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Comparative Analysis of Specific Speed Estimation Methods: INVIAS and Local Equations in the Ecuadorian Context

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***Abstract* -** In geometric road design, specific speed serves as a complementary approach to design speed, aiming to enhance alignment consistency and road safety. This study evaluates the applicability of the method proposed by the Colombian Institute of Roads (INVIAS) in Ecuador, comparing it against local equations for operating speed prediction. Differences between the two methods were assessed using the mean absolute error (MAE) to identify speed ranges and geometric conditions where discrepancies are most and least significant. The findings indicate that the smallest differences between the INVIAS procedure and Ecuadorian equations occur within design speed ranges of 50–80 km/h, suggesting that the Colombian method can be more confidently applied under these conditions. Additionally, the local equation corresponding to gradients between -3.99% and 0%, with maximum superelevations of 8% and 10%, showed the closest alignment with the INVIAS procedure. As a result of this analysis, specific speed estimation tables were developed based on gradient, expanding the method's utility in local geometric design. This study highlights the importance of validating and adapting international methodologies to local contexts, fostering more consistent and safer road designs.

***Keywords*:** Specific Speed, Geometric Road Design, INVIAS Methodology, Operating Speed Prediction

1. Introduction

In geometric road design, design speed is one of the fundamental parameters that influence most layout elements, such as the minimum radius of horizontal curves, which is defined based on the maximum superelevation and the lateral friction coefficient [1]. However, relying exclusively on design speed can lead to inconsistent configurations, increasing the risk of road crashes. Research indicates a discrepancy between design speed and actual driving speed on horizontal curves [2]. Drivers' speed choices are more strongly related to curve radius [3], lane number [4], lane width [5], pavement condition [6], lateral object density [7], land use [8], weather conditions [9], and many more. To address this issue, some countries have adopted specific speed as a complementary criterion in geometric road design.

In Colombia, the National Roads Institute (INVIAS) [10] proposes a method that assigns specific speeds to horizontal curves based on parameters such as design speed, preceding tangent length, deflection angle, and prior speed, as shown in Table 1. This approach allows the adjustment of minimum radii and other geometric design elements according to expected speeds, improving alignment consistency and providing designers with greater control over future road operation.

Table 1: Specific speed of a horizontal curve (VCH) based on the design speed of the homogeneous section (VTH) and certain geometric characteristics for INVIAS

<table>
<tr><th rowspan="3">VCH of the previous curve (km/h)</th><th colspan="5">VTH ≤ 50 km/h</th><th colspan="5">VTH > 50 km/h</th></tr>
<tr><th rowspan="2">L ≤ 70</th><th colspan="2">70 < L ≤ 250</th><th rowspan="2">250 < L ≤ 400</th><th rowspan="2">L > 400</th><th rowspan="2">L ≤ 150</th><th colspan="2">150 < L ≤ 400</th><th rowspan="2">400 < L ≤ 600</th><th rowspan="2">L > 600</th></tr>
<tr><th>Δ < 45°</th><th>Δ ≥ 45°</th><th>Δ < 45°</th><th>Δ ≥ 45°</th></tr>
<tr><td>VTH</td><td>VTH</td><td>VTH</td><td>VTH</td><td>VTH+10</td><td>VTH+20</td><td>VTH</td><td>VTH</td><td>VTH</td><td>VTH+10</td><td>VTH+20</td></tr>
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</table>

In contrast, in Ecuador, current geometric design standards [11] are outdated, and the country lacks an equivalent procedure to that proposed by INVIAS. Although the "Ecuadorian Road Standard NEVI-12" was introduced in 2013 [12], it has not been officially implemented. Local studies have developed equations to predict operating speeds on horizontal curves

[13] (Table 2), considering variables such as curvature radius and gradients. However, these equations are designed to evaluate design consistency rather than assign specific speeds.

Table 2: Equations for predicting operating speed on horizontal curves.

Gradient (%)	Equation	Radj²	Range of applicable radii (m)
6 to 10%	Vc85 = 74.95 - 794.59/R	0.40	45 to 400
4 to 5.99%	Vc85 = 78.33 - 740.66/R	0.48	50 to 300
0 to 3.99%	Vc85 = 91.42 - 2039.59/R	0.67	80 to 400
-3.99 to 0%	Vc85 = 94.59 - 2366.42/R	0.85	80 to 400
-5.99 to -4%	Vc85 = 86.44 - 1433.64/R	0.78	50 to 300
-10 to -6%	Vc85 = 81.10 - 1304.97/R	0.45	45 to 430
Vc85 = Operating speed on horizontal circular curves (km/h), R = radius of the horizontal circular curve (m), Radj² = adjusted determination coefficient.			

Calibrating tables or equations to estimate specific speeds requires significant resources, as it involves detailed measurements across various geometric configurations. Therefore, a practical alternative for Ecuador could be the adaptation of validated procedures from other countries, such as Colombia, provided these are evaluated and adjusted to the local context.

This study aims to analyse the applicability of the procedure proposed by INVIAS in the Ecuadorian context. For this purpose, specific speeds estimated using the INVIAS table (Table 1) and local operating speed prediction equations (Table 2) were compared, evaluating the differences between both methods through the mean absolute error (MAE). By assessing the MAE, the study was able to identify where the two methods (INVIAS and local equations) showed the most significant discrepancies in terms of speed ranges and geometric conditions, such as curve radius and gradients. This analysis seeks to provide evidence for the adoption or adaptation of methods that improve the safety and consistency of geometric design in Ecuador.

2. Materials and Methods

2.1. Selection of Geometric Configurations

Representative geometric configurations were selected based on the various cases outlined in the INVIAS procedure. These configurations included combinations of tangent lengths, deflection angles, and design speeds, grouped into two categories: for speeds ≤ 50 km/h, tangent lengths of 35 m, 160 m ($\Delta = 22.5°$), 160 m ($\Delta = 45°$), 325 m, and 401 m were considered; for speeds > 50 km/h, tangent lengths of 75 m, 275 m ($\Delta = 22.5°$), 275 m ($\Delta = 45°$), 500 m, and 601 m were used. These configurations ensured that the equations accounted for all the cases within the INVIAS procedure, with the assumption that the preceding speed was equal to the design speed for all cases.

2.2. Calculation of Minimum Radii for Ecuadorian Equations

Since the Ecuadorian equations require a radius as input, a parameter not included in the Colombian standard, minimum radii were calculated based on the design speed for maximum superelevations of 6%, 8%, 10%, and 12%, following AASHTO recommendations [1]. Speed ranges were then established between 40 km/h and 100 km/h, excluding speeds outside this range as they do not fall within the applicable radius ranges for the Ecuadorian equations.

2.3. Estimation of Differences of both Procedures

Using the calculated radii and selected design speeds, the specific speeds obtained via the INVIAS procedure were compared with those generated by the Ecuadorian equations. The differences were estimated using the Mean Absolute Error (MAE). Errors were analysed for the four superelevation values (6%, 8%, 10%, and 12%).

2.4. Proposed Correction Values for Ecuador

Finally, the adjustment process aimed to reconcile differences between the INVIAS methodology and the Ecuadorian equations. By iteratively refining calculated speeds and incorporating correction factors based on gradient and observed discrepancies, a unified table was developed. This table complements the application of the INVIAS procedure under Ecuadorian conditions, ensuring that design speeds align with local road performance characteristics.

3. Results

3.1. MSE Analysis

The mean squared error (MSE) results are shown in Fig. 1. Overall, Ecuadorian and INVIAS equations display consistent patterns across different maximum superelevation values. It is important to note that the equations produce results not rounded to multiples of 10. If rounding were applied, MSE values might change, affecting direct comparisons.

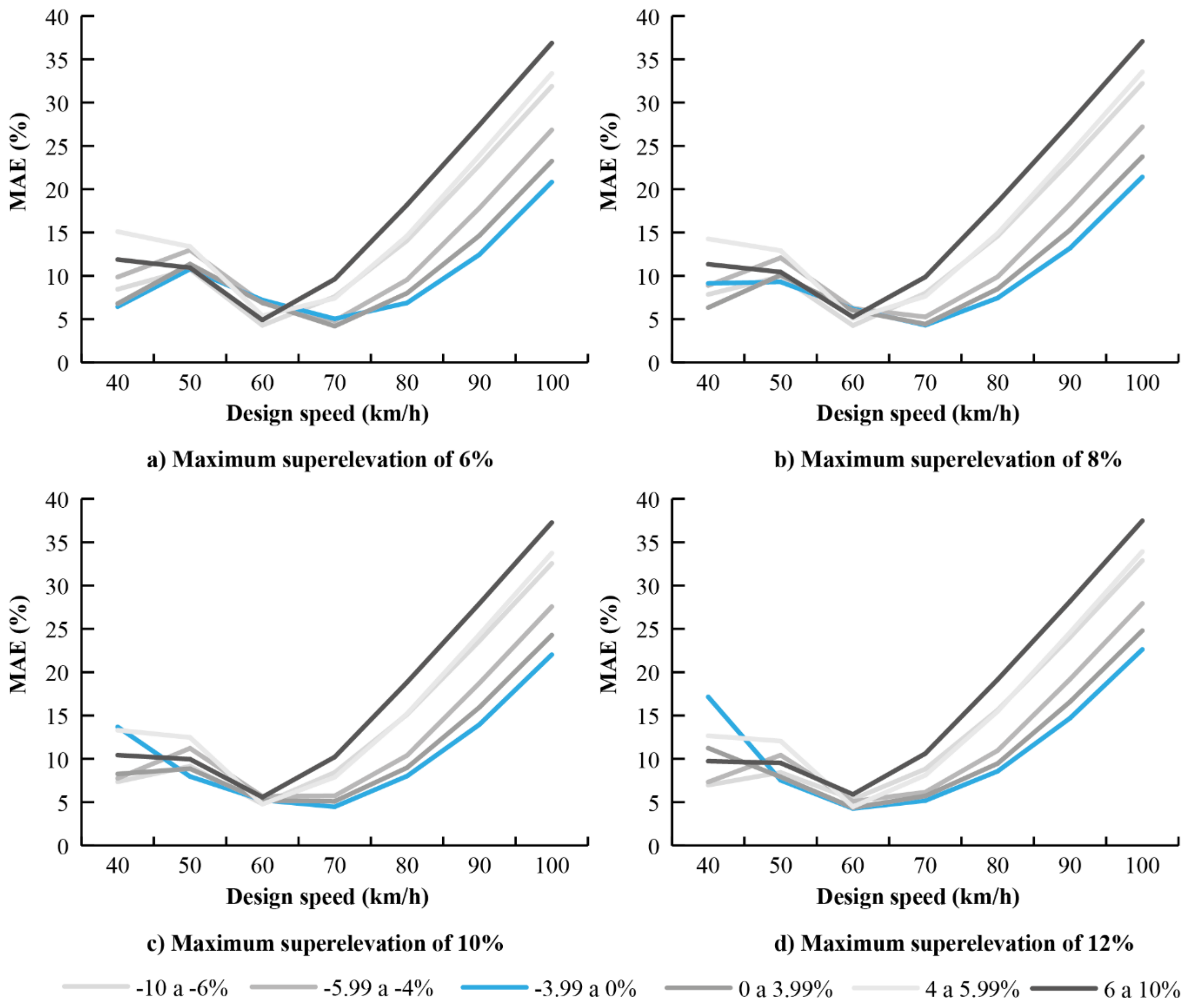

Fig. 1: Mean Squared Error (MSE) Analysis of Ecuadorian and INVIAS Equations Across Speed Ranges and Maximum Superelevation Values.

Relative errors in Fig. 1 are observed to remain around 10% for speeds between 40 km/h and 80 km/h. However, at speeds above 80 km/h, MSE increases significantly, indicating reduced precision of the equations in these ranges. Lower

MSE values are concentrated in specific speed ranges between 50 km/h and 80 km/h, regardless of the maximum superelevation considered. This suggests that within this speed range, both procedures could be effectively used to calculate the specific speed in Ecuador.

Additionally, the results indicate that the INVIAS equations seem to have been calibrated for relatively flat terrains, with gradients between -3.99% and +0%. This is reflected in the higher number of low MSE values observed for these equations across different speeds and maximum superelevations. Fig. 1 support this observation, showing a consistent trend toward lower errors on gentle gradients. The comparison reveals that INVIAS equations perform acceptably in flat terrains and moderate speeds, while Ecuadorian equations may be better suited for broader geometric and speed conditions.

3.2. Proposed Corrections for Ecuador

It was identified that the lowest MSE values are concentrated in specific speeds between 50-80 km/h, regardless of the maximum superelevation considered. However, significant differences between the analysed methodologies persist. Consequently, an adjustment to the INVIAS procedure was proposed, adapting it to Ecuadorian equations. Table 3 presents calculated speeds for maximum superelevations of 8% and 10%, including a proposed grouping based on gradients, design speeds, and respective values rounded to 10 km/h.

In this table, the closer the calculated speeds are to the design speed, the lower the error associated with the INVIAS procedure. For instance, at 8% superelevation and a design speed of 40 km/h, the values obtained for gradients between 0 and 3.99% (42 km/h) and -3.99 to 0% (37 km/h) are very close to the design speed. This suggests that the INVIAS method produces values consistent with Ecuadorian conditions. Conversely, for positive gradient between 4 and 10%, the calculated speeds (56 km/h and 60 km/h) exceed observed values in Ecuador, indicating overestimation. In contrast, for negative gradients between -5.99 and -4% and -10 and -6%, calculated speeds (51 km/h and 49 km/h) are lower, though the differences are not as significant as for positive gradients.

Table 3: Specific Speed calculated by the Ecuadorian Equations and Proposed Gradient and Speed Range for Ecuador.

Speed (km/h)	**Ecuadorian equations**						**Proposed gradient range**			**Rounded proposed gradient range**		
	6 to 10%	4 to 5.99%	0 to 3.99%	-3.99 to 0%	-5.99 to -4%	-10 to -6%	4 to 10%	3.99 to -3.99%	-3.99% to 10%	4 to 10%	3.99 to -3.99%	-3.99% to 10%
Maximum superelevation 8%												
40	56	60	42	37	51	49	58	39	50	60	40	50
50	64	68	63	62	67	63	66	63	65	70	60	60
60	68	72	73	74	74	70	71	77	74	70	80	70
70	70	74	79	81	78	73						
80	71	75	83	84	80	75	74	86	79	70	90	80
90	72	76	85	87	82	77						
100	73	76	86	89	83	78						
Maximum superelevation 10%												
40	54	59	38	32	49	47	56	35	48	60	40	50
50	63	67	61	60	65	62	65	61	64	70	60	60
60	67	71	72	72	73	69	70	75	73	70	80	70
70	70	74	78	79	77	73						
80	71	75	82	83	80	75	74	85	79	70	90	80
90	72	76	84	86	81	76						
100	73	76	86	88	82	77						

3.3. Proposed Correction Values for the Ecuadorian Context

In Table 3, it can be seen that for both superelevations, the results of the recommended values are identical. Therefore, it is not practical to create a new table for each speed range; instead, it is more efficient to add correction value to the existing table. For example, for a speed of 40 km/h on a gradient between -3.99% and 3.99%, the table is used as is. If the gradient is between 4% and 10%, 20 km/h should be added to the result, while for gradients between -4% and -10%, 10 km/h should be added to the calculated value. The proposed correction factors are presented in Table 4.

Table 4: Correction Values for the INVIAS Table for Specific Speeds (VCH) Adopted in the Ecuadorian Context.

VCH range (km/h)	**Gradient range (%)**		
	4 to 10	3.99 to -3.99	-4 to -10
40	+20	0	+10
50	+10	+10	+20
60-70	+10	+20	+10
80-100	-10	+10	0

4. Discussion

The results show reasonable agreement between the specific speeds estimated using the INVIAS method and the local equations within the design speed range of 50 to 80 km/h. This interval aligns with typical operating conditions for secondary and tertiary roads in Ecuador. However, outside this range, particularly at speeds above 80 km/h, discrepancies increase significantly, as indicated by the elevated mean squared error (MSE) values. This behaviour may be attributed to differences in the calibration conditions of the models, as the Ecuadorian equations incorporate adjustment factors specific to several curves and gradients, whereas the INVIAS method appears optimized for flatter terrain. Additional contributing factors include high variance in vehicle pace and skewness, especially in congested traffic [14]. Driver perception also plays a role, with studies showing that drivers tend to underestimate their speed when the speedometer is obscured, particularly at higher speeds [15].

The analysis shows that the smallest discrepancies between the two methods occur for gradients ranging from -3.99% to 0%, highlighting the INVIAS method's effectiveness for flat or gently sloping terrain. This alignment is supported by the high correlation coefficient of the Ecuadorian equation compared to other calibrated equations. In contrast, for positive gradients exceeding 4%, larger differences in calculated speeds emerge, suggesting that the local equations are better suited to addressing the challenges posed by the steeper gradients typical in Ecuador. Previous studies indicate that for horizontal curves, the radius and grade at the point of curvature significantly influence heavy vehicle speeds, with grades over 3% having a more pronounced impact on loaded trucks [16]. On tangent segments, the length and local grade are key predictors of operating speed [17]. Comprehensive speed profile models incorporate weighted values of horizontal curvature and vertical grade from preceding and following road segments, reflecting driver expectations and perceptions [18]. Region-specific models, such as those developed for Costa Rican rural roads in flat terrain, have demonstrated lower estimation errors compared to international models [19]. These findings underscore the importance of adapting the INVIAS model to scenarios where topography imposes greater geometric demands.

At speeds exceeding 80 km/h, the INVIAS method shows reduced accuracy compared to local equations, suggesting it was not designed for high-speed road conditions. This limitation likely stems from its original calibration, which appears to focus on geometries with lower technical requirements. Consequently, its application in Ecuador is restricted, particularly for major roads or those connecting regions with complex topography. Calibrating speed models for high-speed roads requires diverse approaches and considerations. A general framework has been proposed for calibrating car-following models using loop detector data on open motorway sections, formulating it as an optimization problem [20]. Another methodology uses GPS devices for continuous speed data collection, enabling more accurate operating speed models and deceleration analyses on two-lane rural roads [21]. State-space models have been applied for online calibration of speed-density relationships, achieving improved speed estimation and prediction through advanced techniques such as the extended Kalman filter (EKF) and unscented Kalman filter (UKF) [22]. Additionally, optimal traffic stream models have been identified for high-speed urban roads with heterogeneous traffic in India [23].

The inclusion of correction values based on gradients and speed ranges, as presented in Table 4, represents a significant step toward integrating the INVIAS method into the Ecuadorian context. These tables reduce the identified discrepancies and adjust the specific speeds to local conditions, providing a tool more aligned with the needs of road designers in Ecuador.

This adjustment not only improves estimation accuracy but also facilitates a transition to a standardized and adaptable methodology. Previous studies, research on road speed models incorporating gradient and speed variables has advanced significantly. Studies have developed operating speed prediction models for two-lane rural roads, considering both horizontal and vertical alignment elements [24]. These models account for factors such as grade, slope length, and curvature, with some incorporating weighted values of geometric features preceding and following the vehicle position [18]. These advancements in speed modelling contribute to improved road design consistency and safety by better aligning road geometry with drivers' expectations [21].

This study has several limitations. First, the analysis relies on a limited dataset of geometric and topographic conditions specific to certain regions of Ecuador, which may not fully capture the variability present across the country. Second, the calibration of the local equations was performed using a constrained range of design speeds, potentially limiting their applicability to higher-speed roads or those with atypical geometries. Third, the INVIAS method was evaluated without considering possible updates or adjustments that could improve its adaptability to Ecuadorian conditions. Finally, the study focuses on secondary and tertiary roads, and its findings may not be directly transferable to urban or primary highway networks, where operational and environmental conditions differ significantly. These limitations highlight the need for further research to validate and expand the scope of the proposed adjustments to enhance their generalizability and robustness. Despite these limitations, the results demonstrate that while the INVIAS method can be applied with certain adaptations in Ecuador, its effective use depends on careful adjustments to reflect the country's unique geometric, topographic, and operational characteristics. This analysis underscores the importance of validating international methodologies before their adoption, ensuring more consistent and safer road designs.

5. Conclusion

This study demonstrated that, although the INVIAS procedure provides a solid foundation for calculating specific speeds, its direct application in Ecuador presents limitations due to the local road characteristics. The proposed adjustments, through the introduction of correction values, allow the method to be adapted to Ecuadorian conditions, significantly reducing error margins and improving the accuracy of operational speed predictions. These adjustments are not only consistent with the principles of operational consistency but also promote safer road design that meets the real needs of users. Additionally, the proposed approach offers a practical and easily implementable solution, avoiding the need to develop specific tables for each combination of parameters. In conclusion, this study contributes to the geometric design of roads in Ecuador by adapting an international procedure to local conditions, strengthening the safety and functionality of the roads. Future work could expand this approach by considering other relevant variables, such as the dynamic behaviour of vehicles and weather conditions, to further refine operational speed predictions.

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