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Development and Performance Evaluation of a GNSS-Based Speed Monitoring and Limiting Device Using the House of Quality Approach

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Abstract

In Nigeria, over-speeding remains one of the leading causes of road accidents, despite existing regulations mandating the installation of speed limiting devices in commercial vehicles. The high cost and limited availability of these devices have significantly hindered widespread adoption. This study focuses on the development and performance evaluation of a cost-effective and reliable Global Navigation Satellite System (GNSS)-based speed monitoring and limiting device using the House of Quality (HoQ) sustainability approach. The HoQ framework was employed to align user needs with technical requirements by utilizing structured questionnaires to gather insights from drivers regarding their preferences, experiences, and compliance behaviour. Sound alerts, location tracking, and real-time speed displays were among the most requested features and were integrated into the system design. The device comprises a microcontroller (ATmega328P), GNSS/GPS module, LCD screen, sound buzzer, relay switch, and power regulation components. It operates by detecting vehicle speed via GNSS data, alerting the driver through sound when the speed exceeds a preset limit, and controlling the engine power using a relay switch to ensure compliance. Comparative testing was conducted on 45 vehicles (tricycles, cars, and trucks) across Benin City and Uyo, Nigeria. Speed readings from the developed device were compared against both conventional speed detection devices and the actual speed readings from vehicle dashboards. The results revealed negligible average errors of 0.91%, 0.43%, and 0.24% for tricycles, cars, and trucks, respectively, affirming the accuracy of the device. Statistical analysis using Tukey pairwise, Fisher LSD, and Dunnett multiple comparisons confirmed no significant differences (p > 0.05) between speed readings from the developed device, conventional devices, and vehicle dashboards. Furthermore, compliance indices assessed at various speed limits showed higher driver compliance at higher speed thresholds, with 86.67%, 66.67%, and 80% compliance rates at 100 km/h for tricycles, cars, and trucks respectively. These results underscore the practicality and effectiveness of the device in promoting speed compliance and enhancing road safety. The system provides a promising, low-cost solution to speed regulation, particularly suitable for adoption in developing countries like Nigeria where affordability and simplicity are critical.

Keywords: *Speed limiter, GNSS, House of Quality, microcontroller, road safety, compliance index.*

1. Introduction

Road transportation plays a vital role in the economic and social development of nations, facilitating the movement of people, goods, and services. In Nigeria, as in many developing countries, road transport remains the most accessible and widely used means of mobility due to its relative affordability and availability. However, this mode of transportation is not without its challenges. Among these, the increasing rate of road traffic accidents (RTAs), particularly those resulting from over-speeding, poses a severe threat to public safety and sustainable mobility. Over-speeding accounts for more than half of all traffic-related fatalities in

Nigeria, making it one of the most pressing public health concerns in the transportation sector (FRSC, 2010; WHO, 2015).

According to the Federal Road Safety Commission (FRSC, 2017), excessive speed is the primary contributing factor in nearly 60% of recorded crashes. In response, the Nigerian government introduced regulations mandating the installation of speed limiting devices in commercial vehicles as of October 1, 2016 (FRSC Portal, 2017). Despite this directive, the expected decline in accidents has not materialized. Several factors, including non-compliance, high device costs, and inadequate sensitization, have hindered the effectiveness of this policy (Okafor et al., 2018). Many drivers continue to disregard speed limits due to overconfidence in their driving skills, inadequate traffic enforcement, or a general lack of road safety awareness (Assum, 2018; Odewunmi et al., 2020).Technological solutions such as electronic speed limiters have been explored in both developed and developing economies. For instance, the concept of cruise control, first developed by Ralph Teetor in 1948 (Staci, 2014), has evolved into intelligent speed adaptation (ISA) systems that can autonomously regulate vehicle speeds based on road conditions and speed limits (Croitoru et al., 2014; McDonald et al., 2016). Modern systems often integrate Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS), to provide real-time location and speed data, thereby enabling more accurate speed monitoring and control (Gillespie et al., 2002; Zhang et al., 2019).

Despite these technological advancements, existing speed monitoring solutions are often expensive, difficult to maintain, or unsuitable for the diverse vehicle landscape in sub-Saharan Africa (Akinlade & Owolabi, 2019). Moreover, previous studies have shown that many available systems lack user-centric designs, ignoring the preferences and behaviours of end users, particularly commercial drivers who form the bulk of road users in Nigeria (Ishak et al., 2012; Oni &Olawuni, 2021). These shortcomings call for the development of affordable, reliable, and user-friendly alternatives that can effectively contribute to reducing the number of speed-related road crashes.

A growing body of literature has explored various approaches to speed control technologies. Burje et al. (2017) proposed a microcontroller-based system capable of adjusting throttle responses using pedal position sensors to manage speed in remote regions. While innovative, their approach was limited to theoretical modelling with limited real-world applications. In a related study, Chikezie et al. (2017) developed a voice-controlled speed warning system for cars, which alerts drivers at incremental thresholds starting from 80 km/h to 100 km/h. Although this technique proved effective in reducing sudden speed changes, it still lacked mechanisms to physically limit speed in real-time. Similarly, Oni and Olawuni (2021) presented a GSM-based remote highway speed limiter, which sends SMS alerts to vehicle owners when pre-set thresholds are exceeded. This system provided useful post-incident data but offered limited real-time control over vehicle speed. Other researchers, such as Prano et al. (2022), explored the integration of GPS-triggered fuel cutoff mechanisms to control speed in trucks and buses. While this represents a step forward in enforcing speed regulations, the high costs associated with implementation and maintenance have restricted its adoption in low-income settings.

These studies collectively highlight the need for a holistic design approach that incorporates user preferences, technological feasibility, and economic sustainability. The House of Quality (HoQ) methodology, a core tool of Quality Function Deployment (QFD), has proven useful in translating customer needs into engineering specifications during the product development phase (Hauser & Clausing, 1988; Akao, 1990). In the context of speed monitoring and limitation, this approach ensures that user requirements—such as alert type, device affordability, real-time feedback, and ease of use—are adequately prioritized and integrated into the design process.

The current study employs the HoQ methodology to design and develop a GNSS-based speed monitoring and limiting device tailored to the Nigerian road environment. It integrates real-time speed data acquisition using a GPS module, driver alerts via sound buzzers, and visual feedback through an LCD screen. A microcontroller unit processes incoming GNSS data and activates a relay switch to limit vehicle power once the preset speed threshold is exceeded. By emphasizing user experience and incorporating behavioral feedback into the design, the developed device aims to bridge the gap between technology adoption and practical road safety outcomes.

Furthermore, the effectiveness of the device is evaluated through comprehensive field tests conducted on tricycles, cars, and trucks in two major Nigerian cities—Benin and Uyo. The study assesses device accuracy by comparing speed readings with conventional speed detection tools and vehicle dashboard readings. Statistical techniques, including Tukey pairwise, Fisher LSD, and Dunnett multiple comparisons, are employed to validate the consistency and precision of the developed device across different vehicle types. Beyond technical evaluation, the study also investigates driver compliance behavior under varying speed limits (70 km/h, 80 km/h, and 100 km/h). This aspect is critical because even the most sophisticated systems can fail without adequate behavioral response from end-users. The compliance index derived from experimental trials reveals that drivers exhibit higher compliance at higher speed thresholds, likely due to greater comfort levels and reduced perception of inconvenience. These findings align with earlier observations by Ishak et al. (2012) that driver cooperation is influenced not just by enforcement mechanisms but also by the perceived practicality of imposed limits.

Importantly, this research aligns with Sustainable Development Goal (SDG) 3.6, which seeks to halve the number of global deaths and injuries from road traffic accidents by 2030 (UN, 2015). By providing a cost-effective, accurate, and user-friendly solution tailored to local needs, the device contributes toward safer mobility and aligns with broader efforts to build resilient infrastructure and promote inclusive transportation systems.

In conclusion, the persistent challenge of road traffic accidents in Nigeria—driven largely by excessive speeding—demands innovative, user-focused interventions. While numerous technological solutions have been proposed, most suffer from high cost, complexity, or a lack of contextual suitability. The development of a GNSS-based speed monitoring and limiting device using the House of Quality approach represents a novel and pragmatic response to this problem. It not only addresses the technological and financial barriers to adoption but also integrates behavioural feedback and local preferences into the solution framework.

This study contributes significantly to the growing field of intelligent transport systems in developing countries, offering insights into how sustainable design methodologies can enhance safety, affordability, and user satisfaction. As road transport continues to expand in Nigeria and across sub-Saharan Africa, innovations such as this can play a pivotal role in reducing road casualties, enhancing driver accountability, and promoting a culture of safety among vehicle operators.

2. Methodology

The methodology adopted for this research integrates a user-centered design approach with systematic engineering analysis. It comprises three core components: user requirement analysis using the House of Quality (HoQ) framework, the technical development of the GNSS-based speed monitoring and limiting device, and experimental performance evaluation across different vehicle categories. This structured approach ensured that both technical robustness and user acceptability were prioritized in the development process.

2.1 User Needs Assessment and House of Quality (HoQ) Design

The first step in the methodology involved identifying the key needs and preferences of road users, particularly commercial drivers, who are the primary target users for speed monitoring and limiting devices in Nigeria. A structured questionnaire was designed to capture critical information including preferred alert mechanisms (sound or visual), awareness of existing speed limiter technologies, perceived obstacles to usage, and expectations from an ideal speed limiting system. Respondents consisted of 100 drivers across two Nigerian cities—Benin City and Uyo—selected using a stratified random sampling technique to cover tricycle (keke), car, and truck operators. Feedback was analyzed to extract common user requirements, which were then translated into design specifications using the House of Quality (HoQ) approach, a core tool within the Quality Function Deployment (QFD) methodology (Hauser & Clausing, 1988).

The HoQ matrix served as a decision-making framework for prioritizing technical features based on customer importance ratings. Key parameters derived from the user feedback included affordability, ease of installation, real-time alert system, GPS integration for location tracking, and minimal maintenance requirements. Each technical requirement was correlated with the corresponding user need, weighted, and assigned a relative score. This analysis guided component selection and informed system architecture, ensuring that the final device was tailored to end-user expectations while remaining functionally efficient (Akao, 1990; Bayazit, 2005).

2.2 System Architecture and Component Description

The developed speed limiting device integrates a Global Navigation Satellite System (GNSS) module, a microcontroller (ATmega328P), a Liquid Crystal Display (LCD), a buzzer for auditory alerts, a power supply system, and a relay switch to manage engine speed.

The GNSS module, which operates based on GPS technology, serves as the primary sensor for capturing real-time speed and positional data. It establishes a satellite connection to determine the vehicle's current velocity using triangulation, which is a method involving distance calculations from at least three satellites (Misra&Enge, 2006). These values are transmitted to the microcontroller, which acts as the central processing unit of the device.

The microcontroller continuously compares the real-time speed data against a predefined threshold value set by the system user or regulatory authority. When the threshold is exceeded, the controller activates the buzzer to emit an alert tone, drawing the driver's attention. If the driver maintains the excessive speed for a defined time interval (e.g., 5 seconds), the controller then triggers the relay switch, which temporarily limits engine power by controlling power supply to specific engine components, thereby reducing the vehicle's speed.

The LCD screen provides continuous visual feedback to the driver, including current speed, threshold value, alert status, and geographic location. This enhances driver awareness and aids in compliance. The system is powered by a regulated 12V DC supply, stepped down to 5V as required by the microcontroller and peripheral modules. The Printed Circuit Board (PCB) housing was designed using Eagle software, with careful routing of copper traces to minimize signal interference and improve device reliability.

2.3 Device Fabrication and Enclosure

A robust and compact design was prioritized for field durability. Components were soldered onto the PCB and encased in a weather-resistant plastic enclosure with heat ventilation slots. The enclosure was designed to be mountable on the vehicle dashboard and included an external power input via a female DC jack. All external connectors were reinforced to reduce the risk of disconnection due to road vibrations.

2.4 Experimental Setup and Testing Protocol

Field testing was conducted on 45 vehicles—comprising 15 tricycles, 15 cars, and 15 trucks. Testing locations included high-traffic urban roads and semi-rural highways in Benin and Uyo. Vehicles were selected using purposive sampling to represent typical commercial traffic. Speed readings were collected at increments of 5 km/h from 25 km/h to 70 km/h.

For each test run, vehicle speed was simultaneously measured using three tools: the developed GNSS-based device, a conventional digital speed detection device, and the vehicle's dashboard (used as the control or reference). Each measurement was repeated three times for consistency. The error percentage for each reading was calculated using Equation 1:

$$\text{Error } (\%) = \left(\frac{|\text{Measured Speed} - \text{Dashboard Speed}|}{\text{Dashboard Speed}} \right) \times 100$$

This allowed for comparison of the developed device's accuracy against the conventional system. In addition, Minitab version 19 software was used to conduct Tukey pairwise comparisons, Fisher LSD tests, and Dunnett multiple comparisons to statistically assess the closeness of mean speed values between devices.

2.5 Compliance Index Assessment

To evaluate real-world applicability, a compliance index was introduced. Drivers were asked to operate their vehicles with the device set at speed limits of 70, 80, and 100 km/h. Compliance was recorded based on whether they slowed down upon hearing the alert. A compliance index was then calculated as the percentage of drivers who reacted to the alert within one minute.

This behavioural evaluation provided insights into how likely drivers were to adhere to auditory cues, and how compliance varied across speed limits and vehicle types, validating the device not only on technical performance but also on its practical effectiveness in influencing driver behaviour (Ishak et al., 2012).

3. Results and Discussion

The results of the study are presented in three subsections: comparative error analysis of the developed GNSS-based speed monitoring and limiting device, statistical validation of recorded speeds using established statistical tests, and behavioural analysis of driver compliance at varying speed thresholds. Each of these aspects provides insights into the reliability, accuracy, and user responsiveness associated with the developed device.

3.1 Comparative Error Analysis of Speed Measurement Devices

To evaluate the performance of the developed GNSS-based speed monitoring and limiting device, comparative assessments were carried out against conventional speed detection devices and vehicle dashboard readings, which served as the reference values. Three categories of vehicles were tested: tricycles (keke), cars, and trucks. For each category, 15 vehicles were evaluated under varying speed conditions (25–70 km/h). The speed recorded by the developed device was compared to both the conventional speed detector and the dashboard speedometer to determine error margins.

In the case of tricycles, the developed device recorded an error range between 0% and 3.33%, resulting in an average error value of 0.91%. The conventional speed detector showed a slightly higher error range between 0% and 3.64%, with an average of 1.41%. This indicates that while both devices performed reasonably well, the developed device demonstrated superior precision and closer alignment with dashboard readings. For cars, the error range for the developed device was narrower (0% to 1.67%), yielding an average error of 0.43%, compared to the conventional device's average error of 0.79%. Similarly, testing on trucks revealed the highest precision from the developed system, with error values ranging from 0% to 1.33% and an average of 0.24%, whereas the conventional device recorded a slightly higher average error of 0.51%.

These results affirm the reliability and accuracy of the developed GNSS-based system, especially in vehicle categories where vibration and road surface irregularities often introduce inaccuracies. The negligible differences in error values across all vehicle types highlight the robustness of the system's design and confirm that it is a suitable alternative to commercially available systems, especially in developing countries where cost and maintenance pose significant constraints.

3.2 Statistical Validation of Speed Measurement Accuracy

To validate the observed performance of the developed device from a statistical perspective, multiple statistical comparison tests were conducted using Minitab version 19 software. The tests included the Tukey pairwise comparison, Fisher's Least Significant Difference (LSD), and Dunnett multiple comparisons, all carried out at a 95% confidence level.For the tricycle category, the Tukey pairwise comparison grouped the dashboard, developed device, and conventional device speeds within the same statistical grouping (denoted as group A). The adjusted p-values were all above 0.05, indicating no statistically significant differences between the three speed values. Similar results were obtained using the Fisher LSD and Dunnett tests, reinforcing the reliability of the developed device's measurements.

The car category showed identical trends. Tukey and Fisher tests confirmed statistical similarity across all three speed recording methods. The developed device consistently recorded values that were within a close margin of the dashboard speed, as evidenced by the overlapping confidence intervals and high adjusted p-values (ranging between 0.94 and 1.00). Dunnett's test, which directly compared each device to the dashboard as a control, further confirmed these findings, with all comparisons yielding p-values above the significance threshold.

Truck category tests yielded similar conclusions. The developed device and the conventional detector both produced speed readings statistically identical to those of the dashboard. The Tukey test showed grouping under the same category (A), while Fisher and Dunnett tests supported the observation with insignificant p-value differences. These findings confirm that the GNSS-based speed limiting device is both statistically and practically indistinguishable in accuracy when compared to existing commercial solutions and vehicle on-board systems.

Overall, the statistical validation reinforces the credibility of the device across multiple conditions and vehicle classes. It proves that the integration of GNSS and microcontroller logic provides dependable results under dynamic driving conditions.

3.3 Driver Compliance Behaviour and Signal Response Analysis

Beyond technical evaluation, it was essential to assess how drivers responded to the system's over-speed alert functionality. This behavioural aspect is critical for determining the device's effectiveness in real-world usage. The compliance index was calculated by observing how many drivers responded promptly to the sound alert once the vehicle exceeded a pre-set speed limit.

At a threshold of 70 km/h, compliance rates were relatively low—40% for tricycle drivers, 33.33% for car drivers, and 40% for truck drivers. Many drivers reported discomfort operating at such low limits, citing time constraints and perceived inefficiencies. The continuous beeping alert was noted as a source of irritation by some drivers, yet it proved successful in prompting compliance among more cautious users.

As the speed threshold increased to 80 km/h, compliance improved moderately. Tricycle drivers showed a 53.33% compliance rate, while car and truck drivers recorded 46.67% and 60%, respectively. The higher tolerance threshold allowed drivers to operate at speeds they found more acceptable while still receiving timely alerts when limits were exceeded.

At 100 km/h, compliance reached its peak across all categories. Tricycle drivers recorded an 86.67% compliance rate, car drivers 66.67%, and truck drivers 80%. This trend suggests that higher threshold limits, when paired with effective alert mechanisms, are more likely to elicit driver cooperation. It also highlights that behavioural responses are influenced not only by technology but also by driver perceptions and the realism of the speed limits set.

These findings are consistent with previous studies which emphasized that behavioural change is crucial in ensuring the success of speed management technologies (Ishak et al., 2012; Oni & Olawuni, 2021). Drivers are more likely to respond positively to systems that provide intuitive feedback without being overly intrusive or restrictive.

Summary of Findings

i. The developed GNSS-based speed monitoring and limiting device demonstrated lower average error margins compared to conventional speed detectors.
ii. Statistical tests showed no significant differences between the developed device, conventional devices, and vehicle dashboards across all vehicle types.
iii. Driver compliance improved with higher speed thresholds, suggesting that practical limit settings and non-invasive alert mechanisms enhance behavioural compliance.
iv. The integration of user feedback in the design phase contributed significantly to the device's usability and acceptance in real-world conditions.

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4. Conclusion

This study successfully developed and evaluated a GNSS-based speed monitoring and limiting device using the House of Quality (HoQ) sustainability approach. By integrating customer-centric design principles with reliable technological components such as a GNSS module, microcontroller, LCD interface, and sound alert system, the research addressed critical gaps in affordability, usability, and performance of existing speed monitoring systems in Nigeria. The HoQ framework proved instrumental in translating user requirements—gathered through structured surveys—into technical specifications that directly informed the design, fabrication, and testing of the device.

Performance evaluations were carried out through comparative testing on tricycles, cars, and trucks across two urban centres in Nigeria. Speed readings from the developed device demonstrated high accuracy, with average error values of 0.91% for tricycles, 0.43% for cars, and 0.24% for trucks. These values were consistently lower than those recorded from conventional speed detection devices. Furthermore, statistical tests including Tukey pairwise, Fisher LSD, and Dunnett multiple comparisons confirmed that there was no significant difference between the developed device, the conventional device, and dashboard readings at a 95% confidence level. These results underscore the reliability of the developed system and its suitability as an alternative to expensive commercial solutions currently on the market.
In addition to technical performance, driver compliance behaviour was also assessed. Results showed that compliance with the device's over-speed alert system increased significantly at higher speed thresholds. At a pre-set limit of 100 km/h, compliance reached 86.67% for tricycle drivers, 66.67% for car drivers, and 80% for truck drivers. This indicates that realistic and context-sensitive speed settings play a vital role in influencing user behaviour and enhancing road safety.

The outcomes of this study have important implications for road traffic management in Nigeria and other developing countries facing similar challenges. The affordability, accuracy, and user-friendly nature of the device make it a viable tool for reducing speed-related road accidents, particularly among commercial vehicle operators. The design approach demonstrated here can also be replicated or scaled for broader applications, including public transport systems and fleet management services.

In conclusion, the developed GNSS-based speed limiting device represents a practical, cost-effective, and technically sound solution for improving road safety, with strong potential for national adoption and policy integration. Future research could explore real-time data logging, integration with mobile applications, and expanded deployment across other vehicle categories.

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