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Smart In-Car Speed Monitoring System, The Effect of Grace Period on Driving Behavior

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Abstract

High and excessive speed is one of the leading causes of traffic accidents, leading to fatalities and serious injuries worldwide. In Iraq, there was a 21% increase in casualties by 2017. This study presents a speed monitoring system in which the driver gets alerted by an audible alarm in case of over-speeding. A grace period of 10 seconds is allowed so that the driver tries to reduce the car's speed. A ticket is issued via SMS message if the driver fails to decelerate within that period. Thus, prioritizing safety awareness over immediate punitive measures. The system was tested through 40 car trips, carried out by four drivers, 20 trips without an alarm and 20 with an alarm. Multiple statistical tests were used to evaluate the system. Results revealed that incorporating the alarm achieved a reduction of 21%, with *p*=.039 in speed mean, and 14% with *p*=.002 in speed variability. Additionally, tickets were decreased by 89% with high statistical significance (*p* < .001). Furthermore, statistically, trips with an alarm revealed 84% lower odds of receiving a ticket in comparison with the trips without an alarm. On the other hand, results showed that there is no correlation between temperature and speeding ($p > .05$, indicating that there is no statistical significance).

1. Introduction

Excessive speed is the leading cause of traffic accidents, resulting in deaths and serious injuries worldwide. According to the World Health Organization [1], a large percentage of road accidents, up to 30% in high-income countries and more than 50% in low- and middle-income countries, are caused by high or inappropriate speed. Traffic accidents in Iraq have witnessed a dramatic increase recently. A study highlighted a 21% increase in casualties by 2017 [2], also 3% of accidents have been linked to driver behavior [3]. Additionally, the authors in [4] showed that pedestrians are the most endangered road users in Iraq, where 49% of traffic fatalities include women and children. Due to the increasing density of vehicles and the construction of increasingly complex urban road networks, there is an urgent need for intelligent systems that automatically monitor vehicle behavior and enforce compliance with traffic safety rules (speed).

To address this issue, this study presents an automated speed monitoring and violation system, in which, when the driver exceeds the pre-set speed, the system issues an immediate warning. The proposed system differs from other traditional systems by giving the driver a period of ten seconds to reduce speed. If the driver does not respond appropriately and slow down, the system automatically issues a ticket and links it to the vehicle for enforcement. This work allows drivers to decelerate and correct their behavior in real-time. Therefore, the grace period affects a better driving habit and giving the perspective of prioritizing safety over fines.

2. Related Work

There are many traditional ways used to prevent speed violators e.g. red-light systems, fixed cameras, and mobile police patrols. Despite that these approaches are effective; they lack the real-time interaction with the driver so that they usually do not immediately affects behavior. Intelligent Speed Assistants (ISA) provide real-time feedback, so that recently the focus has been on such systems [5]. ISA systems are classified into passive systems where an audible or visual alerts are given to the driver when the speed is exceeded, and active systems in which, an actual intervention occurs to limit the speed when exceeded [6].

Lehtonen et al. (2020) carried out simulator-based eye tracking studies in which, a real-time alert system for drivers improved their compliance because they reduce their speed before receiving warnings [7]. Another study conducted by Khan et al. (2022) showed an IoT system to detect and warn in case of high speed and achieved a significant speed reduction during urban test [8]. Several ISA systems provides an immediate alert, and some of them gives a chance of reducing speed before enforcement, which our system provides.

Timely feedback can influence Drivers'behavior as confirmed by transportation psychology. Reagan et al. (2013) conducted an in-depth study on the effect of external motivation resulting from instantaneous automated feedback on speeding behavior in natural environments. The results concluded that these systems (ISA) can effectively improve safe driving behavior among drivers, which highlights the need to continuously implement and develop real-time feedback mechanisms [9]. Soole et al. (2013) showed that there is an improvement in driver response when there is a short delay between the detection of a speeding violation and the enforcement of the law [10]. Boylan et al. (2025) note that when the feedback is clear and immediate in mixed autonomous driving environments, driver behavior dynamically adapts to that feedback [11]. To encourage a self- correction instead of immediate punishment, our system is built on this evidence to allow a 10 seconds grace period to alter speed.

Modern vehicles use combinations of systems for speed detection e.g. GPS-OBD II telematics, computer vision, and radar-LiDAR. Fernandez-Llorca et al. (2021) made a vision-based speed estimation techniques survey using road cameras or dash-cams, providing a tradeoff between accuracy and cost [12]. On the other hand, Njuu et al. (2025) presented frameworks that combine cloud computing, AI, block chain, and IoT to enhance security, scalability, and transparency in speed monitoring systems [13]. Additionally, Fonseca and Ferreira (2025) conducted a review of vehicle monitoring systems that uses telematics and biometrics, showing their effect on driving behavior [14].

Regarding school zones, empirical assessments of speed enforcement implementation showed that automated systems reduce speeding significantly. A 2024 Nevada study showed that initially speed enforcement was poor (only 24%); after the integration of speed cameras, speeding and traffic violations have significantly decreased [15]. Another study showed that the implementation of speed enforcement systems resulted about 45% reduction in speeds and a 10.7% decrease in the 85th percentile [16]. On the other hand, another study warned that depending only on speed limit changes and neglecting other supportive measures may lead to mixed results [17].

Sensors are the basic components that forms the ISA systems, used especially in car-cabin driver monitoring systems. Weird and IIHS (2023) reports explain how IR cameras are implemented inside vehicles to oversee drivers' attention and warns them in case of distraction [18]. Also, Muiz et al. (2025) conducted an IoT warning system that modifies the vehicle speed or stops it completely within 15 seconds in case of drowsiness or alcohol detection [19].

The real-time communication between vehicles and infrastructure defines the accuracy of warnings [20]. Records that are resistant to manipulations are crucial for transparent enforcement and can be provided by integrating driver data records with ISA systems, telematic systems, or infrastructure [21]. For the purpose of eliminating ethical concerns e.g. privacy, public trust, and fairness, pre-enforcement intervals are common in many regions [22].

The already implemented systems fines drivers immediately without considering unintended and occasional overspeedings. Conversely, this study investigates the following question: Does a 10-second grace period affect driving behavior and effectively reduce speed and ticket numbers, while prioritizing safety over punishment? The proposed work can be summarized as follows:

- Affordable.
- Self-sustaining in terms of power, eliminating the need for an external power source, as it is supplied directly from the vehicle USB port.

- Grace period: allowing drivers to decelerate within 10 seconds before ticketing.
- Behavioral correction: prioritizing safety awareness over immediate punitive measures.

3. Materials and Method

3.1 System Development

The proposed work conducted an empirical study with two groups: 20 real-world car trips using a speed alarm and another 20 without an alarm. The 40 car trips were performed by four drivers, each of whom made 10 trips (five without a speed alarm and five with an alarm). The trips were carried out under similar circumstances and demographics in the urban environment of Mosul, Iraq. The identities of the drivers were anonymized during all stages of the analysis.

The proposed system is designed to constantly observe the speed of a car and alert the driver if the speed limit is exceeded. The speed limit is predefined as a fixed threshold of 80 kmph following the urban boundaries of the city of Mosul, Iraq. The system automatically tickets the driver via SMS message to be sent to the authorities if the driver ignores the warning for more than 10 seconds and proceeds to exceed the speed limit. The SMS message contains information on the driver's location and speed. In addition, the system logs data, specifically timestamp, cabin temperature, speed, latitude, longitude, total over-speeds, with ticket, and without ticket for offline analysis.

The system consists of:

1. Arduino Mega microcontroller as the main controller, interfacing with all the modules and sensors.
2. GSM SIM900 to send SMS violation tickets.
3. GPS NEO-6M module for real-time coordinates and speed.
4. Buzzer for audible alert purposes.
5. DHT11 temperature sensor for cabin temperature measuring.
6. For further offline analysis: SD-card module to save the logged data.

Figure 1 shows the hardware setup installed in the car cabin during one of the 40 trips. The system power is supplied from the vehicle via a standard USB port. Therefore, there is no need for an external battery, which ensures the system's operation during all test trips.

Before deployment, an initial test with the car in a stationary state was performed to ensure sensor performance accuracy and system stability. The purpose of this test is to validate the overall performance in a controlled environment. After the validation process, real-world driving conditions were considered to deploy the system in multiple car trips for data collection.

3.2 System Operation

The car speed is continuously checked by the system, then compared to a predefined speed limit. An audible warning is issued when the speed limit is exceeded. It tickets the driver if the speed limit is exceeded for more than 10 seconds. The system also logs the data every second (sampling rate = 1 Hz) and records the number of times the driver exceeds the speed limit, and how many warnings are triggered with and without tickets on the SD-card. For clarity, the system flowchart is presented in three parts: Figure 2a shows the whole system, Figure 2b extends the speed handling logic, and Figure 2c describes the data logging process.

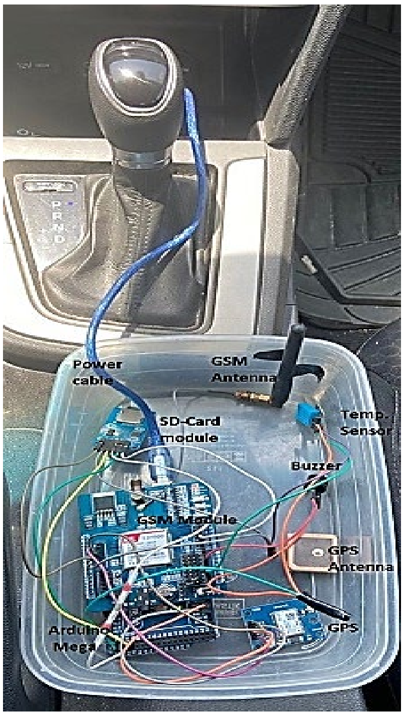
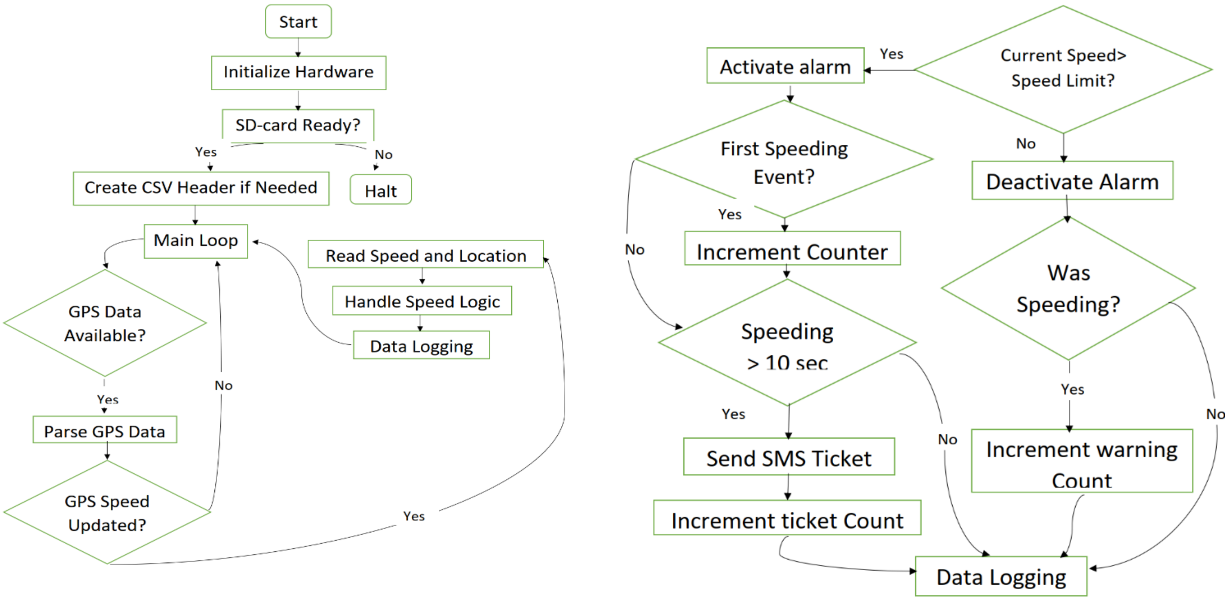
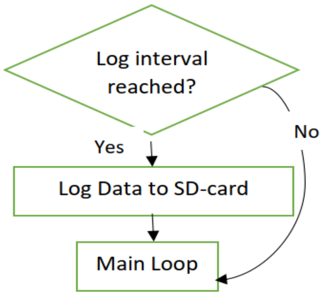


Fig. 1 *Hardware setup of the proposed system installed inside the car, powered from the built in USB port*



(a) System flowchart **(b) Speed handling logic**



(c) Data logging process

Fig. 2 *System flowchart is presented in three parts*

3.3 Statistical Analysis

Diverse statistical tests were conducted depending on variable type and distribution to assess the effectiveness of the proposed speed alarm system and discover prospective behavioral correlations. Although the sample size is small (20 car trips in each group), the system produces perceptions of real-world applications. Table 1 demonstrates the tests used in this study.

Table 1 *Statistical tests, metrics, rationale, and effect types used in the study*

Test	Metrics	Rationale	Effect type
Welch's t-test	Mean speed, Speed Stdev, Max speed	Handles unequal variances/ sample sizes	Cohen's d
Mann–Whitney U	Cabin temperature, Temp Stdev, Ticketed overspeed, Unticketed overspeed	For non-normal variables (central trend comparison)	Mann–Whitney r
Chi-square	Ticket issuance ratio (with vs without alarm)	Test association between alarm and ticketing	Odds ratio OR

Cohen's d (0.2 is small, 0.5 is medium, 0.8 is large), while r = $\frac{Z}{\sqrt{N}}$ where Z is the standard score, N is the total number of observations, and the Odds ratio from 2×2 contingency table, OR = $\frac{a\,x\,d}{b\,x\,c}$ (> 1 positive association). a, b are ticket counts with/without alarm; c, d are warning (no ticket) counts with/without alarm.
Python 3.11 is used to conduct all the mentioned statistical tests [23], with functions from the scipy.stats module [24]. Moreover, pandas and numpy libraries were used in data preprocessing and validation. A significance level of α = 0.05 was used for all analyses.

3.4 Ethics Statement

The proposed work involved four volunteer drivers who agreed to participate in testing the system. All data are anonymized, and no identifying information was collected. The study was risk-free and did not require personal data; therefore, formal IRB approval was not required.

4. Results and Discussion

4.1 System Accuracy Evaluation

A total of 904 data samples were collected over an approximate 15-minutes period, deployed in a stationary car. The sampling frequency was 1 Hz (sampling interval = 1 second). The purpose of the stationary car deployment is to inspect the collected dataset and to test the performance of the sensors used. To identify outliers, a $\mp \mathbf{2.5\sigma}$ threshold is considered in this work, balancing strictness and flexibility. It is strict enough to identify outliers and flexible enough to ignore small noise where occasional fluctuations are expected in engineering and sensor analysis. Performance metrics are shown in Table 2:

Table 2 *Summary statistics of GPS drift, speed, temperature, and time interval with outlier counts and percentages*

1	Mean	StdDev	Min	Max	Outliers	Percentage
GPS drift (kmph)	9.426087	5.116805	0.089127	26.77384	15	1.7 %
Speed (kmph)	0.052544	0.062205	0	0.5	8	0.9 %
Temperature (C)	29.62909	0.807307	28	30.7	0	0.0 %
Time interval (s)	1.015504	0.187713	1	5	8	0.9 %

Regarding GPS drift outliers (1.7%), the result is expected, especially in urban environments, due to multipath problems arising from tall and congested buildings. Consequently, the acquired GPS data is stable. In terms of speed, it should be near zero in a stationary test. Although the acquired speed outliers were 0.9%, the system performance is robust, with very few false speed spikes. On the other hand, the temperature sensor performance was perfect with no recorded outliers. Eventually, the time interval outlier percentage of 0.9% implies that many logging intervals are uniform, with rare delays due to lag of SD-card logging, sensor delay reads, or blocking GPS reads. Thus, the results of the stationary analysis indicates that the system is robust and ready to deploy in a live drive test.

GPS drift over time during the stationary test is shown in figure 3. To distinguish the outliers, a $\pm 2.5\%$ threshold is considered in the analysis. A small expected fluctuations is appeared, while the majority of the data remains with this range, indicating a robust GPS results. Nevertheless, multiple data points override the upper threshold, and they are identified as outliers in red. This behavior is expected because the GPS is deployed in an urban environment, which affects accuracy. The overall impact of these outliers is minimal; also, our intended application does not require centimeter-level accuracy. Thus, this drift is acceptable and does not affect the system's reliability.

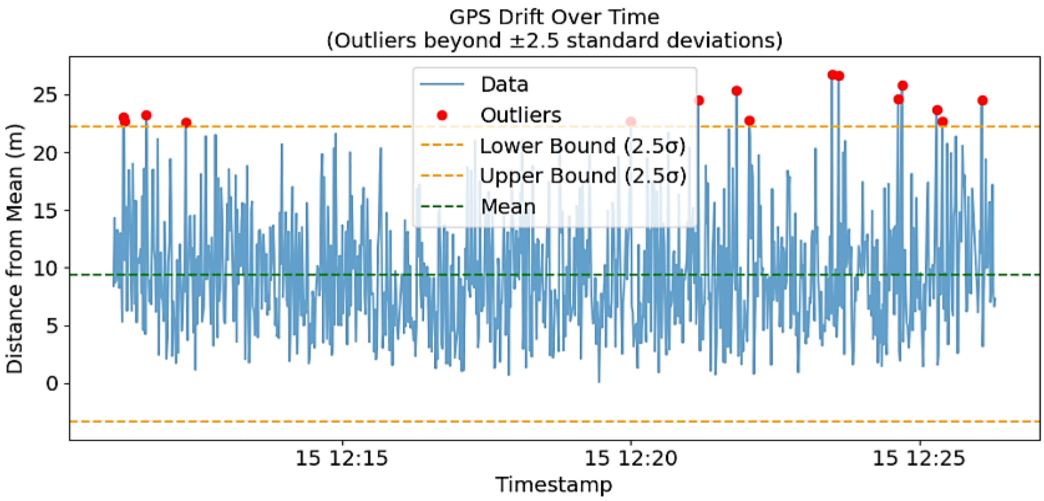


Fig. 3 *A stationery test of GPS drift from the mean location (green dashed line). The x-axis describes the time as HH:MM format, prefixed by the day of the month (e.g., 15 12:20 means 12:20 PM on the 15th). Outliers override the* $\mp \mathbf{2.5}$ *threshold (orange dashed lines) is marked in red. The sampling frequency is 1Hz*

Figure 4 shows a time series of speed (km/h) during the stationary period. The figure visually presents the speed outliers that exceed the $\mp \mathbf{2.5}$ threshold. A small number of speed spikes occurred in this stationary test, which is normal and does not affect the system performance. Most data points fall between the $\mp \mathbf{2.5}$ threshold, which validates the results of the proposed work.

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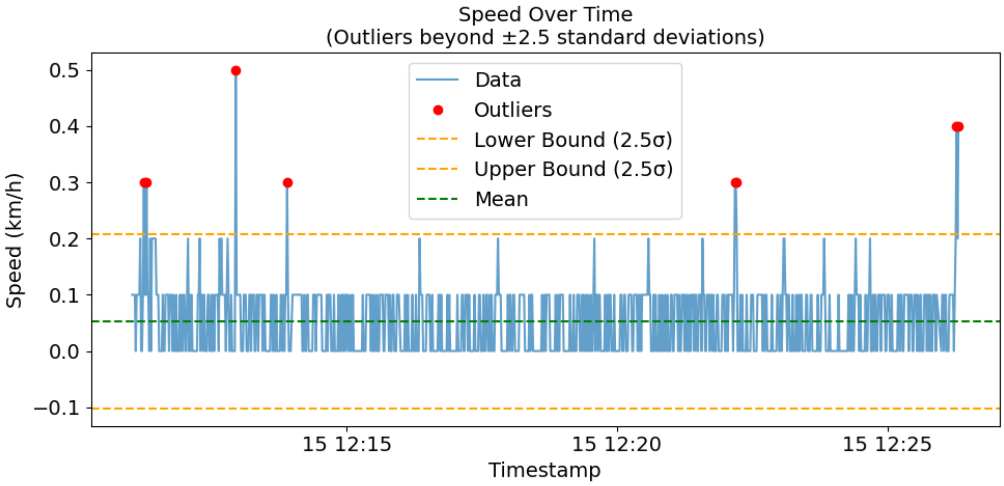


Fig. 4 *A stationery test of speed over time. The x-axis describes the time as HH:MM format, prefixed by the day of the month (e.g., 15 12:20 means 12:20 PM on the 15th). Outliers override the ∓2.5 threshold (orange dashed lines) are marked in red. The sampling frequency is 1 Hz*

Figure 5 shows a time series of temperature measurements during the stationary period. The figure shows no anomalies in the $\mp\mathbf{2.5}$ threshold, indicating that the sensor performance is stable and consistent throughout the observation period. The recorded temperature range was between 28 °C and 35.7 °C, with no unexpected drops or spikes. These findings prove the suitability of the sensor in the proposed work, as it does not require high-resolution thermal monitoring. Therefore, the stationary test implies that the system results are within feasible real-world tolerances and can be deployed for on-drive tests.

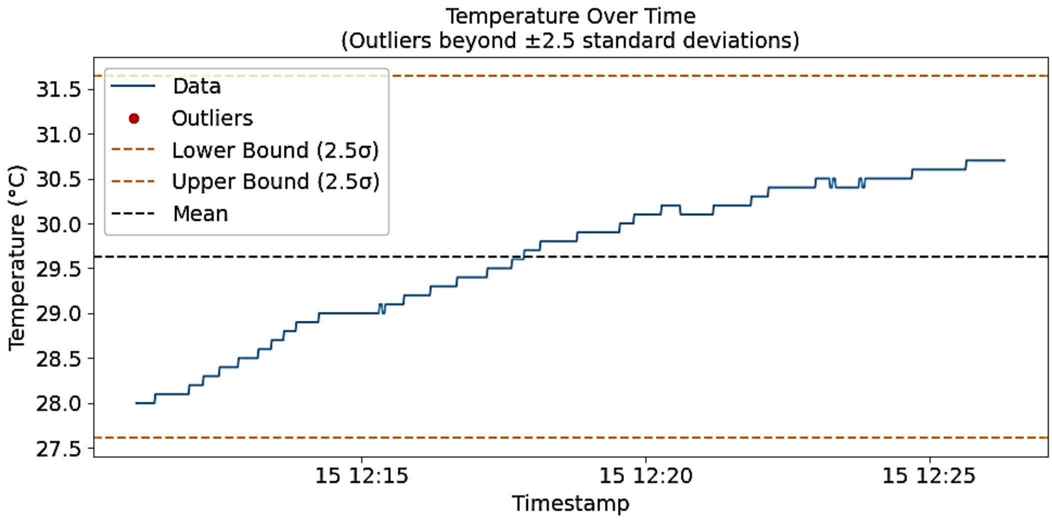


Fig. 5 *A stationery test of temperature over time. The x-axis describes the time as HH:MM format, prefixed by the day of the month (e.g., 15 12:20 means 12:20 PM on the 15th). No outliers observed in the* $\mp\mathbf{2.5}$ *threshold (orange dashed lines). The sampling frequency is 1Hz*

4.2 Effect of Alarm on Driving Behavior

Figures 6-8 belong to one trip out of the conducted trips. Figure 6 is a car trip route map generated by the Python Folium library using the acquired GPS coordinates. The route map indicates the start of the trip, end of trip, over-speed events that lasted < 10 seconds (without ticket), and tickets (>10 seconds). Figure 7 shows the speed of the car, which exceeded the limit (80 kmph) in three instances, one of which lasted for more than 10 seconds (a ticket). Figure 8 shows the car cabin temperature during that trip. The data shows that around 11:46, the temperature started to rise. This is due to the car being stationary at that time (Figure 7), which caused the AC to decline. Then the temperature began to drop when the car started to move again.

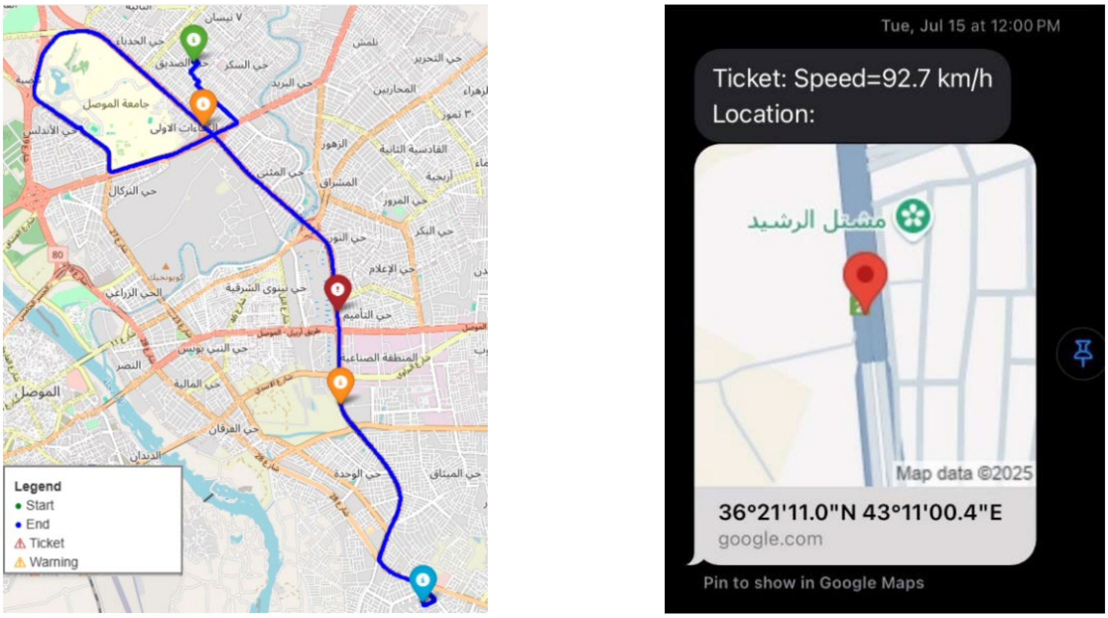


Fig. 6 *A-car trip route map generated by Folium library in Python, that map indicates the starting point of the trip, the end point, the over-speeding events without tickets (warnings) and the tickets. b- Ticket sent via GSM as an SMS indicating the speed and the location of the violation*

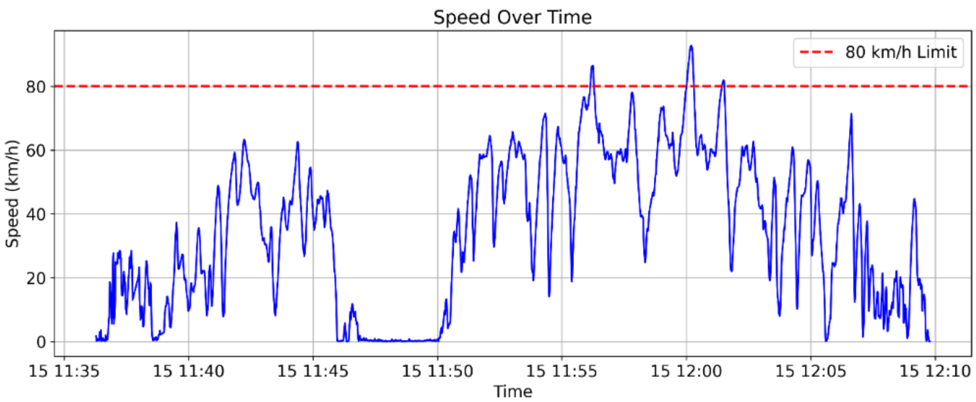


Fig. 7 *Speed over time of the trip*

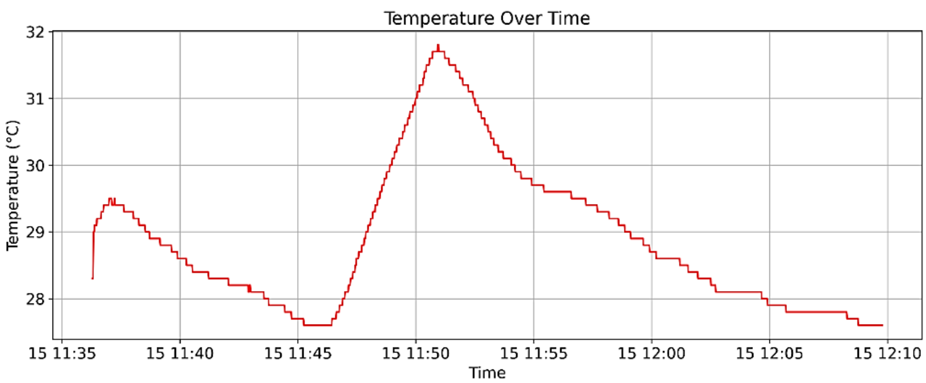
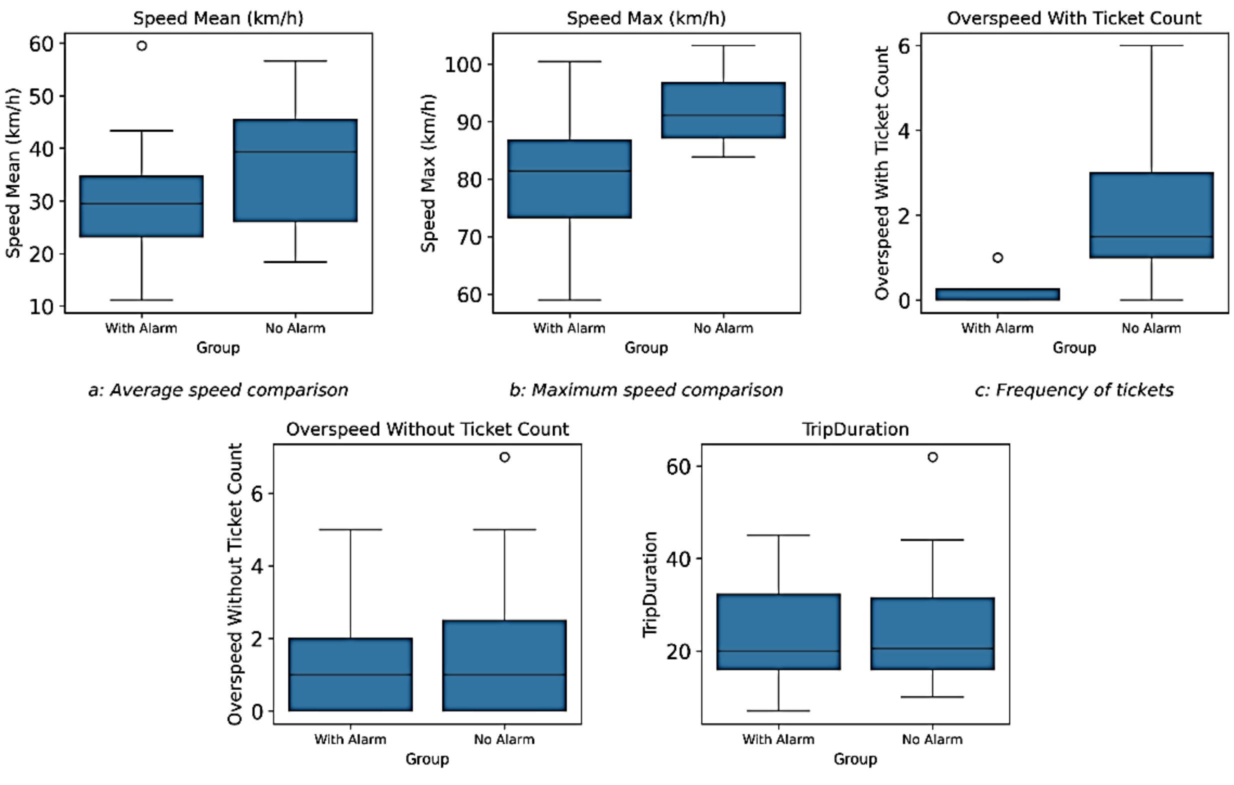


Fig. 8 *Time series of car's cabin temperature*

4.3 With-Alarm vs Without-Alarm Groups' Visualization

Figure 9 - (a) shows the mean speed (kmph) comparison between the with-alarm vs. without-alarm groups. The interquartile range is more compact for the with-alarm group, revealing steadier driving speeds. Conversely, the without alarm group has a wider spread with outliers, indicating that some drivers conducted much faster speeds. Thus, the alarm effect seems to have a substantial impact on average speed reduction and yields more consistent behavior. Figure 9 - (b) illustrates the maximum speed differences between the two groups. On average, the without-alarm group delivered a significantly higher maximum speed while the with-alarm speed drivers recorded lower speeds. Also, the without-alarm group showed frequent severe outliers. Consequently, the alarm probably contributed to lowering the high-risk peak speeds. On the other hand, the drivers in the with-alarm group showed lower average maximum speed. The reason might be the buzzer alarm; So, the driver hears the buzzer, lowers the speed, knowing that there is a chance of 10 seconds before getting a ticket. Figure 9 - (c) demonstrates the ticket count in each group. The drivers in the with-alarm group recorded 0-1 ticket, while the without-alarm group had drivers with up to 6 tickets. This is evidence that the alarm system had a precautionary effect on the drivers. Therefore, the buzzer alarm significantly reduces the overspeeding tickets (> 10 seconds). Figure 9 - (d) shows the overspeeds recorded without a ticket (< 10 seconds). The same distribution is shown in both groups (a few outliers in the without-alarm group). Considering the without-alarm group had no audible alarm, indicating that the speed limit was reached. Also, the with-alarm drivers know that they have a 10-second period to lower the car speed before getting a ticket. Thus, Alarm has a slight effect in reducing the without ticket overspeed violations. Figure 9 - (e) shows the car trip duration. The distribution is also similar in both groups, with almost identical average trip duration, indicating that the alarm system does not affect traffic flow when incorporated.



a: Average speed comparison *b: Maximum speed comparison* *c: Frequency of tickets*

d: Violations without tickets (<10 seconds) *e: Trip duration comparison*

Fig. 9 *Box plot visualization for different measurements taken with the alarm and without the alarm*

Figures 10 and 11 are the line plots and the metrics averages per driver. The purpose is for visual comparison between using the proposed system with the alarm and without it for each driver, to see the driving behavior change (if any) across the trips. The figures demonstrated that all drivers exhibited a significant decrease in ticketed speed violations. Additionally, three drivers out of the four reduced their average speed, overspeeding time percentile, and the number of warnings issued. On the other hand, driver-A showed an increase in the average speed and other metrics with the alarm, but the ticketed overspeedings were enormously reduced. This situation refers to the fact that the driver might have had a safer feeling knowing that there is a 10-second period to decelerate before being fined.

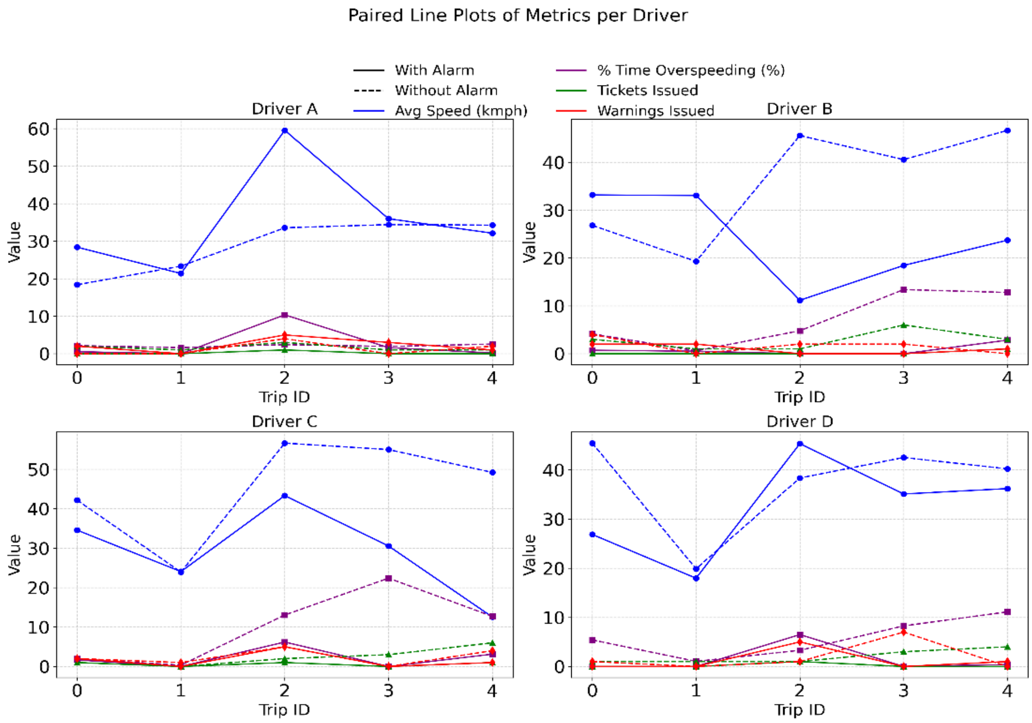


Fig. 10 *Comparison of metrics for each driver (5 trips with the alarm, and another 5 without the alarm)*

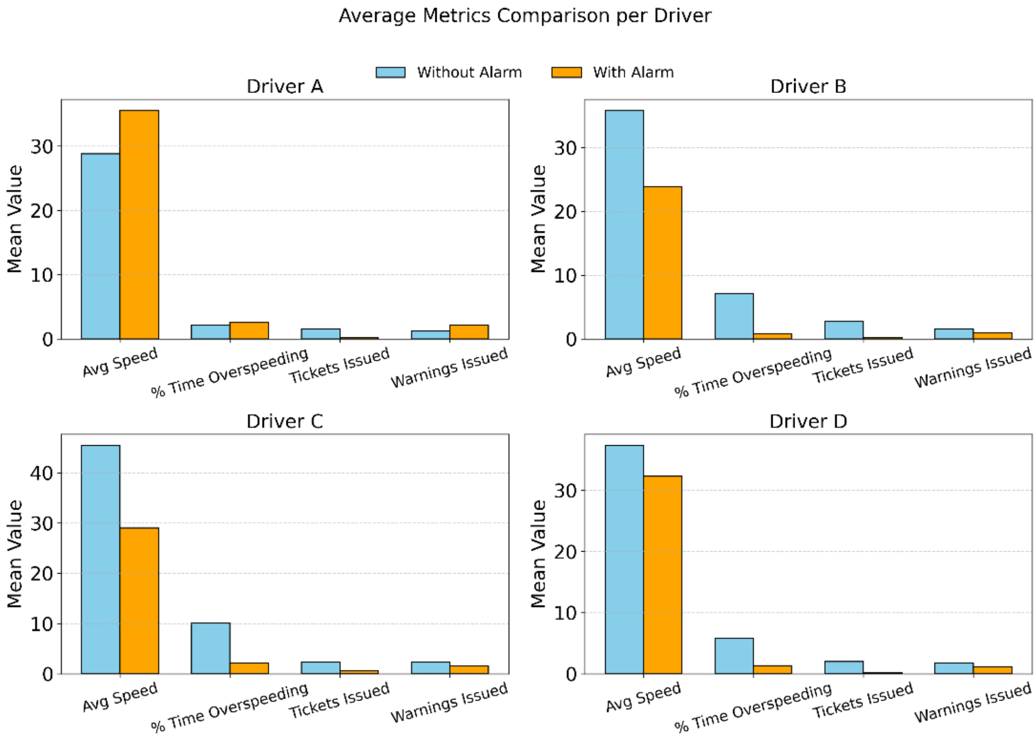


Fig. 11 *Average metrics comparison for each driver (5 trips with the alarm, and another 5 without the alarm)*

4.4 Statistical Analysis

Table 3 shows the statistical findings of the data collected, which are a comparison between the with-alarm and the without-alarm groups. Regarding speed analysis, the buzzer alarm led to significant speed subjugation as follows:

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Table 3 *Comparison of metrics between No Alarm and With-Alarm groups, statistical tests, p-values, and effect sizes. Significant p-values (p < 0.05) are highlighted in green, nonsignificant in red*

Metric	With-Alarm Mean	No Alarm Mean	With-Alarm No-Alarm Std	With-Alarm Max	No Alarm Max	With-Alarm Min	No Alarm Min	Test Used	P-value	Effect Size	Effect Type
Speed Mean (km/h)	29.1115	36.814	11.03517 11.7393	59.53	56.64	11.17	18.39	Welch's t-test	0.039035	-0.67609	Cohen's d
Speed Std (km/h)	21.4775	24.8795	3.050508 3.322123	26.05	31.37	15.03	19.74	Welch's t-test	0.001729	-1.06672	Cohen's d
Speed Max (km/h)	79.785	92	10.00922 5.769977	100.4	103.2	59	83.8	Welch's t-test	0.0000488	-1.49522	Cohen's d
Temp. Mean (°C)	35.2165	35.7695	7.594065 9.356797	50.02	54.11	26.39	23.22	Mann-Whitney U	1	0.5	Mann-Whitney r
Temp.Std (°C)	2.149	2.09	1.48649 1.686042	6.03	6.8	0.18	0.19	Mann-Whitney U	0.569964	0.55375	Mann-Whitney r
Overspeed With Ticket	0.25	2.2	0.444262 1.67332	1	6	0	0	Mann-Whitney U	0.0000024	40.0875	Mann-Whitney r
Overspeed Without Ticket	1.25	1.75	1.585294 2.048748	5	7	0	0	Mann-Whitney U	0.541992	0.445	Mann-Whitney r
Trip Duration (minutes)	23.05	24.3	10.24168 13.04688	45	62	7	10	Mann-Whitney U	0.892248	0.48625	Mann-Whitney r
Ticket Ratio	0.166667	0.556962						Chi-square =11.85409	0.000575	0.159091	Odds Ratio

- The Mean speed is reduced by 21% (with-alarm M=29.11 kmph, while without alarm M=36.81 kmph). Also, *t*(38) =-2.15 and *p*=.039 implies that the difference due to chance is unlikely. Finally, Cohen's *d*=-0.68 references that the effect is medium to large (the negative sign means that the alarm group has a lower speed).
- The variability of speed with alarm was lower by 14% (with-alarm M=21.48, without alarm M=24.88). The metric *p*=.002 implies that it is statistically highly significant and t(38) =-3.44 implies that the with-alarm group had lower variability. Furthermore, *d*=-1.07 reflects a substantial magnitude of effect according to conventional benchmarks.
- The maximum speed is reduced by 13% (with-alarm M=79.9 kmph, without alarm M=92 kmph). The metric ∗p∗ < .001 indicates it is more than 99.9% confident that it is not due to chance. Moreover, *d*=-1.5 implies a strong effect size.

Additionally, dangerous driving is enormously reduced by the buzzer alarm system as follows:

- Speed violations with a ticket (more than 10 seconds) were decreased by 89% (with-alarm M=0.25, without alarm M=2.2). The metric ∗p∗ < .001 indicates a high significance (probability of only 1 in 1000 that this reduction occurred due to chance). On the contrary, the metric *r*=0.087 refers to a small effect size, suggesting inconsistent enhancement across trips. Although the system efficiently prevented extreme violations (6 tickets decreased to 1), it may need improvement for general effectiveness.
- The ticket-to-warning ratio showed a significant improvement (the warning counts are the total over speed events that lasted less than 10 seconds), 16.7% with alarm and 55.7% without alarm.

On the other hand, temperature profiles are almost identical between the two groups, with all p > .05, indicating that there is no correlation between temperature and speeding. Similarly, trip durations between the two groups are similar, with no significant statistical metrics indicating that the alarm did not affect trip duration. In other words, the alarm improved the driving behavior without disrupting traffic flow.

Eventually, Chi-square is another test implemented to inspect the association between the issuance of tickets and the existence of the alarm system. It shows a statistically significant relationship (X^2 = 11.85, *p* = .000575), revealing that ticket issuance is different by the presence of the alarm system. An odd ratio of 0.159 is acquired, meaning that the with alarm group had about 84% lower odds of receiving a ticket in comparison with the no alarm group, so that the alarm system is significantly affects the ticket issuance.

5. Conclusions

The proposed work presents a speed monitoring system that offers a 10 second grace period, giving drivers a chance to decelerate before a ticket is issued. Results showed that the alarm system led to disciplined driving behavior, lower frequency of speed violations, and average speed reduction. On the other hand, the non-ticketed overspeeds (< 10 seconds) might be slightly ignored, given that no ticket is triggered. The system transfers the focus from making revenue from fines to encouraging safer driving practices.

Despite the small number of drivers involved in this study, the findings revealed potential as a practical tool to maintain driver compliance while enhancing road safety. Future research should investigate Long-term behavioral effects.

Acknowledgment

Many thanks to the drivers who volunteered to test the proposed system.

Conflict of interest

The authors declare no conflicts of interest in this paper.

Author contributions

Hakam Zaidan ***conducted the hardware and software of the system, wrote the methodology and results sections***. *Younis Al Rozz* ***managed a review of the technical content***. *Dheyaa Alhelal* ***wrote the introduction and literature review section***. *Emad Mohammed* ***made a strict review of the acquired results***. *Ibrahim Mujhid* ***drafted the manuscript preparation.*** *The final version of the manuscript was reviewed and approved by all authors.*

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