figure 94. Sight distance perspective for a 1:4 side slope

Figure 95 shows the variation of the visibility distance according to the speed of movement on the main road, for the left side.

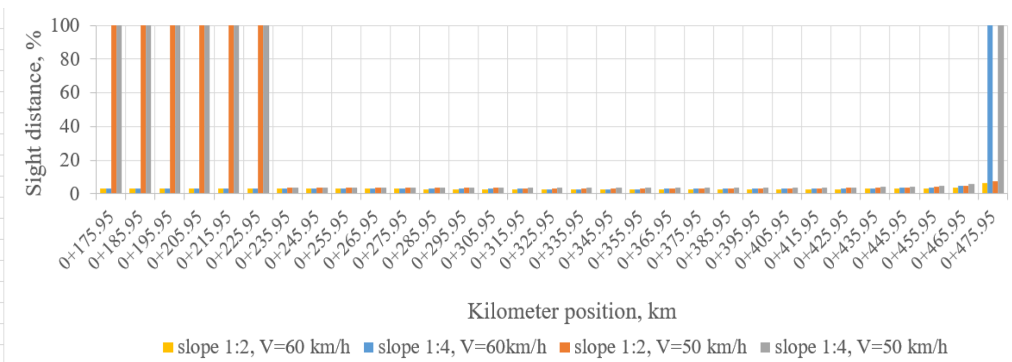


Figure 95. Sight distance as a function of speed on the left side

Figure 96 shows the variation of the visibility distance according to the speed of movement on the main road, for the right side.

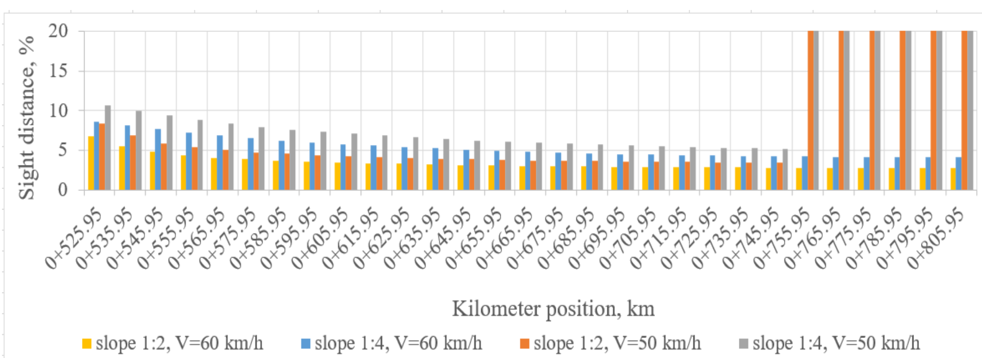


Figure 96. Sight distance as a function of speed on the right side

4. CONCLUSIONS

From the case study carried out for the motorway, it was observed that sight distance is influenced both in the horizontal curve area and in the horizontal alignment (vertical crest curve) by the driver's eye height and the object height. The influence of the radius of the vertical crest curve on sight distance was also observed in the horizontal alignment area.

It can be observed that sight distance increases with speed, but the influence of the driver's eye height decreases as speed increases in the case of horizontal curves.

Regarding sight distance in the case of vertical crest curves, the driver's eye height and speed have a much greater influence than in the case of horizontal curves. Sight distance is the key factor for braking safety when the driver encounters obstacles during the vehicle braking process, an aspect closely related to the safety of life and national assets, which is why studies on the determination of sight distance are of great importance. In the limited number of studies identified in the international literature, it was observed that sight distance is influenced by the factors considered in this study; however, in Romania such studies have not been identified.

For future studies, more variations should be considered regarding: horizontal curve radius values, vertical crest curve radius values, and vertical grade values, in order to improve the conclusions obtained in this study.

From Study II, for roads, it resulted that sight distance is influenced by the driver's eye height and the object height.

The greater the driver's eye height, the greater the sight distance for the same speed and object height.

The greater the object height, the greater the sight distance, regardless of speed and driver's eye height.

According to the plan layout, the buildings located near the roadway edge have a significant influence on sight distance.

The geometric elements of the plan alignment and longitudinal profile, as well as their correlation, have an important influence on sight distance.

Roads must be designed so that road users can perceive, understand, and use them as intended by road administrators and designers, by creating a self-explaining road environment that conveys clear messages.

From Study III, it was observed that visibility at an intersection is an important component of road safety. The necessary checks for these critical points on public roads must become standard practice for designers in order to create the necessary conditions for road users to perform maneuvers in the vicinity of such connections.

From the case study, it can be observed that sight distance at an intersection is influenced by the shape of the side slope and the surrounding terrain.

The Romanian standard does not differentiate between maneuver directions at an intersection; therefore, further studies are necessary to improve traffic safety.

Based on this study, considering the verified sight distance conditions, it is recommended to limit the speed on both the main and secondary roads to 30 km/h and to install the STOP sign (B2) at the edge of the roadway platform.

Sight distance as a function of the left-side slope gradient increases by 9%–42% for a 1:4 slope compared to a 1:2 slope. Sight distance for a 1:4 slope is satisfied starting from chainage 0+365.95, while for a 1:2 slope it is satisfied starting from chainage 0+385.95.

Sight distance on the right side does not vary with slope gradient; however, it varies between 13%–32% of the required sight distance according to AND 600.

Sight distance for a 1:4 slope is satisfied for 59% of the required distance, while for a 1:2 slope it is satisfied for 50% of the required distance according to AND 600.

Sight distance on the right side does not vary with slope gradient.

Sight distance on the left side varies depending on slope gradient and speed. For a speed of 50 km/h, sight distance varies between 7%–14% of the required distance, while for a speed of 60 km/h it varies between 5%–12% of the required distance.

Sight distance on the right side does not vary with slope gradient and speed; however, for a speed of 50 km/h, sight distance varies between 20%–46% of the required distance, and for a speed of 60 km/h it varies between 14%–32% of the required distance.

Sight distance as a function of the left-side slope gradient increases by 2%–15% for a 1:4 slope compared to a 1:2 slope. Sight distance for a 1:4 slope is satisfied starting from chainage 0+475.95, while for a 1:2 slope it is satisfied starting from chainage 0+485.95.

Sight distance as a function of the right-side slope gradient increases by 21%–40% for a 1:4 slope compared to a 1:2 slope. Sight distance for a 1:4 slope is satisfied for 9% of the required distance, while for a 1:2 slope it is satisfied for 6%.

Sight distance as a function of the right-side slope gradient increases by 21%–38% for a 1:4 slope compared to a 1:2 slope. Sight distance for a 1:4 slope is satisfied for 5%–10% of the required distance, while for a 1:2 slope it is satisfied for 3%–8%.

Sight distance as a function of slope gradients increases between 11%–60% on both sides of the intersection for a 1:4 slope compared to a 1:2 slope. At chainage 0+475.95, the sight distance requirement is satisfied for the 1:4 slope.

Sight distance across the entire intersection, depending on slope shape, varies between 13%–21%. On the left side of the intersection, sight distance for a 1:4 slope is approximately 9% higher than for a 1:2 slope. On the right side, sight distance for a 1:4 slope is approximately 16% higher than for a 1:2 slope.

Sight distance on the left side varies depending on speed: for 60 km/h, it varies between 3%–6% of the required distance; for 50 km/h, between 4%–8%; for 40 km/h, between 21%–74%; for 30 km/h, between 47%–100% of the required sight distance according to AND 600.

Sight distance on the right side varies depending on speed: for 60 km/h, between 3%–8%; for 50 km/h, between 4%–9%; for 40 km/h, between 38%–72%; for 30 km/h, between 65%–100% of the required sight distance according to AND 600.

Following the analyses performed, it can be stated with certainty that adopting a slope design with lower gradients in the vicinity of intersections leads to increased sight distance.

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