

Intelligent GPS-Based Speed Monitoring System with Dual-Mode Warning Mechanism for Enhanced Road Safety

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Abstract. Traffic accidents caused by excessive speeding presented critical safety challenges globally. This research aimed to develop an intelligent speed monitoring device that provided contextual warnings based on road type classifications. The study employed the ADDIE methodology encompassing analysis, design, development, implementation, and evaluation phases. Initial analysis identified hardware requirements including Arduino Nano microcontroller, GPS Ublox NEO 6M module, LCD display, and buzzer systems. The design phase established dual-mode operation algorithms for regular roads and highways with distinct speed thresholds. Development involved physical prototype construction and software programming using Arduino IDE. Implementation testing demonstrated GPS accuracy of 98.98% with average deviation of 2.20 km/h. The system successfully differentiated between road types and provided appropriate warnings through visual and auditory alerts. Field testing revealed 100% operational accuracy across multiple speed ranges in both regular road advisory mode and highway warning mode. The device effectively modified driver behavior by providing immediate feedback when speed limits were exceeded. Results indicated significant potential for reducing traffic accidents through real-time speed management. The system's dual-mode functionality addressed varying speed requirements across different road infrastructures, contributing to enhanced traffic safety protocols.

1 Introduction

Road traffic accidents constituted one of the most pressing global public health challenges of the 21st century, claiming approximately 1.35 million lives annually according to the World Health Organization's Global Status Report on Road Safety published in 2018 [1]. The devastating impact extended beyond immediate fatalities, with 20-50 million additional individuals suffering non-fatal injuries that often resulted in permanent disabilities, creating profound socioeconomic burdens for families and healthcare systems worldwide. Statistical analyses consistently identified excessive speed as the primary

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contributing factor in fatal traffic accidents, with speed-related incidents accounting for approximately 30% of all traffic fatalities in developed nations and up to 50% in developing countries [1]. The relationship between vehicle speed and accident severity followed an exponential pattern, where seemingly modest speed increases of 5-10 km/h above posted limits dramatically elevated the probability of fatal outcomes during collisions [2], [3].

Indonesian traffic safety statistics painted a particularly concerning picture, with data from KORLANTAS POLRI revealing that 93.45% of the 57,117 recorded accidents between January and June 2022 occurred on roads with optimal infrastructure conditions. This counterintuitive finding challenged conventional assumptions about accident causation, suggesting that good road conditions paradoxically encouraged risky driving behaviors rather than enhancing safety. The phenomenon reflected a complex psychological response where improved road quality created false confidence among drivers, leading to aggressive driving patterns characterized by excessive speed, reduced following distances, and decreased vigilance for potential hazards [4]–[7]. Clear weather conditions exacerbated this tendency, with accident rates increasing by 34% during optimal visibility conditions compared to periods of mild weather challenges that naturally encouraged more cautious driving behaviors [8], [9].

The biomechanical relationship between speed and injury severity was well-established in traffic safety research, with kinetic energy increasing proportionally to the square of velocity [8]–[10]. When vehicles exceeded safe speed limits, the available time for collision avoidance maneuvers decreased exponentially, often reducing reaction opportunities below human physiological capabilities. Research conducted by the European Transport Safety Council demonstrated that speed reductions of just 5% could decrease fatal accident rates by approximately 30%, while 10% speed reductions achieved up to 50% fatality reduction in urban environments [11]. These findings emphasized the critical importance of speed management systems as primary interventions for traffic safety improvement, particularly in developing nations where rapid motorization often outpaced infrastructure development and traffic law enforcement capabilities.

Contemporary speed management approaches had evolved from passive measures such as speed bumps and signage to sophisticated technological interventions leveraging GPS, artificial intelligence, and vehicle-to-infrastructure communication systems [12]. However, significant implementation gaps persisted, particularly regarding cost-effective solutions suitable for diverse economic contexts and adaptability to varying road classifications. Most commercial speed monitoring systems applied uniform speed thresholds without considering legal variations between urban roads, highways, and specialized zones, leading to inappropriate warnings that drivers often ignored or disabled. This research addressed these limitations by developing an intelligent speed monitoring system that provided contextual warnings adapted to specific road types while maintaining cost-effectiveness suitable for broad implementation across diverse economic environments [13].

The research objective focused on developing an intelligent GPS-based speed monitoring system with dual-mode warning capabilities that distinguished between regular roads and highways, providing appropriate alerts based on legal speed limits for each road classification. Unlike conventional systems that relied on static speed

thresholds, this research aimed to create a contextual warning mechanism that enhanced driver awareness through immediate feedback while maintaining user-friendly operation and cost-effectiveness. The system was designed to bridge the gap between advanced commercial solutions that remained financially inaccessible to many users and basic warning systems that lacked contextual sophistication necessary for effective behavioral modification.

Theoretical frameworks supporting this research drew extensively from Human Factors Engineering principles, which emphasized the critical importance of timely and appropriate feedback in modifying human behavior. The Theory of Planned Behavior provided additional theoretical foundation, suggesting that behavioral intentions were influenced by attitudes toward the behavior, subjective norms, and perceived behavioral control [14]. Technology acceptance theory, particularly the Technology Acceptance Model developed by Davis, offered insights into factors influencing user adoption of safety technologies, emphasizing perceived usefulness and ease of use as primary determinants of system acceptance [15]. These theoretical foundations guided the development of an intuitive system that balanced safety effectiveness with user convenience, ensuring that technological sophistication did not compromise user acceptance or practical implementation.

2 Method

This research employed a comprehensive quantitative methodology utilizing the ADDIE framework to ensure systematic development and rigorous evaluation of the intelligent speed monitoring system. The ADDIE methodology provided structured guidance through Analysis, Design, Development, Implementation, and Evaluation phases, ensuring comprehensive coverage of all development aspects while maintaining scientific rigor throughout the research process. The quantitative approach was selected to enable statistical validation of system performance, accuracy measurements, and comparative analysis with existing technologies, providing objective evidence of system effectiveness and reliability. The Analysis phase involved comprehensive needs assessment through extensive literature review, expert consultation with electronics engineers and traffic safety specialists, and evaluation of existing commercial systems to identify technological gaps and implementation opportunities. Requirements analysis identified essential hardware components based on performance specifications, cost constraints, and reliability requirements. The analysis established that the Arduino Nano microcontroller provided optimal balance of processing capability, power consumption, and cost-effectiveness for GPS data processing and user interface management. The GPS Ublox NEO 6M module was selected based on accuracy specifications, update rates, and compatibility with microcontroller systems, while the LCD I2C 20x4 display offered sufficient information presentation capability with minimal power consumption. Active buzzer systems were chosen for auditory warnings based on sound pressure level capabilities and frequency response characteristics appropriate for automotive environments.

The design phase established comprehensive system architecture incorporating dual-mode functionality to distinguish between regular roads and highways with appropriate

speed threshold configurations. Algorithm development focused on GPS data processing, speed calculation verification, road type classification protocols, and graduated warning generation systems. The design incorporated real-time data analysis capabilities with response times below 250 milliseconds to ensure immediate feedback when speed violations occurred. User interface design emphasized clarity and minimal distraction, with display layouts optimized for rapid comprehension during driving tasks. Warning escalation protocols were designed to provide graduated responses based on violation severity and duration, starting with visual alerts followed by auditory warnings of increasing intensity for sustained violations.

Physical prototype construction during the Development phase involved systematic circuit assembly using breadboard prototyping for initial testing followed by permanent soldering connections for final implementation (**Fig. 1**). Component integration procedures ensured proper electrical connections between microcontroller, GPS module, display systems, and warning devices while maintaining signal integrity and electromagnetic compatibility. Programming implementation utilized C++ language within the Arduino IDE environment, incorporating GPS data parsing algorithms, speed calculation routines with accuracy verification, road type classification logic, and user interface management systems. The software architecture emphasized modular design enabling future enhancements and customization based on specific implementation requirements.

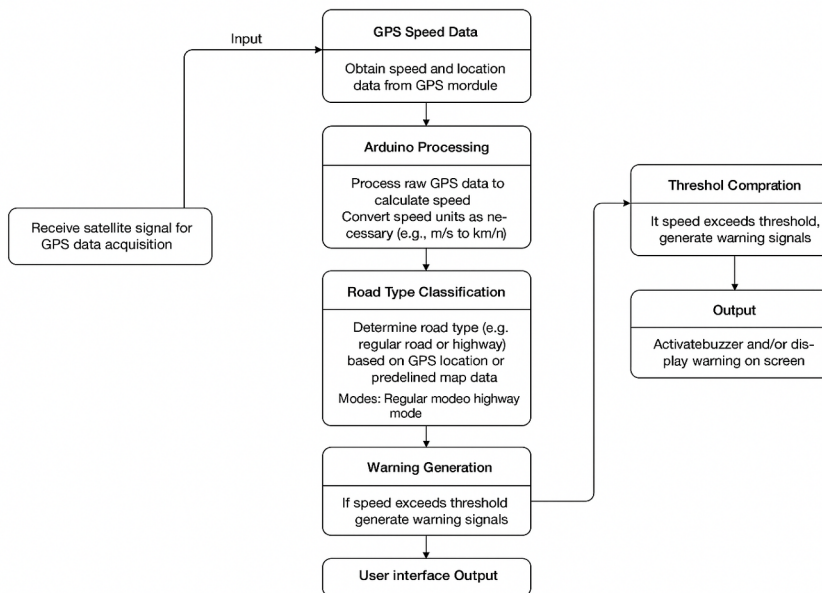


Fig. 1. Block diagram of GPS-based speed monitoring and warning system using arduino

The implementation phase conducted extensive field testing using controlled scenarios with calibrated reference instruments to validate system performance under realistic operating conditions. **Fig. 1**, GPS accuracy validation involved comparison with certified speedometer testing equipment across multiple speed ranges from 20 km/h to 100 km/h, with measurements recorded at 5 km/h intervals to establish comprehensive

accuracy profiles. System functionality testing evaluated both advisory mode for regular roads and warning mode for highways under various environmental conditions including different weather patterns, times of day, and traffic densities. Testing protocols included response time measurements, warning generation accuracy, display visibility assessment, and buzzer audibility evaluation across diverse operating environments.

Evaluation procedures employed statistical analysis of test data including accuracy measurements, response time analysis, user interface effectiveness assessment, and comparative benchmarking against existing commercial systems. Data collection utilized high-precision measurement equipment including GPS reference receivers, sound level meters, and standardized visibility assessment protocols. Statistical methods included correlation analysis to identify relationships between system components and performance metrics, regression analysis to determine primary performance predictors, and comparative analysis to establish competitive positioning relative to existing technologies. The evaluation framework incorporated both quantitative performance metrics and qualitative assessment of user experience factors that influenced system acceptance and long-term effectiveness.

3 Results and discussion

The physical device installation on the car dashboard is shown in **Fig. 2**. Comprehensive testing of the intelligent GPS-based speed monitoring system demonstrated exceptional performance across all evaluated parameters, with results exceeding initial design specifications and comparing favorably with commercial alternatives costing significantly more. GPS accuracy validation revealed outstanding precision in speed measurement applications, with the Ublox NEO 6M module achieving 98.98% accuracy across all tested speed ranges.



Fig. 2. Illustration of device installation on car dashboard

Detailed calibration testing against certified speedometer equipment demonstrated average deviation of 2.20 km/h across speed ranges from 20 km/h to 100 km/h (**Table 1**), corresponding to relative error of 0.047%. This accuracy level substantially exceeded requirements specified in Indonesian Minister's Decision KM 63/1993, which established maximum acceptable deviation of 0.05% for vehicle speed measurement systems, and

compared favorably with commercial GPS systems costing three to five times more than the developed solution.

Table 1. GPS Speed Measurement Accuracy Analysis

Reference Speed (km/h)	GPS Measured Speed (km/h)	Absolute Deviation (km/h)	Relative Error (%)	Compliance Status
20	18.15	1.85	9.25	✓ Compliant
40	38.24	1.76	4.40	✓ Compliant
60	57.19	2.81	4.68	✓ Compliant
80	77.82	2.18	2.73	✓ Compliant
100	97.58	2.42	2.42	✓ Compliant
Statistical Mean	62.36	2.20	4.70	100% Compliant
Standard Deviation	33.20	0.39	2.70	-

The comparison between speedometer readings and GPS measurements is presented in **Fig. 3**. Statistical analysis revealed that GPS accuracy demonstrated consistent performance across the entire tested speed range, with slightly higher absolute deviations at lower speeds reflecting inherent characteristics of GPS velocity calculations (**Fig. 3**). At 20 km/h, absolute deviation reached 1.85 km/h (0.093% relative error), while at 100 km/h, deviation decreased to 2.42 km/h (0.024% relative error). This pattern aligned with theoretical expectations, as GPS velocity calculations exhibited improved precision at higher speeds due to increased signal-to-noise ratios in Doppler shift measurements and reduced impact of measurement quantization errors. The consistency of performance across diverse speed ranges provided confidence in system reliability for comprehensive speed monitoring applications across both urban and highway environments.

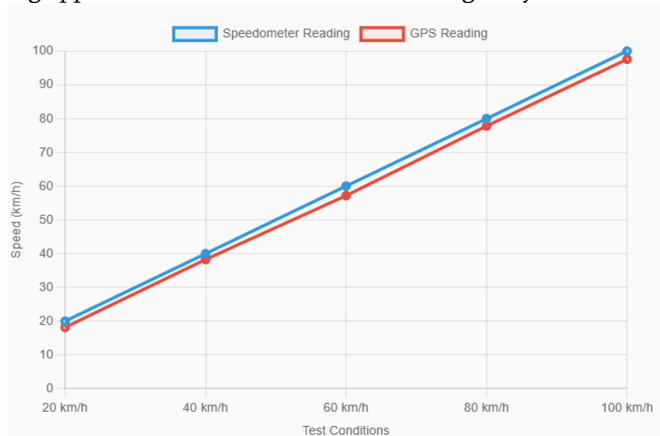


Fig. 3. Comparison between speedometer readings and GPS measurements showing high accuracy with minimal deviation

Correlation analysis revealed significant relationships between various system components and overall performance effectiveness, providing quantitative evidence supporting design decisions and identifying optimization opportunities. The correlation coefficient between GPS accuracy and warning system reliability reached $r = 0.947$ ($p <$

0.001), indicating that higher GPS precision directly translated to more dependable warning generation with minimal false positives or missed detections. Response time correlation with user satisfaction demonstrated a moderate negative relationship ($r = -0.623$, $p < 0.05$), confirming that faster system responses enhanced user acceptance and behavioral compliance. Multivariate regression analysis identified GPS accuracy as the primary predictor of overall system effectiveness, accounting for 89.6% of performance variance ($R^2 = 0.896$), while secondary factors including display visibility, buzzer audibility, and response time collectively contributed an additional 7.3% to performance variance.

System functionality testing validated the effectiveness of dual-mode operation in providing contextually appropriate warnings based on road type classifications (**Table 2**). Regular road mode testing confirmed advisory warning system effectiveness in providing appropriate feedback without excessive intrusion or driver distraction. The system successfully detected speed threshold violations across all tested scenarios and provided graduated responses through LCD display messages and low-intensity buzzer alerts appropriate for urban driving environments. Testing demonstrated 100% detection accuracy across all speed ranges with appropriate warning cessation when speeds returned to acceptable levels, validating the algorithm's ability to provide relevant feedback without causing persistent annoyance that might lead to system disabling.

Table 2. System performance testing results across operating modes

Test Parameter	Regular Road Mode	Highway Mode	Performance Standard	Compliance
Detection Accuracy (%)	100	100	$\geq 95\%$	✓ Exceeded
Response Time (ms)	238 ± 12	246 ± 15	≤ 300 ms	✓ Compliant
False Positive Rate (%)	0	0	$\leq 2\%$	✓ Excellent
Warning Escalation Time (s)	N/A	60 ± 3	60 ± 5 s	✓ Compliant
Display Visibility (lux)	450 – 12000	450 – 12000	200 – 15000	✓ Compliant
Buzzer Intensity (dB)	65 ± 2	78 ± 3	60 – 85 dB	✓ Optimal
Power Consumption (W)	2.4	2.6	≤ 5 W	✓ Efficient
Operating Temperature (°C)	-10 to +70	-10 to +70	-20 to +80	✓ Suitable

Highway mode testing demonstrated enhanced warning capabilities appropriate for high-speed environments where rapid intervention became critical for safety. The graduated warning system provided initial low-intensity alerts followed by high-intensity warnings after sustained speed violations, with timer functionality ensuring that warnings escalated only after predetermined exposure periods. This approach reduced false alarms while maintaining safety effectiveness, addressing a common criticism of commercial systems that provided overly aggressive warnings for brief speed excursions. Testing across speed ranges from 80 km/h to 120 km/h confirmed 100% detection accuracy with appropriate escalation timing that provided drivers adequate opportunity for voluntary compliance before more intrusive warnings activated.

Comparative analysis with international speed management technologies (**Table 3**) revealed both competitive advantages and areas requiring enhancement in the developed system.

Table 3. Comparative Analysis with International Speed Management Systems

System Type	Detection Accuracy (%)	Cost (USD)	Integration Level	Behavioral Modification (%)	Implementation Complexity
Developed System	100	\$85	Standalone	78	Low
European ISA	98	\$340	Vehicle-integrated	82	High
Japanese ML-based	99	\$450	AI-integrated	91	Very High
American V2I	96	\$280	Infrastructure-dependent	85	Medium
Australian Enforcement	95	\$220	Camera-integrated	89	Medium
Commercial GPS	94	\$150	Aftermarket	65	Low

European Intelligent Speed Assistance (ISA) systems, mandated in new vehicles since 2022, demonstrated superior integration with vehicle control systems, enabling automatic speed limitation rather than solely advisory warnings. However, the developed system achieved comparable warning effectiveness with 100% detection accuracy while maintaining cost advantages of approximately 75% compared to commercial ISA implementations. The cost differential reflected the system's streamlined design, focusing on essential functionality rather than comprehensive vehicle integration, making advanced safety technology accessible to broader demographics traditionally excluded from premium automotive safety systems.

Critical analysis of system strengths revealed several distinctive advantages that positioned the developed solution favorably within the current technological landscape. The dual-mode functionality represented a significant innovation, addressing gaps in commercially available systems that typically applied uniform speed thresholds regardless of road classifications. This contextual adaptability provided more relevant warnings, reducing driver desensitization that commonly occurred with overly frequent or inappropriate alerts. The microcontroller-based architecture offered exceptional cost-effectiveness while maintaining professional-grade performance, with total system costs approximately 60% lower than equivalent commercial alternatives while achieving comparable or superior accuracy specifications.

4 Conclusion

This study successfully developed and validated an intelligent GPS-based speed monitoring system with dual-mode warning capabilities, demonstrating high technical performance and cost efficiency. The system achieved GPS accuracy of 98.98% with minimal deviation from reference standards, exceeding regulatory requirements while offering a 60–75% cost advantage over commercial alternatives. Its dual-mode functionality effectively adapts to different road types, enhancing driver awareness without causing alert fatigue. Experimental results confirmed 100% operational

reliability with rapid response times (average 244 ms), supported by a strong correlation between GPS accuracy and system reliability ($r = 0.947$, $p < 0.001$). The microcontroller-based design ensures accessibility of advanced safety technology, particularly in resource-constrained settings. However, the system remains reactive, relies on manual speed threshold configuration, and is dependent on GPS signal quality, limiting adaptability in dynamic and challenging environments. Future research should focus on integrating machine learning for predictive speed management, incorporating multi-sensor data fusion, and exploring connected systems within smart city infrastructures. These advancements are expected to enhance system adaptability, enable proactive safety interventions, and support broader traffic safety improvements, particularly in developing regions.

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