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Impact of Horizontal Curves and Gradient on the Speed of Heavy Vehicles on Two-Lane Rural Mountain Roads: Case of the Loja-Catamayo Road

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Abstract **-** This study analyzes the speed behavior of heavy vehicles on rural mountain roads, specifically on the Loja-Catamayo road in Ecuador. This analysis is crucial for improving road safety as the operating speed of these vehicles is influenced by multiple factors, including road geometric design, topography, and weather conditions. The study focuses on evaluating the impact of curve radii and gradients on the speed of heavy vehicles. Data collection was performed using a high-precision GPS device installed in a follow-up vehicle that accompanied 14 trucks during their journeys on the road. The obtained data were analyzed using statistical methods, including normality tests and one-way ANOVA, considering two main variables: curve radii and gradients. The results show that both curve radii and gradients have a significant impact on the speed of heavy vehicles. Curves with radii less than 50 meters and steep gradients tend to reduce vehicle speed, indicating greater caution by drivers on these road segments. Additionally, it was found that vehicle speeds are higher on the outbound route (Loja-Catamayo) due to the terrain characteristics. The study's conclusions highlight the importance of considering these geometric variables in the design and maintenance of rural roads in mountainous environments to improve road safety. The findings provide valuable information for planning and implementing speed control measures and optimizing road design.

Keywords**:** Safety, Heavy Vehicles, Mountain Roads, Geometric Design.

1. Introduction.

In road studies, speed analysis is one of the most important components when conducting a study to obtain a road safety indicator [1]-[3]. This element, in turn, depends on various interrelated components, such as the environment, road geometric design, driver, vehicle type, and operability [3]-[5]. From the perspective of the environment and design, it is essential to understand the relationship between operating speed and the road's geometric characteristics, i.e., gradients, curve radii, among others [6]-[8]. The joint evaluation of all these components allows understanding and predicting speeds for each element, leading to a design consistency analysis. This minimizes the possibility of road accidents and ensures driver safety [9]-[11].

In Ecuador, a crucial aspect to consider in speed analysis is the relationship between the vehicle type and the environment. This comparison is necessary since the country's road network includes numerous long mountainous sections and highly irregular topography. In these environments, heavy vehicles often operate at relatively high speeds, making it important to understand their speed behavior and variation [12]-[15].

The Andean region, especially Ecuador, lacks studies analyzing heavy vehicle speeds in mountainous environments. This research gap is concerning, considering that in 2021, Ecuador recorded 21,352 traffic accidents with 19,663 victims, resulting in a mortality rate increase of 7.6 per 100,000 inhabitants in Loja [16]. These data reinforce the importance of SDG 3.6, which aims to reduce deaths and injuries from traffic accidents globally [17]. Traffic in mountainous environments presents specific risks due to road conditions, and inadequate speed exacerbates these risks [1]. A thorough analysis of heavy vehicle speeds in these areas can contribute to accident prevention, ultimately reducing the number of deaths and injuries on the roads [15]. Therefore, analyzing the speed of heavy vehicles in mountainous environments is crucial for achieving SDG 3.6 and promoting road safety.

The objective of this study is to determine whether gradient and curve radius significantly impact the speed of heavy vehicles traveling on the E35 road segment between Loja and Catamayo. To this end, an exhaustive literature review was conducted, and field data were collected using GPS devices to record vehicle speed and position. These data were statistically analyzed to identify correlations between vehicle speed and road geometric characteristics. In the study, the collected data were analyzed using statistical techniques, including one-way ANOVA, to evaluate the influence of curve radii and gradients on the speed of heavy vehicles. The results of this analysis provide valuable insights into the behavior of heavy vehicles on mountain roads and can serve as a basis for implementing more effective road safety measures in these environments.

2. Materials and Methods.

2.1 Study Area.

The study was conducted in the Loja canton, Loja province, on the E35 road (Troncal de la Sierra). This road has a flexible pavement with two lanes of 4.5 meters each and a maximum allowed speed of 70 km/h. The road traverses a mountainous area, connecting Loja with Catamayo and including branches that extend through the Ecuadorian mountain range and connect small communities.

2.2 Equipment.

For data collection and analysis, a high-precision GPS model Garmin Montana 750i was used, known for its ability to record location data with an accuracy of up to 10 meters. Microsoft Office software was used to process and analyze the location data, Minitab for statistical data analysis, and Civil3D for the road alignment. Additionally, a 2023 SUV was used to follow and monitor the heavy vehicles during their journeys.

2.3 Road Information Collection.

Vehicle Classification: According to the Ministry of Transport and Public Works, heavy vehicles are those with a gross vehicle weight of 3.5 tons or more. The vehicles selected for the study included cargo trucks, tractor-trailers, dump trucks, and specialized cargo transport.

Identification of Road Characteristics: A road inspection was carried out using a light vehicle (SUV) to detect and note any irregularities that could bias the information obtained, such as potholes, landslides, material detachments, and collapses. The considered factors were:

- Road condition: No potholes, collapses, material detachment, settlements, and pavement deformations.
- Vehicle load: The heavy vehicle must be loaded.
- Presence of speed-reducing elements: No speed bumps, traffic lights, or intersections.

Traffic flow: Free flow with optimal weather conditions.

Vehicle Monitoring: The Montana 750i GPS was installed in the follow-up vehicle, which accompanied 14 trucks during their journeys on the road, precisely recording and analyzing the speed of the trucks along the route. Speed and position data of the cargo vehicles were collected on weekdays to avoid traffic flow variations from weekends.

Route Alignment: Using AutoCAD Civil3D software and the topography of the work area, the route alignment was carried out, highlighting the direction, radius, and gradient of the curves. These data were used for statistical analysis.

2.4 Data Processing.

For data analysis, probability plots were generated using Minitab software to assess if the data fit a normal distribution, assuming the data follow this distribution if the p-value is greater than the significance level ($p > \alpha$). Additionally, one-way ANOVA statistical analysis was used to determine if there were statistically significant differences in the means of different groups, considering curve radius and gradients as factors and speed as the response data with a 95% confidence interval. Subsequently, the influence of gradients and curve radii on the speed of heavy vehicles was inferred.

3. Results.

The results are presented in two parts: first, the journeys conducted in the Loja-Catamayo direction, and second, the journeys in the opposite direction, Catamayo-Loja. For each direction, general descriptive statistics and an analysis of the influence of curve radius and gradient on the speed of cargo vehicles are provided. Additionally, an analysis of variance (ANOVA) is included to determine the statistical significance of these factors. The specific findings for each journey direction are detailed below.

3.1 General Journeys Loja-Catamayo.

Fourteen journeys were conducted from the exit of the city of Loja (3+815) to the entrance of the city of Catamayo (32+640). Figure 1 presents journey number 2 as an example. The graph shows the abscissas, speed, and natural terrain profile.

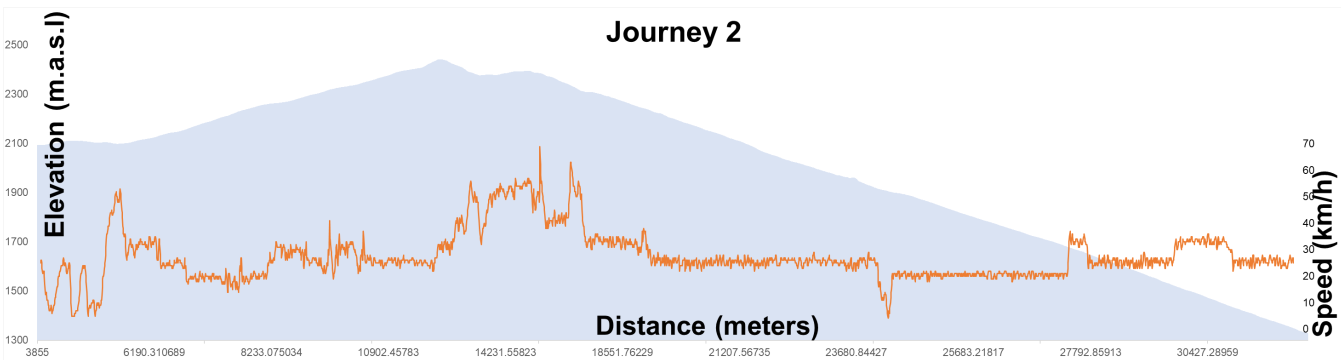

Fig. 1: Journey number 2 conducted, direction Loja - Catamayo

Using Minitab software, the total average of the mean speeds was found to be 39.83 km/h with a standard deviation of 9.15, a minimum average of 26.2 km/h, and a maximum of 56.88 km/h (Table 1).

Table 1: General statistical data, direction Loja – Catamayo

Journey	N	Mean	Standard Deviation	Minimum	Maximum
	14	39.83	9.15	26.20	56.88

3.1.1 Statistical Analysis: Loja-Catamayo.

The analysis focused on the curves of the route with their respective gradients and directions. The most important curves in this research were those with smaller radii, as they result in sharp curves that condition the speed of cargo vehicles.

Considering the direction of the curves (left and right), heavy vehicles traveling through right curves had a mean speed of 24.81 km/h with a standard deviation of 13.45 and a p-value of 0.060, while heavy vehicles traveling through left curves had a mean speed of 24.71 km/h, a standard deviation of 25.74, and a p-value of 0.159. The p-value meets the condition of $p>0.05$, so the data distribution is normal.

Considering the curve radii (42, 45, and 51 meters), heavy vehicles traveling through curves with a 42 m radius had a mean speed of 22.77 km/h, a standard deviation of 1.973, and a p-value of 0.381. Heavy vehicles traveling through curves with a 45 m radius had a mean speed of 24.81 km/h, a standard deviation of 1.345, and a p-value of 0.060. Journeys passing through curves with a 51 m radius had a mean speed of 26.65 km/h, a standard deviation of 1.319, and a p-value of 0.086. The p-value for the analysis of curves with radii of 42, 45, and 51 meters meets the condition of $p>0.05$, so the data distribution is normal.

Considering the gradients of the curves (-0.5 to -5% and -5 to -7%), heavy vehicles traveling through curves with a gradient between -0.5 and -5% had a mean speed of 26.65 km/h, a standard deviation of 1.319, and a p-value of 0.086. Heavy vehicles traveling through curves with a gradient between -5 and -7% had a mean speed of 24.13 km/h, a standard deviation of 1.837, and a p-value of 0.145. The p-value in the gradient analysis of curves meets the condition of p>0.05, so the data distribution is normal.

3.1.2 Variance Analysis (ANOVA) Section: Loja-Catamayo.

The variance analysis focused on the curves of the route with their respective gradients and directions. The most important curves in this research were those with smaller radii, as they result in sharp curves that condition the speed of cargo vehicles. The variance analysis of speed (Table 2) shows that the p-value for radius and gradient is 0.000, which than the condition p>0.05, indicating that the null hypothesis (Ho=All means are equal) is not fulfilled.

Table 2. Variance analysis for curves (radius 40 to 50 m, slopes -7% to -0.5%)

Source	**DF**	**SS**	**MS**	**F-value**	**P-Value**
Radius	2	105.8	52.90	22.96	0,00
Slope	1	66.93	66.93	22.45	0,00
Error	52	55.17	2.526		
Total	55	240.2			

3.2 General Journeys Catamayo-Loja.

Fourteen journeys were conducted from the exit of the Catamayo canton (32+640) to the entrance of the city of Loja (3+815). The respective abscissas and speeds along the natural terrain profile are presented. A certain trend can be observed in all journeys.

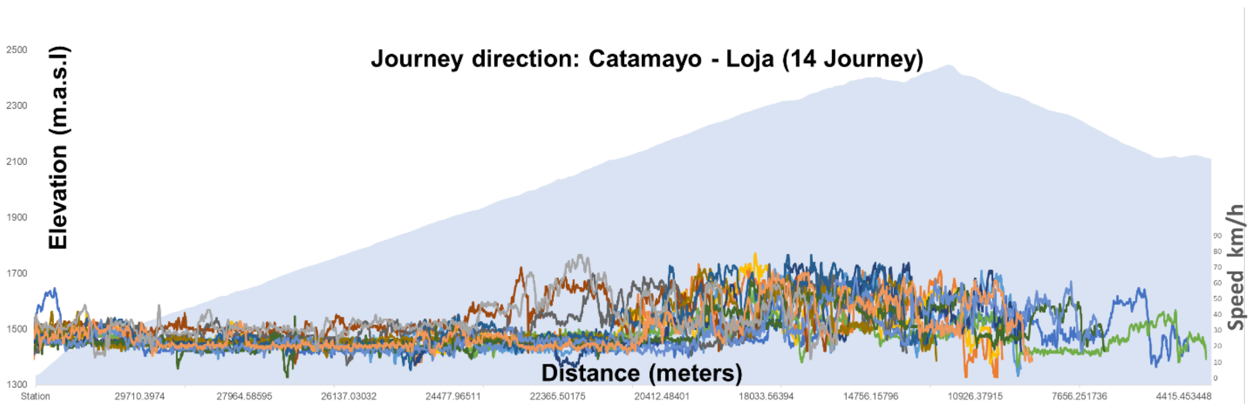

Fig. 2: 14 Journeys conducted, direction Catamayo – Loja.

Using Minitab software, the total average of the mean speeds was found to be 31.45 km/h with a standard deviation of 3.693, a minimum average of 25.96 km/h, and a maximum of 38.05 km/h (Table 3).

Table 3: General statistical data, direction Catamayo

Journey	N	Mean	Standard Deviation	Minimum	Maximum
Media	14	31,45	3,693	25,96	38,05

3.2.1 Statistical Analysis: Catamayo-Loja.

Considering the direction of the curves (left and right), heavy vehicles traveling through right curves had a mean speed of 34.00 km/h with a standard deviation of 8.054 and a p-value of 0.065, while heavy vehicles traveling through left curves had a mean speed of 19.17 km/h, a standard deviation of 4.175, and a p-value of 0.169. The p-value meets the condition of p>0.05, so the data distribution is normal.

Considering the curve radii (42, 45, and 51 meters), heavy vehicles traveling through curves with a 42 m radius had a a mean speed of 25.70 km/h, a standard deviation of 2.639, and a p-value of 0.259. Heavy vehicles traveling through curves curves with a 45 m radius had a mean speed of 19.17 km/h, a standard deviation of 4.175, and a p-value of 0.169. Journeys Journeys passing through curves with a 51 m radius had a mean speed of 41.27 km/h, a standard deviation of 4.785, and a p-value of 0.351. The p-value for the analysis of curves with radii of 42, 45, and 51 meters meets the condition of p>0.05, so the data distribution is normal.

Considering the gradients of the curves (0.5 to 5% and 5 to 7%), heavy vehicles traveling through curves with a gradient between 0.5 and 5% had a mean speed of 41.27 km/h, a standard deviation of 4.785, and a p-value of 0.351. Heavy vehicles traveling through curves with a gradient between 5 and 7% had a mean speed of 21.13 km/h, a standard deviation of 4.819, and a p-value of 0.522. The p-value in the gradient analysis of curves meets the condition of p>0.05, so the data distribution is normal.

3.2.2 Variance Analysis (ANOVA) Section: Catamayo-Loja.

The variance analysis of speed (Table 4) shows that the p-value for radius and gradient is 0.000, which is less than the condition p>0.05, indicating that the null hypothesis (Ho=All means are equal) is not fulfilled.

Table 4. Variance analysis for curves (radius 40 to 50 m, slopes -7% to -0.5%)

Source	DF	SS	MS	F-value	P-Value
Radius	2	4564.6	2282.3	137.76	0.00
Slope	1	4206	4205.9	181.73	0.00
Error	50	55.17	16.57		
Total	53	8828			

4. Discussion.

4.1. Curves with Smaller Radii.

The results of this study confirm that heavy vehicles tend to significantly reduce their speed on curves with smaller radii. This finding is consistent with previous studies that have developed speed prediction models for heavy vehicles on horizontal curves of two-lane rural roads. Specifically, it has been demonstrated that both the curve radius and the gradient at the curve point significantly influence the speed of heavy vehicles. Smaller radii and steeper gradients tend to reduce the speed of these vehicles, with different trends identified for loaded and unloaded trucks [18]. Another study on the speed behavior of heterogeneous traffic found that a curve radius less than 500 meters significantly affects the operating speed of all vehicle classes, including heavy vehicles [19]. Using the 85th percentile speed under free-flow conditions, it was observed that heavy vehicles considerably reduce their speed on small-radius curves to maintain safety and control [19].

Additionally, a study on safety evaluation of horizontal curves on two-lane rural roads using machine learning algorithms established reliability index thresholds associated with sight distance for various operating speed ranges. This study indicated that smaller radius curves require vehicles to reduce their speed to maintain safety [20].

Collectively, these findings support the conclusion that heavy vehicles reduce their speed on smaller radius curves on rural roads to maintain safety and control. In the specific case of the Loja-Catamayo road, it was observed that heavy vehicles had a significantly lower mean speed on curves with radii between 40 and 50 meters. This behavior aligns with trends observed in previous studies, reaffirming the importance of considering larger curve radii and less steep gradients when designing roads.

4.2. Negative Gradients.

Speed control of heavy vehicles on steep descents (negative gradients) is crucial to avoid loss of control and prevent accidents. In our research on the Loja-Catamayo road, a significant reduction in speed was observed on steeper gradients, specifically between -5% and -7%. This finding is consistent with existing literature highlighting the importance of the risks associated with uncontrolled heavy vehicles on steep descents.

For example, case studies of Mount Ousley Road and Bulli Pass, which are roads frequented by heavy vehicles, feature steep vertical gradients and tight horizontal curves. The history of out-of-control accidents on these roads has led to the implementation of various risk management strategies, including the construction of gravel arrester beds. However, the effectiveness of these beds has been questioned, leading to the search for alternative road safety technologies and customized applications focused on road safety outcomes [21].

Truck speeds were negatively affected by gradients greater than 3%, with a more significant effect on loaded trucks compared to unloaded trucks [18]. Our research also corroborates the need for speed control mechanisms to manage the risk of uncontrolled vehicles. Effective speed control can be achieved through various methods, such as the use of speed control cameras and traffic signals. These methods help maintain appropriate speeds, especially on steep descents where the risk of loss of control is higher [22]-[23]. Additionally, in case of loss of control due to brake overheating, designing an emergency escape ramp would be necessary [24].

In summary, controlling the speed of heavy vehicles on steep descents is essential for maintaining road safety on two-lane rural roads. Implementing appropriate speed control measures and addressing geometric challenges can significantly reduce the risk of accidents and improve overall road safety. The results of our research on the Loja-Catamayo road confirm that steeper gradients require a significant reduction in speed by heavy vehicles, underscoring the importance of considering gradient in the design and evaluation of mountain roads.

4.3 Implications of the Findings.

These results have important implications for the design and management of roads in mountainous regions:

Road Design Improvements: Road engineers can use these findings to design safer roads by implementing measures such as widening the curve radii where possible and adding warning signs on steep gradients to alert drivers of the risks and the need to reduce speed.

Road Safety Policies: Relevant authorities can base policies on these results to impose specific speed limits on road sections with tight curves and steep gradients, thereby improving road safety and reducing the number of accidents.

An unexpected finding was the variability in speeds on curves with larger radii (60 to 90 meters). Despite expecting lower variability due to easier maneuvering on wider curves, speeds varied considerably. This could be due to additional factors such as pavement conditions, individual driver behavior, or even specific vehicle characteristics. This phenomenon suggests the need for further investigation into other factors that may influence vehicle speed in these conditions.

4.4 Study Limitations.

This study has some limitations that should be considered:

Limited Sample: Data collection was limited to a specific segment of the Loja-Catamayo road and a limited number of journeys. To generalize the results, it would be necessary to replicate the study on other road segments with similar characteristics and with a larger dataset.

Weather Conditions: Measurements were taken under optimal weather conditions. However, adverse conditions such as rain or fog could significantly affect the speed of heavy vehicles and were not considered in this analysis.

Measurement Technology: The accuracy of the data collected with the Garmin Montana 750i GPS, while adequate for this study, has a margin of error that could have influenced the results.

5. Conclusions

In this research, the effects of curve radius and gradient on the speed of heavy vehicles on the Loja-Catamayo mountain road were analyzed. The results demonstrated that heavy vehicles significantly reduce their speed on curves with smaller radii, especially between 40 and 50 meters. This finding suggests greater caution by drivers when maneuvering through tight curves, aligning with previous studies on the influence of small curve radii on speed reduction to maintain vehicle control.

Additionally, it was observed that steeper gradients (-5% to -7%) result in a significant decrease in speed. This behavior behavior confirms the need to control speed on steep descents to avoid loss of control and prevent accidents, corroborating the existing literature on the additional challenges posed by negative gradients for heavy vehicle drivers.

These findings have important implications for the design and management of roads in mountainous regions. Road engineers can use these results to implement safety measures such as increasing curve radii and installing warning signs on steep gradients. Transport authorities can also develop policies to impose specific speed limits on critical road segments and use speed control mechanisms to maintain appropriate speeds.

Future research could focus on evaluating the impact of different weather conditions on the speed of heavy vehicles in curves and gradients, as well as replicating this study on other mountain road segments to generalize the results. Additionally, it would be valuable to investigate other geometric factors such as superelevation and lane width to obtain a comprehensive view of the elements that influence road safety in mountain roads.

In conclusion, both curve radius and gradient are critical factors affecting the speed of heavy vehicles on mountain roads. Implementing recommendations based on these results can help reduce accidents and improve road safety in these regions.

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