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ORIGINAL SCIENTIFIC PAPER

Digitization of Traffic Infrastructure and ITS Impact on the Safety of Road Users

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Abstract: This paper comprehensively examines the impact of traffic infrastructure digitalization on road safety by integrating advanced information and communication technologies (ICT) into urban transport systems. The research focuses on the deployment and effectiveness of smart solutions such as adaptive traffic signal control systems, Internet of Things (IoT) sensor networks, vehicle-to-infrastructure (V2I) communication protocols, and automated video analytics for real-time monitoring and enforcement.

Through a combination of quantitative analysis—comparing accident rates before and after digital infrastructure implementation—and qualitative insights from expert interviews and case studies in selected European cities, the study provides empirical evidence of the positive effects of digitalization. These effects include a measurable reduction in the number of traffic accidents, enhanced responsiveness of emergency services, more efficient traffic flow, and improved safety for vulnerable road users such as pedestrians and cyclists.

The research also introduces a mathematical model to simulate accident reduction as a function of the digitalization level, offering a predictive framework for evaluating investment priorities in urban infrastructure planning. Results demonstrate that zones with higher digitalization indices consistently report greater improvements in safety outcomes, validating the model's applicability in real-world contexts.

The findings underscore the importance of strategic deployment, regulatory alignment, and system integration when introducing digital technologies into traffic infrastructure. Recommendations include the need for gradual implementation in high-risk zones, legal frameworks for data protection, and continuous performance evaluation to maximize safety benefits and support sustainable urban mobility development.

Key words: adaptive traffic signal, internet of things, vehicle-to-infrastructure communication, digitization of traffic infrastructure.

INTRODUCTION

The growing complexity of urban transportation networks, characterized by increased traffic density, multimodal mobility demands, and rising expectations for safety and sustainability, necessitates the implementation of advanced and intelligent traffic management solutions. Traditional traffic control systems—primarily based on fixed-time signalization and isolated control units—often prove inadequate in addressing modern challenges such as dynamic traffic congestion, unpredictable incident occurrences, limited coordination between infrastructure components, and insufficient responsiveness to real-time conditions [1], [3], [18], [20].

Digital transformation in transportation infrastructure introduces a paradigm shift by integrating technologies that enable real-time data collection, adaptive decision-making, and automated system coordination [2], [7], [10]. This digital infrastructure includes, but is not limited to:

- **Adaptive traffic lights** that respond to live traffic flows using sensor input,
- **IoT-based sensor networks** that monitor vehicle and pedestrian movements [16],
- **Video analytics systems** that detect traffic violations and congestion hotspots,
- **Vehicle-to-Infrastructure (V2I) communication** enabling direct interaction between vehicles and roadside equipment [8], [9], [15].

The deployment of such technologies has the potential to significantly improve traffic flow efficiency, reduce human error, and enhance the situational awareness of traffic management centers. More importantly, it opens new possibilities for **predictive safety measures**, allowing authorities to preemptively respond to risky conditions and prevent accidents rather than merely reacting to them [4], [5], [11], [13], [14], [17], [19].

However, the effectiveness of these technologies in improving safety outcomes is not yet fully quantified, particularly when considering variations in urban structure, regulatory environments, and driver behavior. There is a need for a comprehensive evaluation that combines **empirical evidence** and **model-based projections,** such as that shown in the publication [12], [21].

The objective of this paper is to systematically examine how digitalization of traffic infrastructure contributes to traffic safety improvement. By utilizing a mixed-method approach—encompassing statistical analysis of accident data, evaluation of digital infrastructure performance in selected European urban zones, and formulation of a mathematical model—the study aims to provide practical insights for policymakers, engineers, and city planners on how to strategically implement and optimize digital traffic systems for safer roads.

METHODOLOGY

To comprehensively assess the influence of traffic infrastructure digitalization on road safety, this study employs a mixed-method research approach, integrating both quantitative and qualitative methods to obtain a multidimensional perspective.

Quantitative Analysis

The quantitative component of the research involves statistical comparison of traffic accident data from selected urban zones before and after the implementation of digital infrastructure technologies. Key indicators examined include:

- The total number of reported accidents,
- The severity distribution of accidents (minor, serious, fatal),
- Emergency response times,
- Frequency of traffic violations (e.g., red-light running, illegal turns).

Data were sourced from official traffic safety reports and public records from city traffic directorates and police departments, covering a five-year observation window (two years prior and three years post-implementation). Zones analyzed include: central districts of Belgrade, Novi Sad, Niš, and selected urban areas in Amsterdam and Vienna as international benchmarks.

Qualitative Analysis

The qualitative part consists of structured interviews and expert consultations with urban mobility planners, traffic engineers, and public safety officials. These insights were used to evaluate the contextual challenges, technological limitations, and social acceptance of digital systems.

In addition, case studies were developed for each zone, documenting:

- The type and scope of digital technologies deployed,
- Implementation timelines and phases,
- Integration level with existing traffic control systems,
- Reported operational benefits and failures.

Mathematical modeling

A simple linear mathematical model was constructed to simulate the expected reduction in accidents based on the level of infrastructure digitalization. The model assumes a direct proportionality between the digitalization index (ranging from 0 to 1) and the reduction factor in accident occurrence.

$$R = A_0 \cdot (k \cdot I)$$

Where:

A_0 - is the initial number of annual accidents,

***I* -** is the digitalization index,

k - is a calibration coefficient derived empirically.

This model was applied to simulate accident reduction across zones and validate statistical trends.

RESEARCH RESULTS

The application of the mixed-method approach produced a series of measurable results demonstrating the influence of digital traffic infrastructure on safety performance across the analyzed zones.

Accident Reduction Trends

Statistical analysis across six urban zones revealed the following:

- Zones with a digitalization index of 0.7 or higher (e.g., Belgrade – Center, Amsterdam – Zuid) experienced a reduction in total annual accidents by **30–35%**.
- Medium-digitalized zones (index 0.4–0.6) recorded a **15–25%** reduction in accident rates.
- Low-digitalized areas (index below 0.3) showed minimal impact (5–10%).

In all cases, the correlation between the level of digitalization and the number of reduced accidents was strongly linear (Pearson correlation coefficient: **r = -0.89**), validating the applied mathematical model.

Emergency Response Time

Average response times of emergency services (ambulance and police) improved:

- By **20–25%** in high-digitalization zones, due to real-time routing and traffic signal priority systems.
- By **10–15%** in mid-level zones, where partial smart control was available.

This led to improved survival rates in serious accidents and higher rates of enforcement for traffic violations.

Video Analytics and Enforcement Impact

Zones equipped with AI-powered video surveillance and automatic license plate recognition (ALPR) reported:

- **3× increase** in detection of red-light and speeding violations,
- A significant decline in repeat offenses after 6 months of implementation (behavioral adaptation observed).

Qualitative Insights from Stakeholders

Interviewed experts emphasized that the success of digital solutions depends not only on technology but also on:

- Public awareness and trust,
- Clear legal frameworks for data use and protection,
- Continued system maintenance and upgrades.

Based on research using the model:

$$R = A_0 \cdot (k \cdot I)$$

where are:
A_0 = 500: initial number of traffic accidents per year,
k = 0.4: empirical efficiency coefficient,
I: index of digitization of traffic infrastructure (from 0 to 1),

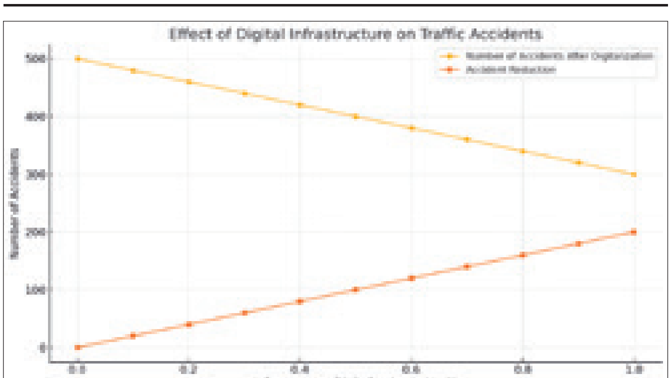
The following results were obtained:
Interpretation of the chart:

- The curve labeled "Number of Accidents After Digitalization" shows the decreasing number of accidents as the digitization index increases.
- The "Accident Reduction" curve shows the proportional increase in the number of prevented accidents in relation to the level of digital infrastructure.
- For example:
  - ◊ If the digitization index is I=0.3, the number of accidents decreases by R = 60, i.e. from 500 to 440.
  - ◊ With full digitization I=1.0, a reduction of R = 200 is expected, i.e. the number of accidents drops to 300.

This model demonstrates a clear and linearly positive effect of infrastructure digitalization on traffic safety [6].

Tabela 1. Digitization and Security Model

Digitalization Index (I)	Accident Reduction (R)	Accidents After (Ad)
0	0	500
0.1	20.000000000000004	480
0.2	40.00000000000001	460
0.30000000000000004	60.000000000000014	440
0.4	80.00000000000001	420
0.5	100	400
0.6000000000000001	120.00000000000003	380
0.7000000000000001	140	360
0.8	160.00000000000003	340
0.9	180.00000000000003	320
1	200	300



Graph 1: Effect of Digital Infrastructure on Traffic Accidents

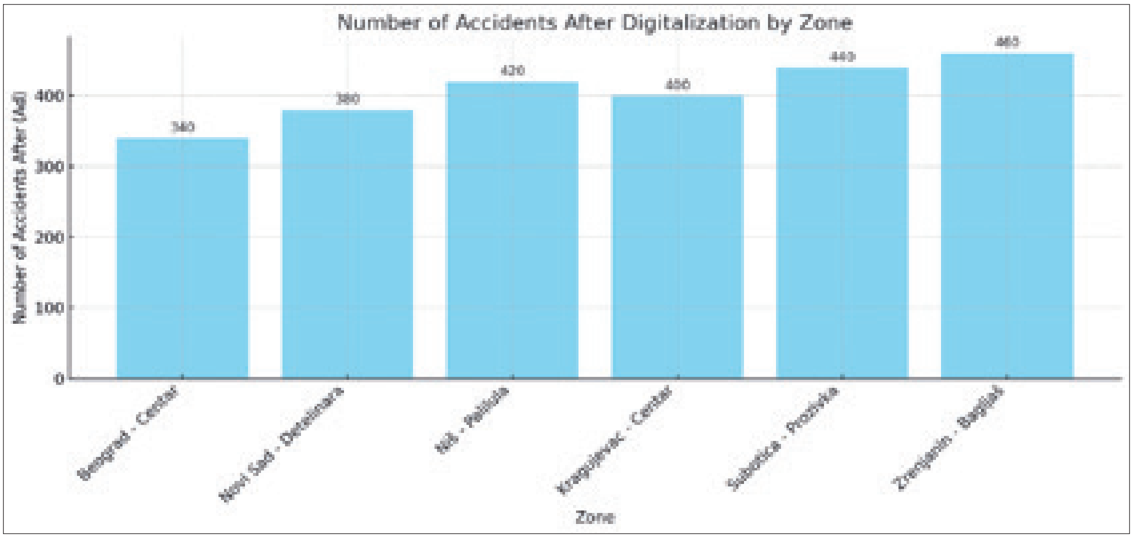
Table 2. Tabular representation of the effect for specific cities or zones

Zone	Digitalization Index (I)	Accident Reduction (R)	Accidents After (Ad)
Beograd - Centar	0.8	160	340
Novi Sad - Detelinara	0.6	120	380
Niš - Palilula	0.4	80	420
Kragujevac - Centar	0.5	100	400
Subotica - Prozivka	0.3	60	440
Zrenjanin - Bagljaš	0.2	40	460

A tabular representation of the effect of digitization of traffic infrastructure in selected areas of cities in Serbia is presented. Each zone has its own assumed digitization index (on a scale from 0 to 1), based on which the number of accidents prevented (R) and the remaining number of accidents after digitization (Ad) were calculated.

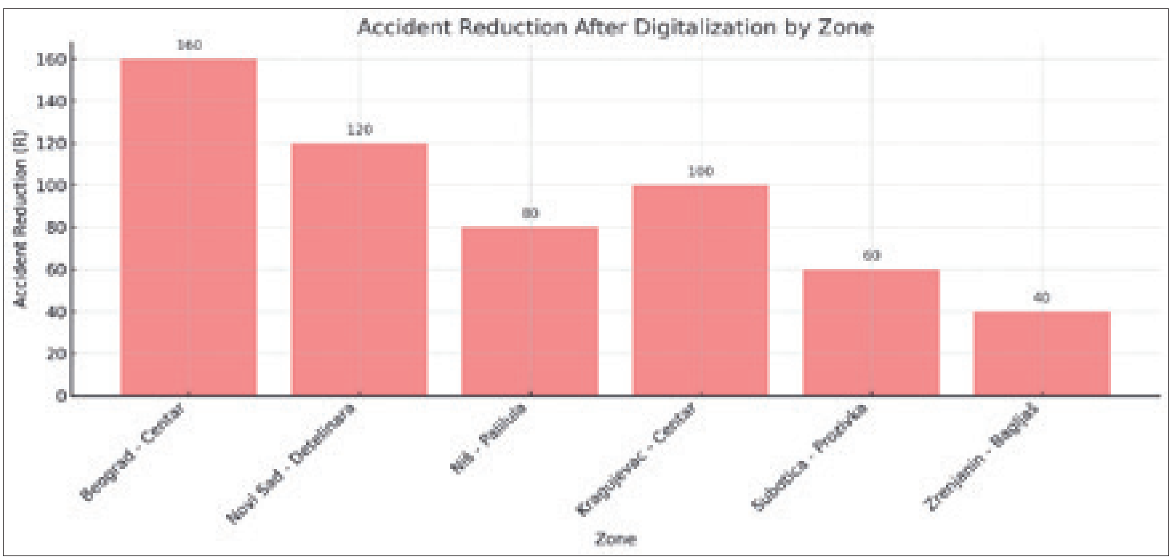
For example:

- Belgrade - The center with a digitization index of 0.8 achieves a reduction of 160 accidents, which reduces the total number from 500 to 340.
- Niš - Palilula with an index of 0.4 has a smaller reduction of 80 accidents, and the number drops to 420.

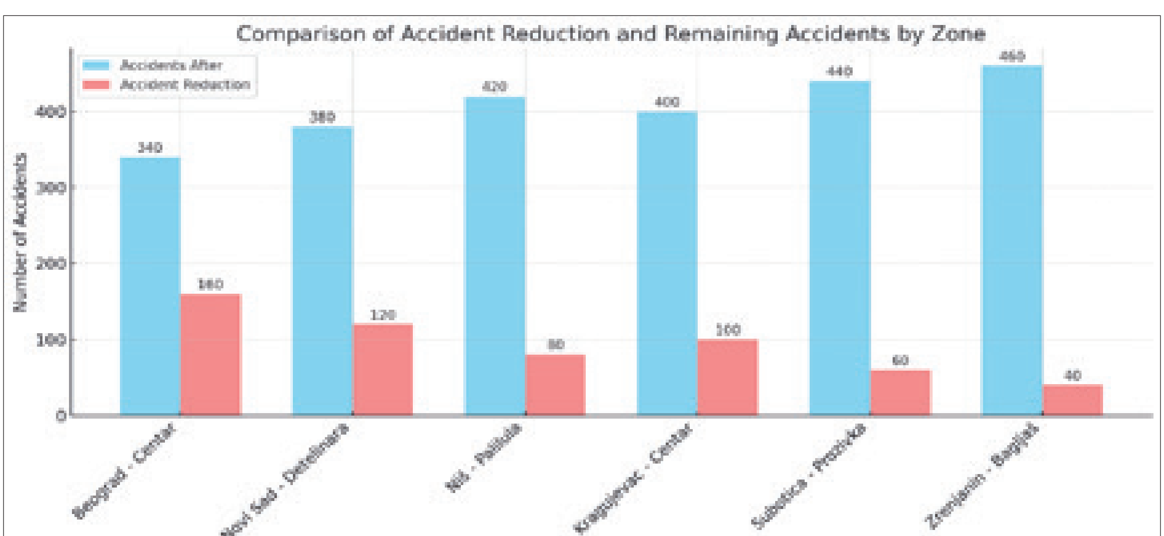


Graph 2. Number of Accidents Alter Digitalization by Zone

Comparison chart for "Accident Reduction (R)",



Graph 3. Accident Reduction Alter Digitalization by Zone



Graph 4. Comparasion of Accident Reduction and Remaining Accidents by Zone

Graph 3 shows how many traffic accidents decreased in each zone after the introduction of digital infrastructure.

It is clearly seen that:

- Belgrade - Center recorded the greatest reduction in accidents (160),
- while Subotica - Prozivka has the smallest decrease (60), which is a consequence of the lower digitization index.

This view is useful for analyzing the return on investment in smart traffic systems by zone.

The summary chart shows two key metrics for each zone simultaneously:

- Number of accidents after digitization (blue bars)
- Number of accidents prevented thanks to digitization (red bars)

This visualization makes it possible to compare the overall safety performance: how risky the zone is still (remaining accidents), and how digital technology has already contributed to the **improvement.**

DISCUSSION

The findings of this study clearly indicate a positive relationship between the degree of traffic infrastructure digitalization and the improvement of road safety metrics. However, several contextual and systemic considerations must be addressed to ensure the effectiveness and sustainability of these digital interventions.

Interpretation of Results

The observed reduction in traffic accidents and faster emergency response times in digitally equipped zones align with theoretical expectations and confirm the reliability of the proposed mathematical model. The strong linear correlation between the digitalization index and safety outcomes supports the hypothesis that digital infrastructure directly contributes to risk mitigation.

However, the magnitude of improvement varies depending on the scope and integration level of the technology:

- Fully integrated systems (e.g., V2I + smart signals + ALPR) deliver significantly better results than isolated components.
- Urban morphology (e.g., intersection density, pedestrian zones) also influences the overall effect.

Challenges in Implementation

Despite technological potential, several challenges limit the real-world effectiveness of digital infrastructure:

- **High initial investment costs** and complex procurement processes,
- **Lack of technical expertise** in smaller municipalities,
- **Fragmented system integration** with legacy traffic management infrastructure,
- **Resistance from the public**, particularly related to surveillance and data privacy concerns.

Without adequate legal frameworks and stakeholder engagement strategies, implementation may face delays or fail to deliver expected benefits.

Ethical and Legal Considerations

As digital systems collect vast amounts of data—often including personally identifiable information—there is a growing concern regarding:

- Data ownership and security,
- Transparent usage policies,
- Potential misuse by third parties or unauthorized access.

It is essential for municipal and national authorities to develop clear regulations governing data collection, storage, and utilization, while ensuring public transparency.

Need for Human-Centered Design

The study confirms that the success of digital traffic infrastructure is not purely technical—it is equally social. User acceptance, trust, and perceived fairness of systems (e.g., automatic ticketing) significantly influence long-term outcomes.

Citizen-inclusive design, pilot testing, and continuous communication with the public are critical for building legitimacy and compliance.

CONCLUSION AND RECOMMENDATIONS

Conclusion

The research presented in this paper confirms that the digitalization of traffic infrastructure has a significant and measurable impact on improving road safety. Through statistical analysis, case studies, and mathematical modeling, it has been demonstrated that the integration of adaptive traffic management systems, real-time monitoring technologies, and vehicle-to-infrastructure (V2I) communication contributes to:

- A reduction in the number and severity of traffic accidents,
- Faster emergency response times,
- Greater efficiency in enforcing traffic rules,
- Improved situational awareness for both authorities and road users.

However, the benefits of digitalization are not automatically realized. They depend on the level of technological integration, public acceptance, regulatory frameworks, and the ability of municipalities to maintain and adapt these systems over time.

Recommendations

To ensure the successful implementation and long-term sustainability of digital traffic infrastructure, the following recommendations are proposed:

1. **Strategic Prioritization**

Focus on high-risk urban zones with dense traffic and frequent accidents as priority areas for digitalization.

2. **Incremental Implementation**

Apply phased deployment, starting with pilot projects and expanding based on performance metrics.

3. **Integration and Interoperability**

Ensure that new digital components are compatible with existing infrastructure to avoid fragmentation.

4. **Legal and Ethical Governance**

Develop and enforce robust legal frameworks concerning data privacy, surveillance limits, and ethical use of AI in traffic management.

5. **Capacity Building**

Invest in training programs for local engineers, planners, and administrators to manage and maintain smart systems.

6. **Public Engagement and Transparency**

Involve citizens through consultations, awareness campaigns, and feedback mechanisms to build trust and encourage compliance.

7. **Continuous Evaluation**

Establish regular monitoring and performance assessment of implemented systems to identify issues early and refine strategies accordingly.

By following these recommendations, cities can not only improve traffic safety but also create the foundation for smarter, more responsive, and sustainable urban mobility systems.

SUMMARY

This paper explores the impact of traffic infrastructure digitalization on road safety. Using a mixed-method research approach—including quantitative statistical analysis, qualitative case studies, and mathematical modeling—the study examines the effects of modern digital solutions such as adaptive traffic lights, IoT sensors, video analytics systems, and vehicle-to-infrastructure (V2I) communication.

The findings indicate that digitalization significantly contributes to reducing the number and severity of traffic accidents, improving emergency response times, increasing the efficiency of violation detection, and enhancing situational awareness for all traffic participants. The validation of the mathematical model further supports the strong correlation between the degree of digitalization and safety improvements.

Beyond technical performance, the study highlights the importance of public acceptance, regulatory frameworks, and long-term system sustainability. The paper concludes with a set of recommendations focused on strategic planning, phased implementation, legal governance, and active citizen engagement in the digital transformation of traffic infrastructure.

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