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Validation of Mobile Applications as Cost-Effective Tools for Operating Speed Measurement on Mountainous Roads: Evidence from Ecuador

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Abstract - This study analyzes the accuracy of mobile applications for measuring vehicle operating speeds on mountain roads compared to professional VBOX equipment. Testing conducted on the 32 kilometer stretch on a rural road section in mountainous environments south of Ecuador, revealed high consistency between both measurement methods, with 91.22% of iOS measurements and 98.6% of Android measurements showing errors of less than 2 km/h. The maximum average difference between all methods was only 0.11 km/h. Although higher altitude sections showed slightly increased error rates, most discrepancies remained within the 0-1 km/h range. The research developed correction equations to further improve measurement accuracy. Results confirm that these mobile applications provide reliable, accessible, and cost-effective alternatives to expensive traditional equipment, making them valuable tools for road safety studies in resource-limited environments, particularly in rural mountainous regions where accurate speed measurement is crucial for identifying hazards and implementing effective safety measures.

***Keywords*: ** Mobile applications, operating speeds, road safety, mountain roads.

1. Introduction

Traffic accidents are a pressing global issue. According to the World Health Organization, approximately 1.19 million people died in road accidents in 2021 across all United Nations Member States, with 67% of these deaths occurring in developing countries [1]. In Latin America, the World Bank reported that 107,000 people lost their lives in traffic accidents in 2016, with 77% belonging to the economically active population [2]. Ecuador ranks seventh in the traffic accident fatality rate and thirteenth worldwide [3]. According to the National Institute of Statistics and Censuses (INEC) traffic accident report for the first quarter of 2024, the province of Loja ranks tenth nationwide in the number of injured persons (107 cases) and has 80 fatalities, representing 6% of the national total [4].

Speed directly influences the severity and cause of traffic accidents, being affected by factors such as road infrastructure and geometry [5]. Measuring speed allows the implementation of efficient safety measures in the construction, rehabilitation, expansion, or any modification of roadways, prioritizing accident severity reduction [6]. This highlights the direct influence of speed on traffic accidents. Evaluating operating speeds on rural roads with mountainous environments is crucial to ensuring road safety. The characteristics of these roads, such as steep slopes and sharp curves, require precise speed adjustments, as speed variations in these sections can be significant. Accurate measurement enables a more precise analysis of design consistency and the implementation of preventive measures in such environments [7].

Traditional methods for measuring operating speed, such as inductive loops, laser devices, specialized equipment (VBOX), and speed radars, are highly accurate but also costly [8]. This makes them impractical in resource-limited contexts. Therefore, obtaining accurate and accessible data is essential for designing and implementing effective road safety measures. In this context, mobile applications with GPS technology provide ease of use, low cost, and wide availability [9]. However, their accuracy has not been evaluated in complex areas such as rural roads in mountainous regions.

The main objective of this research is to compare available mobile applications for measuring operating speed on two-lane rural roads. Additionally, three specific objectives were established: (1) selecting relevant mobile applications for validation, (2) evaluating their accuracy compared to traditional methods, and (3) proposing accessible solutions. This study aligns with Sustainable Development Goal (SDG) 3.6, which focuses on reducing deaths caused by road accidents [10].

This study aims to conduct a comparative evaluation of operating speed measurements using a reliable device, with the goal of applying these findings to similar road environments. The methodology focused on comparison analysis to evaluate the precision and reliability of the applications and included application selection, field data collection, and simultaneous measurements with the VBOX device. This research establishes a foundation for implementing accessible tools on rural roads in mountainous environments, benefiting rural populations and promoting road safety.

2. Materials and Methods

2.1. Study Area

The Loja-Catamayo Road, located in Loja Province, southern Ecuador, is a major mountain road connecting the cantons of Loja and Catamayo. It extends from UTM coordinates 17S (9559633.50; 695175.90) to (9559568.30; 683806.00). The road design is influenced by the irregular topography, featuring longitudinal slopes ranging from -10% to 10% and horizontal curves with a radius between 45 and 430 meters [11]. With an approximate length of 32 kilometers, this road has well-maintained pavement and includes two lanes, one in each direction, ensuring efficient vehicle flow along this mountainous route [11]. The location map was generated using a DEM from the ALOS PASAR satellite [12] and adjusted with Google Maps satellite images [13] in AutoCAD Civil 3D [14]. (Fig. 1)

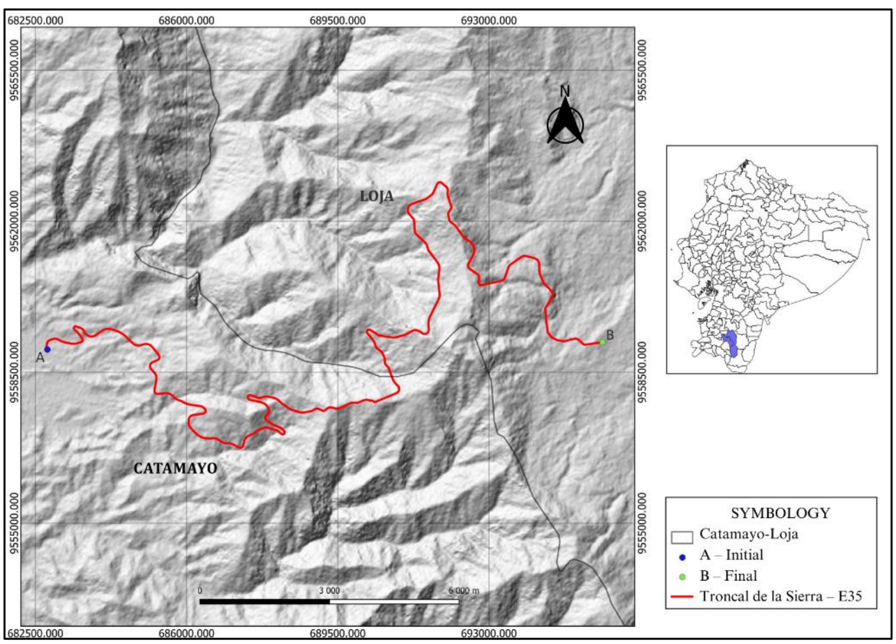

Fig. 1: Study Road Catamayo-Loja.

The study section, being located between two cantons, is influenced by both climates. On one hand, according to the Municipality of Catamayo, it has a hot dry and subtropical humid climate, with an average temperature ranging from 24°C to 26°C [15]. On the other hand, the canton of Loja presents a temperate-equatorial subhumid climate, with an average temperature between 18°C and 20°C [16]. Regarding the socioeconomic context, the road connects two populations with distinct characteristics. Loja, with approximately 214,000 inhabitants, and Catamayo, with around 30,000 inhabitants [17]. The road infrastructure is essential for the transportation of people and goods, making it a vital component for the local economy.

2.2. Data and Materials
2.2.1. VBOX Video Equipment - LITE

Video VBOX Lite equipment (Fig. 2) was used, a device that has been employed in many other studies. It is a real-time data and video recording device used to measure speeds and coordinates on specific routes. This equipment combines a video recorder with a 10 Hz GPS data logger, allowing for the capture and recording of detailed information about driving and vehicle behavior with a speed accuracy of ±0.2 km/h. The equipment includes two cameras, a microphone, GPS, and an SD memory card to store the data [18].

2.2.2. Devices and Applications

For field data collection, two smartphones were used that meet the necessary requirements to record GPS coordinates with high precision. It is essential that the devices are compatible with multiple GNSS systems, as well as with an accelerometer and gyroscope, to improve location accuracy [19]. The devices used were the iPhone 13 Pro Max for iOS, which incorporates positioning systems such as integrated GPS, GLONASS, Galileo, QZSS, and BeiDou, enabling it to offer high precision in geolocation [20]. On the other hand, the Realme 8 Pro (Android) is equipped with A-GPS, Beidou, GLONASS, and NavIC, which also provides adequate precision for geospatial data collection [21].

The selection of applications was based on their ability to meet the necessary characteristics for accurate and efficient data collection in the context of the study. For iOS, the application Speed Tracker: GPS Speedometer, developed by Oxagile LLC [22], was used. This application was chosen due to its low cost, user-friendly interface, and the ability to present results in various intuitive formats for analysis, including coordinates, speeds, and elevations, according to the study's requirements. For Android, the application Speedometer GPS, developed by Luozirui [23], was used. This free application offers an intuitive interface and provides results in .CSV format, facilitating subsequent analysis.

2.3. Methodology
2.3.1. Sample size

Determining the sample size ensures that the data set provides reliable results, for which a formula was used to estimate any velocity percentile according to Pignataro (1973) [24]. In this regard, it is necessary to know the standard deviation of the speeds, considering that the data is uncertain until data collection is completed. A standard deviation of 13 km/h and an error of 5 km/h were assumed [25].

$$n=\frac{K^2 * \sigma^2 * (2+U^2)}{2 * el^2} \qquad (1)$$

n: Sample size
K: Confidence level constant
σ: Standard deviation
U: Normal deviation based on the desired velocity percentile
el: Precision

Considering a confidence level of 95%, a K coefficient of 1.96 was used, and a U value of 1.04, corresponding to the 85th percentile, which represents safe and comfortable speeds. In this sense, it was determined that 40 samples would be sufficient; however, it was deemed reasonable to work with 45 data points to account for any potential errors in the data.

2.3.2. Vehicle and driver selection

The proper selection of drivers and vehicles that participated in the data collection is crucial, as it ensures the validity and representativeness of each result obtained. Therefore, the drivers were selected through non-probabilistic sampling, considering factors such as: having a driver's license, being familiar with the Catamayo-Loja route, and not being novice drivers. Similarly, the selected vehicles are lightweight, and their brand, manufacturing year, and type of lightweight vehicle were recorded, ensuring that the vehicle's condition is in good working order to guarantee that the operating speed is accurate and real.

3. Results

3.1. iOS Results

In Figure 3, the operating speed of the Catamayo-Loja section as measured by the application and the VBOX video equipment is shown to be quite aligned, indicating that both measurements are very similar. In general terms and visually, this suggests that the application can provide results similar to those of the reference equipment.

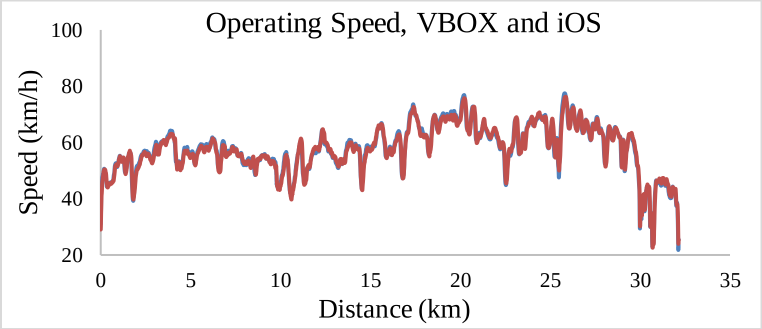

Fig. 2: Operating speeds.

In Figure 4, the distribution of absolute errors is shown, indicating that most of the errors fall within the 0 to 2 km/h range, representing 91.22% of the total measurements. As the errors increase, their frequency decreases significantly, suggesting that larger discrepancies between measurements are less common. The maximum absolute error was 8.47 km/h, though this was an isolated case. The concentration of errors in the smaller ranges (0-2 km/h) indicates that, in most measurements, the differences between data are minimal. Additionally, the low frequency of errors greater than 6 units demonstrates that significant deviations are rare and do not affect overall performance.

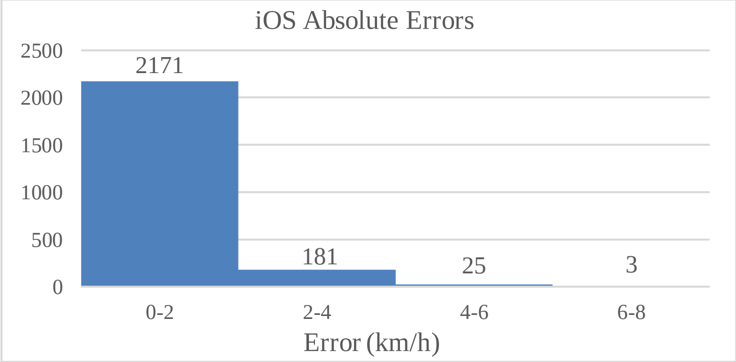

Fig. 3: Absolute Errors.

3.2. Android Results

Figure 5 shows the operating speeds recorded by the Android application and the V-BOX equipment on the Catamayo-Loja section, revealing very similar patterns between both methods. The overlapping measurements allow for a direct visual comparison, where no significant deviations are observed along the distance, indicating that the discrepancies are minimal. Although there are slight variations in some sections, they do not follow a systematic trend, reinforcing the reliability of the application for measuring speeds in mountainous environments.

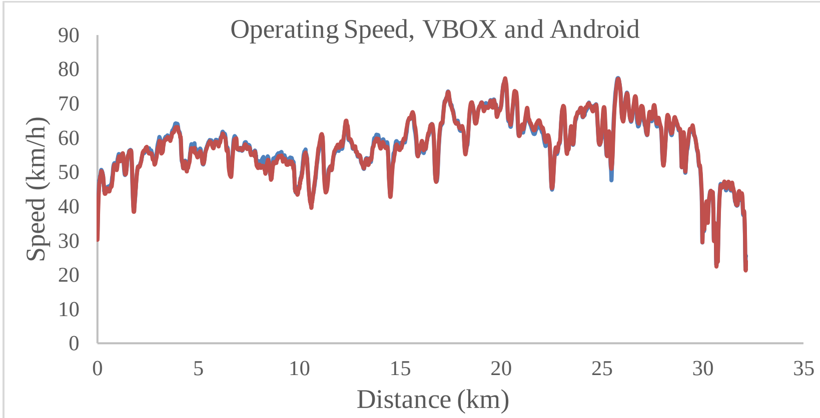

Fig. 4: Operating speeds.

The analysis of the absolute error allowed for an evaluation of the Android application's performance compared to the V-BOX equipment, showing a maximum absolute error of 3.513 km/h, although it was infrequent. The average absolute error was 0.664 km/h, indicating minimal differences between measurements, with a standard deviation of 0.481 km/h, suggesting controlled variability. Figure 6 shows that 98.6% of the measurements have errors between 0-2 km/h, demonstrating high precision compared to the V-BOX, while larger errors were isolated cases.

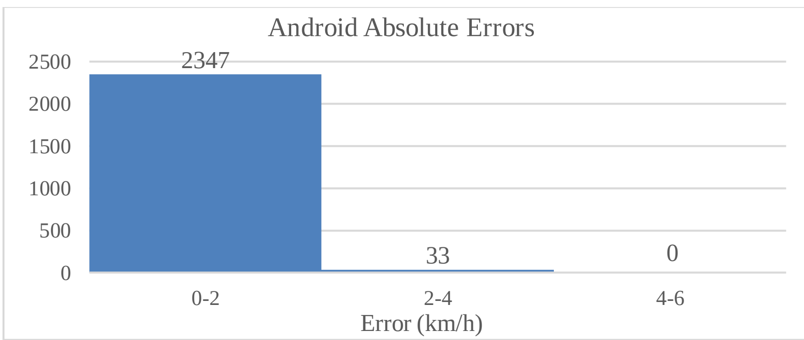

Fig. 5: Absolute Errors.

3.3. Analysis of the Average Operating Speeds

The comparative analysis of the operating speeds showed a high degree of concordance between the iOS, Android applications, and the V-BOX equipment, with a maximum difference of only 0.11 km/h between the highest measurement (V-BOX) and the lowest (iOS). Both Android and iOS recorded slightly lower averages, but with minimal variations (less than 0.2%), indicating that they do not overestimate speeds and maintain a good correlation with the standard. These insignificant differences highlight the viability of the applications as alternative tools for measuring speeds with results comparable to the reference equipment.

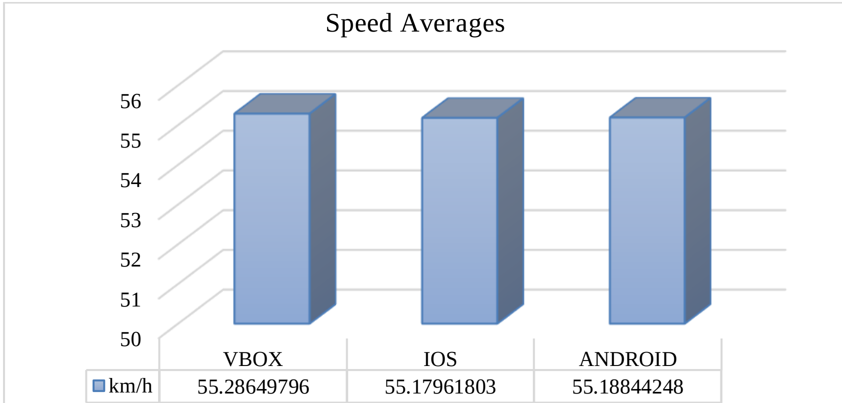

Fig. 6: Absolute Errors.

3.4. Equations of Correction

Based on the analysis performed, correction equations were generated to adjust the iOS and Android measurements to the reference V-BOX equipment. These equations were obtained through scatter plots and a second-degree polynomial regression analysis, which allowed for capturing nonlinear variations with greater precision than a linear model. Equation (2), corresponding to the iPhone (iOS), showed a determination coefficient $R^2 = 0.9831$, while equation (3), used for Android, achieved an $R^2 = 0.9932$, demonstrating an optimal fit. This model ensures that the corrected measurements are more accurate and aligned with the actual values.

$$y = -0.00013926 * x^2 + 1.0246 * x - 0.8131 \quad (2)$$
$$y = -0.00110042 * x^2 + 1.0979 * x - 1.8507 \quad (3)$$

3.5. Influence of Altitude on Measurements

The analysis of altitude as an interference factor in the accuracy of measurements showed that the highest accumulation of errors occurred in the highest section of the road (2341.17 m - 2580.30 m), with 700 errors, compared to the lowest section, which recorded 404 errors (Fig. 8). This increase in errors at higher altitudes is due to the decreased quality of the GPS signal, affected by the topography and the tropospheric delay of GPS microwaves [26]. Furthermore, the accuracy of smartphones depends on corrections sent by mobile base stations, whose distribution is limited in mountainous areas, making precise location more challenging [27]. However, the analysis revealed that, in most sections, the errors were concentrated in the 0-1 km/h range, confirming that, despite the terrain's influence, mobile applications remain reliable tools for assessing operating speed in mountainous environments.

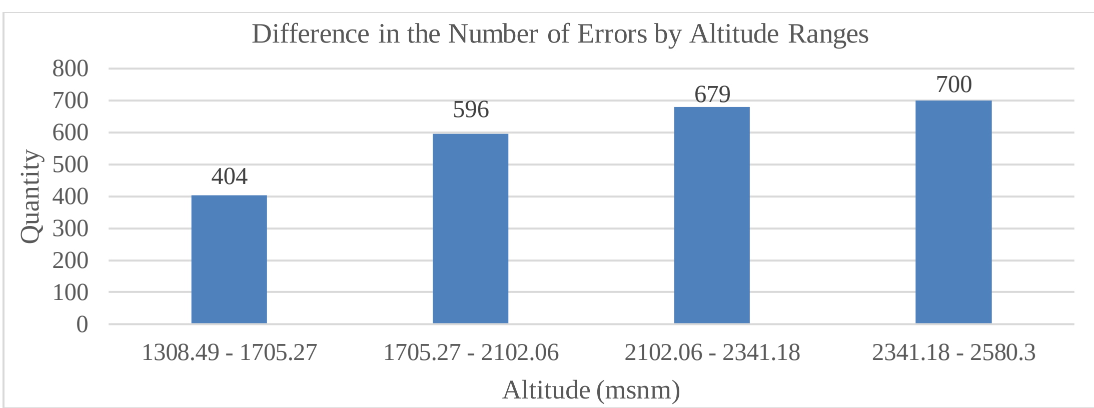

Fig. 7: Error Frequency by Altitude.

4. Conclusion

The Speed Tracker (iOS) and Speedometer GPS (Android) applications have proven to be reliable tools for measuring operating speed on mountainous rural roads. Statistical analyses confirmed that the measurements obtained are comparable to those from the VBOX equipment, as they show minimal differences and no systematic biases.

Although altitude can influence GPS accuracy, this factor was not significant in the study, as most errors were found in the 0-1 km/h range. This demonstrates that the applications remain effective in these environments, even in higher altitude areas where the signal quality might be affected.

To improve data accuracy, correction equations were proposed to adjust the measurements from the mobile applications and reduce errors. These equations achieved better alignment with the values obtained from the VBOX equipment, ensuring more precise and reliable measurements.

The use of mobile applications as a speed measurement tool offers a practical, accessible, and cost-effective alternative to traditional methods, especially on rural roads in mountainous environments. This technology facilitates data collection in areas with limited resources, optimizing road safety studies. Accurate speed measurements allow for identifying risky sections, evaluating the consistency of geometric design, and proposing corrective measures, contributing to the implementation of more effective road safety strategies and the reduction of accidents and their severity.

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