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Research paper

SPEED AND ROAD GEOMETRY EFFECTS ON ROAD SAFETY: INSIGHTS FROM THE ŠTIP–RADOVIŠ SECTION OF THE A4 IN NORTH MACEDONIA

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Abstract

The development of a country is often reflected in its road infrastructure, but true civilization is measured by how well it prioritizes the health and safety of its people. As roads expand, traffic increases, and speeds rise, ensuring human well-being must remain a key focus. Road design plays a crucial role in safety, with vehicle speed being a decisive factor. While higher speeds can save time and reduce costs, they also heighten risks, leading to accidents and casualties. This paper analyzes vehicle speeds along a specific road section, comparing them to official speed limits. Based on findings, improvements will be suggested, which may involve adjusting speed limits, modifying infrastructure, or enhancing road signage and equipment. Some changes could even impact the road's classification. Ultimately, the aim is to create a safer environment for drivers and pedestrians, minimizing risks while maintaining efficiency in transportation.

Key words: *Road, Speed, Safety, Geometrical Design Elements, Traffic*

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1. INTRODUCTION

Road safety depends on matching speed to road design. Drivers must adjust their speed to suit road geometry, weather, and traffic, while engineers must design roads that guide and support safe travel behavior [1]. Safe speeds on well-designed roads save lives.

Speed doesn't operate in isolation—how fast vehicles can safely travel depends heavily on the design of the road itself. Road safety is significantly influenced by both the velocity of vehicles and the geometric design of the roadway. Understanding this relationship is essential for designing safer transportation systems and encouraging responsible driving behavior. Key elements of road geometry that influence safety include:

- Curvature and Alignment: Sharp horizontal curves at high speeds increase the likelihood of losing vehicle control [2]. Roads must be designed with curves that match safe operating speeds.
- Sight Distance: Roads should provide adequate stopping sight distance—the length of road visible to a driver to safely stop if needed. This distance increases with speed.
- Lane Width and Shoulders: Narrow lanes or shoulders can be dangerous at high speeds, especially for larger vehicles. Wider lanes improve safety on high-speed roads.
- Grade (Slope): Steep downgrades can increase braking distance, especially in wet conditions. Speed limits must consider road slope to prevent runaway vehicles.

A road's design speed is the maximum safe speed that can be maintained under ideal conditions. Safety improves when operating speeds are consistent with this design speed. Sudden changes in road geometry without proper signage or transition can lead to driver error and crashes [3].

The aim of this paper is to compare, in a simple and straightforward way, the permitted vehicle speeds with the speeds that the geometric elements of the road can support. Based on the results of this comparison, appropriate measures will be determined or solutions proposed to improve traffic safety. The defined procedure in the methodology will allow for the assessment of any existing road and its corresponding improvement. Additionally, the methodology will be applicable to roads that are in the design phase, allowing timely implementation of necessary modifications [4].

The objective of this work is to identify the need for and locations where speed should be reduced in order to enhance safety. On the other hand, it will also assess whether there are places where speed could be increased, with the aim of creating longer road sections with consistent speeds [5].

2. METODOLOGY FOR EVALUATING SPEED'S IMPACT ON ROAD SAFETY

To examine the impact of speed on the safety of road users along a specific road, it is necessary to utilize all available theoretical and experimental knowledge. For this purpose, the paper applies a methodology that aligns the geometric elements of the road with the applicable vehicle speeds. This relationship can be illustrated through a design speed diagram [6].

To begin, an existing road alignment is selected as the basis for the study. The start and end points of the alignment are defined. Along the entire length of the road, all traffic signs indicating speed limits are recorded based on actual field conditions. If there is other relevant vertical or horizontal traffic signage, it is also recorded. Using an indicative method, it is assessed whether there are other factors along the route that could influence the results of the analysis [7].

If there are artificial or natural objects, equipment, or obstacles on or near the road, they should be noted by type, location, and size. These may be part of the road infrastructure or independent of it, but what matters is whether or not they impact road safety. All these observations are entered into a special section of the longitudinal profile. Care must be taken to accurately record the direction in which these elements are located, which is especially important for speed limit signs [8].

Once this base layout is prepared, speed diagrams are drawn. Diagrams should be created for both directions of travel, for both the horizontal and vertical projections of the road. These are then superimposed into two summary diagrams—one for each direction. A comparison is made between the summary speed diagram and the actual speed limits on the road [9].

Based on the comparative speed diagram, the following parameters are examined:

- The lengths of the transition curves,
- The radii of the horizontal curves,
- The longitudinal gradients of the road profile,
- The vertical and horizontal traffic signage.

All these parameters define the level of driving safety [10].

If any of the listed parameters do not meet the required standards, improvement measures are proposed for those segments. These measures may include:

- Reconstruction of a horizontal curve to increase its radius,
- Reconstruction to increase the length of transition curves,
- Reconstruction of one or two consecutive vertical curves to reduce the longitudinal slope,
- Addition of a lane for certain types of heavy vehicles if they are slowing down traffic on a segment,
- Installation of traffic-technical signage for speed limitation,
- Application of specific measures for forced speed reduction, etc. [8]

The primary goal of all these measures is to enhance the safety of road users. At the same time, they contribute to greater driving comfort and improved traffic flow. By defining the maximum speeds that the road can safely and comfortably support, the road's potential is assessed, which may also justify an upgrade in its classification [9].

This detailed insight into the relationship between speed and road geometry enables the development of concrete plans, procedures, and projects aimed at enhancing road safety along the examined route [11].

3. ANALYSIS OF THE SELECTED ROAD SECTION

For the purposes of this thesis, the selected section for analysis is the Štip – Radoviš segment of the A4 main road.

The base documentation used for the examination of this road is the original design project upon which the road was constructed. From this project, the cross-sectional profile, horizontal alignment, and vertical alignment were obtained. The consistency between the designed and constructed road was verified by comparing the alignment from the project with satellite imagery on Google Maps. The cross-sectional profile was confirmed through field inspection. Since these elements align with the original design, it is assumed that the constructed vertical profile (grade line) matches the designed one. Consequently, the longitudinal profile from the base project—containing all relevant data—was used to develop the speed diagram [12].

To assess the actual on-site conditions, a continuous video recording was made along the entire length of the road. The video was recorded from a moving passenger vehicle. From the footage, data regarding the placement of speed limit signs was extracted. During the data collection process, continuous comparison and verification were made with the project's alignment plan to avoid errors. No discrepancies between the recorded data and the design documentation were observed.

From both the video recording and a visual field inspection, it was determined that the alignment is completely "clear," meaning there are no additional objects, equipment, or obstructions of any kind that would influence vehicle speed or compromise visibility and road safety. The route includes several bridges, retaining structures, overpasses, and interchanges. All are in good condition and fully functional, without hindering the use of the road.

Along the alignment, there are no tunnels, no railway crossings, no major watercourses or reservoirs, and no parking areas, gas stations, or service facilities of any kind [13].

3.1. Speed Limit Diagram for 110 km/h

In the situational-horizontal design of the expressway, there are 37 horizontal curves. Some of them have transition curves, while others do not. The radii range from 400 m to 5,000 m. Calculations for the lengths of acceleration and deceleration were made using an Excel table. All values for the radii of the horizontal curves, as well as the values for the transition curves, were entered accordingly. The transition curves do not affect the calculations but are included in the same column for practical reasons, facilitating easier comparison with the obtained values for the lengths of acceleration and deceleration.

By inserting the appropriate formulas for calculations, all values for acceleration and deceleration lengths are obtained in a few simple steps. The calculations were based on the maximum allowed speed of 110 km/h, the maximum allowed cross slope i=7%, and the radial friction coefficient f=0.157 [13].

The results from the table show that only one curve does not meet the conditions for movement at a speed of 110 km/h, as shown in Table 1.

The curve's elements allow movement at a speed of 107.39 km/h. This curve is located between station 6+723.72 km and 6+839.80 km. If we examine the speed limit signage, it is evident that before the curve, at station 6+300.00 km, there is a 100 km/h sign—an appropriate measure to ensure safe driving.

Table 1. Calculations for the Speed Diagram, for a Speed of 110 km/h

HORIZONTAL ALIGNMENT – PLAN VIEW							
R и L [m]	Vp' [km/h]	Vp" calculated [km/h]	Vp" selected [km/h]	ΔV [km/h]	Vsr [km/h]	La acceleration [m]	Ld deceleration [m]
400	110	107.39	107	2.61	108.69	43.86	21.93

Similarly, in the opposite direction from Radoviš to Štip, before this curve, at station 7+100.00 km, the speed is limited to 100 km/h by a traffic sign.

The table 1 shows that the curve with a radius of 400 m has transition curves of 50 m, which satisfy the required lengths for acceleration (43.86 m) and deceleration (21.93 m) when entering and exiting the curve, respectively. This indicates that although the radius is relatively small, the curve still has acceptable geometric characteristics from a safety standpoint [14].

The speed diagrams for both directions are shown in the following diagram, in Figure 1.

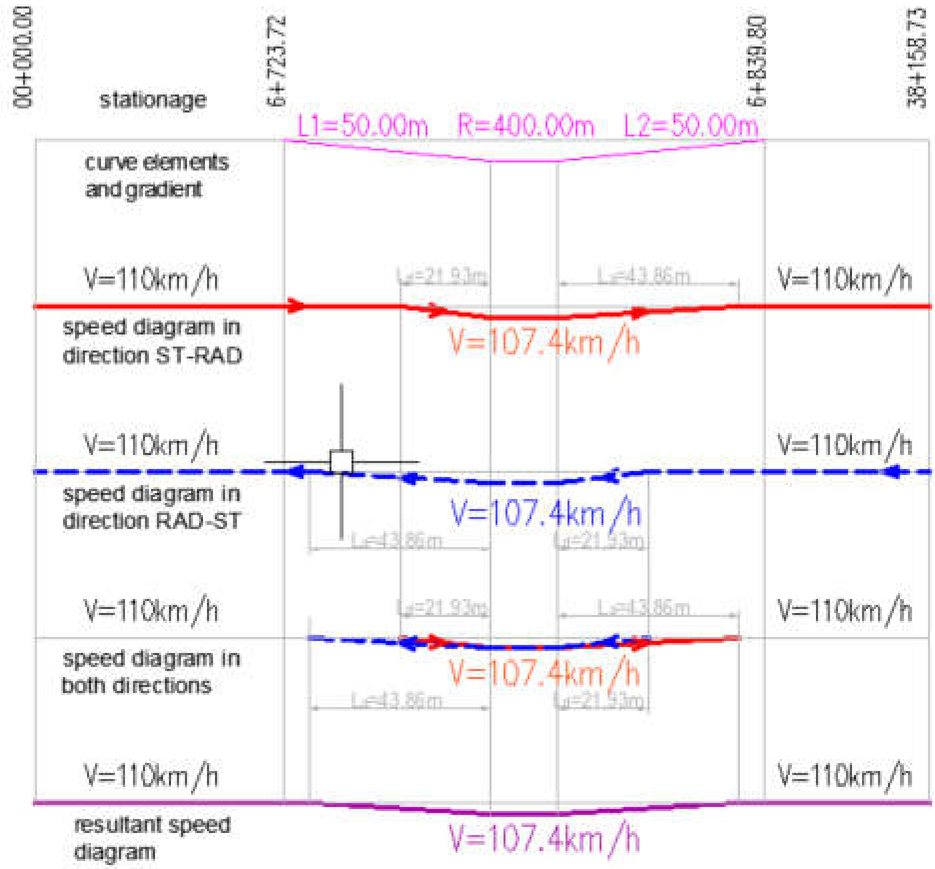

Figure 1. Speed Diagrams for the Curve with the Smallest Radius in Both Directions at V=110 km/h

When constructing the speed diagram dependent on the vertical alignment (grade line), only the longitudinal slopes within the range of i>4% for ascents and i<−5% for descents are considered.

The examined expressway has only one such section. The longitudinal slope has a value of 5.77% from station 33+665 km to 34+035 km, with a total length of 370 meters.

The diagrams for both directions are shown in the following diagram, in Figure 2.

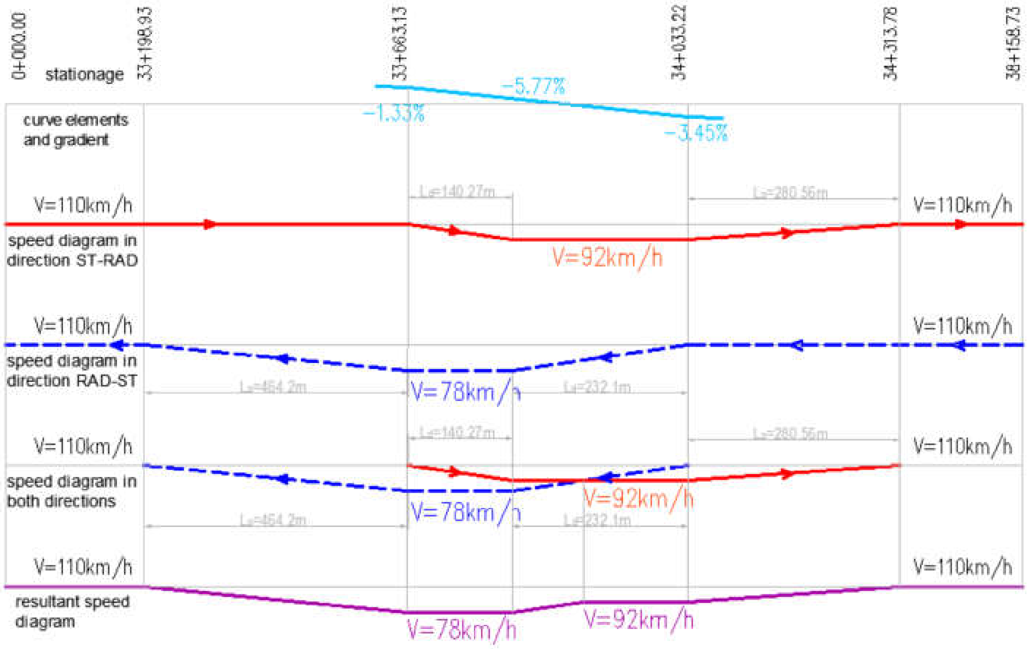

Figure 2. Speed Diagrams in Vertical Projection for Both Directions at V = 110 km/h

Based on the obtained results, speed diagrams were graphically drawn along the entire length of the analyzed route, in both directions of travel. This is presented in the diagram in Figure 3.

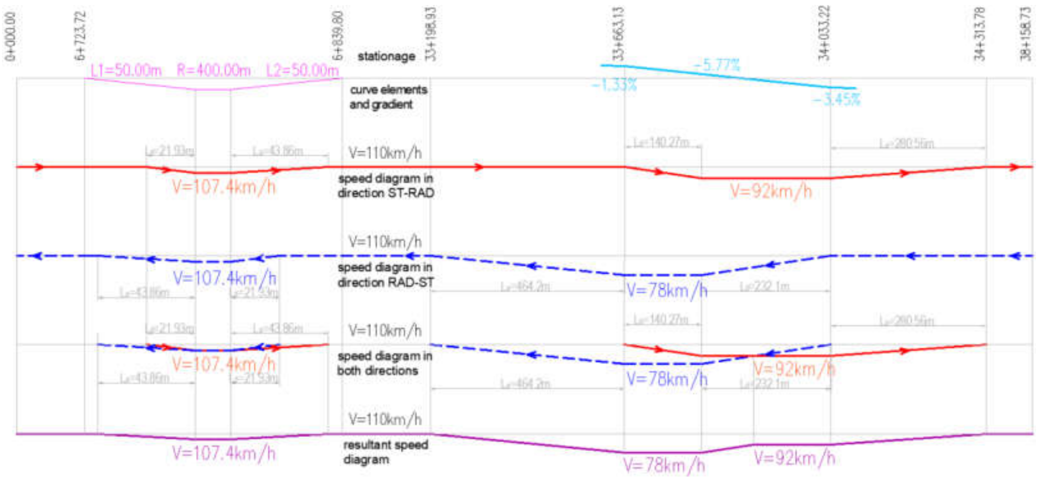

Figure 3. Resultant Speed Diagram for Both Directions at V = 110 km/h

3.2. Speed Limit Diagram for 120 km/h

A calculation was made for a design speed of 120 km/h, using the maximum allowable superelevation of *i* = 7% and the lateral friction coefficient *f* = 0.143. [14]

Table 2. Calculations for the Speed Diagram, for a Speed of 120 km/h

HORIZONTAL ALIGNMENT – PLAN VIEW							
R и L [m]	Vp' [km/h]	Vp'' calculated [km/h]	Vp'' selected [km/h]	ΔV [km/h]	Vsr [km/h]	La acceleration [m]	Ld deceleration [m]
400	120	104.02	104.02	15.98	112.01	276.20	138.10

From the results, it can be observed that the circular curve with the smallest radius of 400 m, although it includes transition curves of 50 m, still does not satisfy the criteria for movement at 120 km/h, as shown in Table 2 [15].

Based on the obtained results, speed diagrams were graphically drawn along the entire length of the examined road section, in both directions of travel. The resultant diagram is presented in Figure 4.

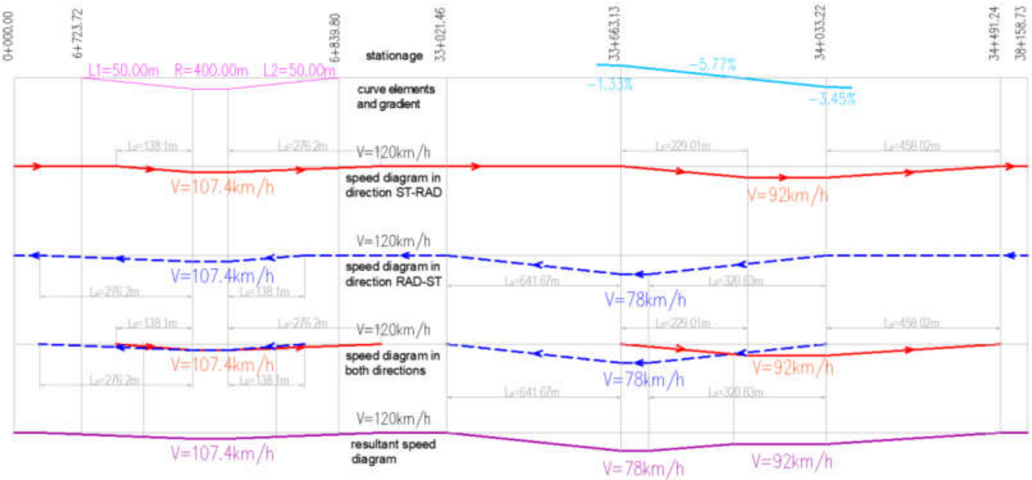

Figure 4. Resultant Speed Diagram for Both Directions at V = 120 km/h

3.3. Speed Limit Diagram for 130 km/h

A calculation was performed for a design speed of 130 km/h, using the maximum allowable superelevation of *i* = 7% and a lateral friction coefficient *f* = 0.143. [15]

All horizontal curves with radii smaller than 600 m were identified as critical points. Through analysis, it was concluded that the radii must be increased to at least 625 m in order to satisfy the conditions for travel at 130 km/h. This is presented in Table 3.

When ensuring design conditions for higher-speed travel, both the number and width of the traffic lanes must be considered. In such cases, a minimum lane width of 3.75 m should be provided, along with at least two traffic lanes in one direction. Given that the total carriageway width is 11.4 m, it can accommodate two traffic lanes of 3.75 m each, along with a slow vehicle lane of 2.5 m. This cross-sectional profile meets the requirements for one direction of a motorway [16].

Table 3. Calculations for the Speed Diagram, for a Speed of 130 km/h

HORIZONTAL ALIGNMENT – PLAN VIEW							
R и L [m]	Vp' [km/h]	Vp'' calculated [km/h]	Vp'' selected [km/h]	ΔV [km/h]	Vsr [km/h]	La acceleration [m]	Ld deceleration [m]
625	130	130.03	130.00	0.00	130.00	0.00	0.00

4. CONCLUSIONS AND RECOMMENDATIONS

By addressing the problem, relevant theoretical principles, mathematical equations, and data from experimental research were identified in the professional literature[17]. Based on these, a methodology for conducting this study was defined. The entire procedure from the methodology was applied to the Štip – Radoviš expressway.

The analysis of the results led to the following conclusions:

- The locations where speed limit signs of 110 km/h are installed genuinely provide safe driving conditions.
- The placement of speed limit signs of 100 km/h at horizontal curves with a radius of R = 400 m is appropriate.
- If the horizontal curve with R = 400 m were reconstructed to achieve a radius of R = 500 m, it would then be possible to maintain a driving speed of 110 km/h on that section as well. This would result in a longer stretch of uniform speed, which is much safer and more favorable for the driver.
- On the road section with a longitudinal slope of 5.77%, speed limit signs of 90 km/h and 70 km/h should be placed in both directions, respectively.
- The locations where speed limit signs of 80 km/h are installed are justified due to the slower movement of vehicles that are merging onto or exiting the road.
- In the areas of the interchanges, the road has geometric characteristics that ensure safe driving at speeds of 120 km/h. If dedicated lanes with sufficient lengths for acceleration and deceleration are provided for vehicles entering and exiting the main road, the speed in the “transit” zone of the interchange could be increased to 120 km/h. This would result in a significantly longer segment with a uniform speed.

Considering that a motorway is planned along the same route, the application of this methodology could be used to assess whether this section meets safety conditions to be used as one direction of the future motorway. The conclusions are as follows:

- The geometric elements satisfy the requirements for driving at a speed of 120 km/h, except for the horizontal curve with R = 400 m and the longitudinal slope of 5.77%.
- By reconstructing all horizontal curves with radii smaller than 625 m, the section could support vehicle movement at a speed of 130 km/h.

Roads are linear structures of considerable length, connected to their surroundings, so any potential "realignment" during reconstruction is a highly complex process. Therefore, when designing a new road, it is essential to conduct a thorough analysis of the topography, geological and geomechanical properties of the terrain, as well as economic indicators and the projected economic development of the regions to be served by the road. This ensures that the most technically sound and economically justified long-term solution is achieved [15].

This paper established that the examined Štip–Radoviš road section, with a length of 37 km, includes only one critical point with a small horizontal radius that necessitates a speed limit of 100 km/h. The remaining horizontal curves on the road allow safe travel at speeds of up to 120 km/h. The longitudinal grade of 5.77% requires a speed reduction on that section: 90 km/h in the Štip–Radoviš direction and 70 km/h in the Radoviš–Štip direction.

Therefore, it is recommended that this procedure be implemented during the road design phase to identify in advance the sections that require reduced speed limits. The design phase is the optimal stage to incorporate the expected operational speed into the selection of geometric road elements.

Furthermore, during the planning and design stages, it is advisable to evaluate the potential for future road reclassification. In addition to assessing current terrain conditions, the investor should consider the projected development of the region and neighboring areas served by the road. Such an analysis can influence the choice of geometric elements in a way that will reduce future financial costs and minimize construction interventions when upgrading or reconstructing the road to a higher classification.

In addition, integrating methodologies for assessing pavement quality and identifying critical black spots, as demonstrated in recent regional and international studies, can further improve the effectiveness of road safety strategies [17].

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