EXAMINATION OF REGIONAL CONNECTIONS BETWEEN SMART TRANSPORT SAFETY SYSTEMS

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Abstract. The landscape of transport safety systems is highly complex and rapidly evolving, with technological advances driving daily innovations that continually shape the urban environment and the transport network. Rising traffic, environmental impacts, and safety concerns collectively underscore the urgent need to develop conscious and intelligent traffic management systems. Technological trends aimed at promoting environmentally conscious transport and preventing accidents are increasingly integrated, affecting various applications of IoT, artificial intelligence, 5G, and BIGDATA systems. Innovative solutions enable real-time traffic monitoring, forecasting, and dynamic interventions, comprehensively improving safety and reducing environmental impact. This not only makes transport infrastructure more efficient but also opens new opportunities for community development and improved quality of life. The primary objective of our study is to examine how research and development in transport safety systems influence the potential of SmartCity concepts and their regional impact. By analyzing collected databases and empirical developments, we demonstrate how effective transport strategies can influence management systems. We analyze the connections and strategic directions of regional traffic safety systems and the modernization and development of road infrastructure. Based on this, we make recommendations for the technical development of traffic safety systems.

Keywords: traffic safety, transport infrastructure, spatial transport systems, SMART transport.

Introduction

SMART transportation systems encompass integrated, intelligent infrastructure solutions designed to enhance the efficiency, safety, and sustainability of transportation. Thanks to modern technological advancements, these systems can collect, process, and interpret large amounts of data, thereby responding dynamically to changes in traffic conditions. SMART transportation systems are based on innovative data processing and communication architectures that enable the integration of vehicle- and infrastructure-controlled solutions, optimized route selection, and an enhanced user experience [1].

One of the most important components of such systems is data collection, which continuously records the location, speed, environmental conditions, and traffic events of vehicles using various sensors and measuring devices. This data serves as the basis for decision-support systems, which analyze the current situation and make predictions to ensure smooth operation of traffic flows. The transportation infrastructure is closely interconnected with communication networks, which ensure fast and reliable data transmission for all involved parties. This enables real-time information sharing between vehicles and infrastructure, which is essential for precise and safe automated control. With the help of automated control systems and vehicle management mechanisms, the system continuously optimizes traffic processes, for example, by improving traffic flow, reducing congestion, and lowering the risk of traffic accidents [2].

It is clear from all of this that establishing appropriate regulatory and ethical frameworks – which provide guidance in the areas of data protection, security, and data management – is of paramount importance and indispensable in today’s transportation development. These components, building upon one another, form the complex, dynamic system that enables more sustainable and intelligent transportation operations, while simultaneously taking into account economic, social, and environmental considerations, and, above all, significantly contributes to the development of safe transportation and the protection of life.

Development of intelligent transportation systems

The development of intelligent transportation systems began in the second half of the 20th century, when rapid advances in information and communication technologies enabled smarter infrastructure. Initially, efforts to address urban transportation problems focused on fixed sensors and simple data management systems. The first integrated systems emerged in the 1990s, using collected data to develop more efficient management strategies. In the following decade, the spread of the Internet technologies

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further increased connectivity, enabling real-time data transmission and processing, thereby enhancing the speed of these systems [2].

Today, the emergence of autonomous vehicles and artificial intelligence has significantly accelerated the development of intelligent transportation systems, enabling dynamic adaptation and complex decision-making. This progress is closely intertwined with the continuous advancement of sensor and communication technologies, which form the foundation for the system's data collection and analysis. In addition, standardized communication protocols and cloud-based services now ensure interoperability and scalability, thereby enabling widespread implementation. Research on the topic clearly demonstrates that the development of intelligent transportation systems requires continuous innovation and integration, while also facing significant challenges, such as data protection and system security, the resolution of which is essential for sustainable and reliable operation. It can be concluded that the main components and the foundation of the architecture are based on the interaction of complex system elements, which are typically characterized by a modular structure [3; 4].

In 2025, there were a total of 14,688 road traffic accidents resulting in personal injury in Hungary, an increase of 1.6% compared to the previous year. The number of fatal accidents (446) was 1.8% higher, the number of accidents resulting in minor injuries (10,099) was 2.7% higher, and the number of accidents resulting in serious injuries (4,143) was 0.9% lower than in 2024. The number of accidents caused by drunk driving decreased by 19% to 844, meaning that alcohol was a factor in 5.7% of all road traffic accidents. Passenger cars accounted for 66% of all accidents, while bicycles and motorcycles accounted for 8.4% and 4.1%, respectively. The overwhelming majority of accidents, 94%, were caused by driver error, typically due to failure to yield the right of way (35% of all accidents), inappropriate speed (27%), and violations of rules regarding driving and turning (17%). About six out of ten accidents caused by these factors occurred between May and October 2024. These trends further underscore the need for rapid, widespread adoption of smart systems [5].

As the number of vehicles has increased, several indicators have begun to change. The table below illustrates the direction of these changes.

Table 1

Causes of traffic accidents [5]

Indicator	Direction of change	Main causes
Fatal accidents	Significant decrease	ADAS systems, passive safety
Accidents caused by drunk driving	Sharp decrease	Stricter smart enforcement (VÉDA), zero tolerance
Total number of accidents	Stagnation/Slight increase	Increase in the number of vehicles, rise of e-mobility devices
Highway accidents	Slight increase	Higher speeds, distractions (smartphones)

According to numerous international studies [6], there is a significant correlation between the number of accidents and engine power, with cars equipped with powerful engines being involved in accidents more frequently. In the analysis, based on vehicle history reports from 43 different car brands, 46,4 percent of Audi vehicles with engine power below 100 kW (136 hp) were involved in accidents, while for models with engine power above 400 kW (536 hp), this rate was 55,6 percent. Ford, Volkswagen, and BMW showed a similar pattern, with accident rates significantly higher for cars with more powerful engines. Among all vehicle brands analyzed in the study, BMW stood out significantly, with 60,3 percent of cars under 100 kW sustaining damage, compared to a 68,6 percent accident rate for vehicles in the over 400 kW category (Table 2).

The evolution of this infrastructure has had a decisive impact on our current level of development. The first key component was data collection and sensor networks, which today encompass various sensors, cameras, radars, and information sources. These devices continuously collect data on vehicle locations, traffic conditions, weather, and other relevant environmental factors. The collected information is essential for decision-support processes, which use data-driven methods to interpret, model, and optimize traffic situations. As a result, wired and wireless networks, communication protocols, and tools that ensure synergy between vehicles and central systems have been developed and integrated into the system. These tools have become indispensable for real-time information flow and synchronized operation. Based on all of this, it can be concluded that automated control and vehicle navigation now involve autonomous decisions and actions based on sensor data, enabling vehicles to respond intelligently to changing conditions. Control algorithms, cloud-based processing units, and vehicle-to-vehicle communications already reliably ensure precise and rapid travel processes; thus, through user interfaces and participation mechanisms, the systems enable users to engage in multi-step control. Based on this, data collection and sensor networks play a fundamental role in the operation of intelligent transportation systems, as they provide real-time, accurate data on the state of the transportation environment [7].

Table 2

Relationship between engine power and accident frequency, percentual share of cars with accident history is shown [6]

Vehicle brand	**Engine power, kW**				
	0-100	**100-200**	**200-300**	**300-400**	**400-**
Alfa Romeo	20.3	21.1	22.7	25.7	28.8
Audi	46.4	47.9	50.5	53.0	55.6
Bentley	–	–	49.5	52.0	43.5
BMW	60.3	61.8	64.0	66.3	68.6
Cadillac		36.9	39.2	40.6	44.2
Chevrolet	35.7	36.6	40.2	42.3	45.7
Chrysler	39.2	40.4	42.8	45.2	–
Citroen	37.1	38.2	–	–	–
Dacia	49.0	50.2	–	–	–
Dodge	30.7	31.2	34.2	36.8	41.0
DS	41.6	42.7	44.9	–	–
Fiat	21.8	22.7	24.5	–	–
Ford	45.0	46.3	48.7	51.5	55.0
Honda	47.3	48.3	51.4	54.3	–
Hyundai	54.8	55.9	58.1	–	–
Infiniti	53.4	54.7	57.3	–	–
Jaguar	42.3	43.6	46.2	49.0	50.8
Jeep	21.9	23.0	24.5	26.9	30.3
Kia	42.3	43.4	47.0	–	–
Lancia	13.0	13.8	–	–	–
Land Rover	38.2	39.8	42.1	45.8	46.8
Lexus	39.6	41.5	43.9	46.4	–
Maserati		43.6	44.9	47.2	49.8
Mazda	41.3	42.5	44.7	–	–
Mercedes-Benz	33.6	34.9	37.6	40.1	42.3
MINI	51.5	52.9	55.4	–	–
Mitsubishi	49.5	50.5	53.0	–	–
Nissan	36.1	37.5	40.3	43.2	44.8
Opel	42.4	43.3	46.4	–	–
Peugeot	33.4	34.4	37.0	–	–
Porsche	–	40.1	42.0	44.2	46.4
Renault	36.3	37.6	39.7	–	–
SAAB	32.5	33.5	35.5	–	–
Seat	44.7	45.9	48.5	–	–
Skoda	51.3	52.5	54.8	–	–
Smart	19.4	20.6	–	–	–
SsangYong	45.1	45.9	–	–	–
Subaru	43.2	44.5	46.8	–	–
Suzuki	50.7	51.1	–	–	–
Tesla	–	53.6	55.6	58.3	62.0
Toyota	36.0	37.1	39.5	–	–
Volkswagen	42.6	43.9	46.4	48.9	–
Volvo	35.4	36.6	39.1	41.9	–

In addition to deploying sensor networks, data management has also become essential. This now encompasses data collection, storage, preprocessing, and analysis, during which the necessary information is extracted using various algorithms and artificial intelligence. This data processing enables the system to respond quickly to real-time events, such as automatically directing traffic or alerting users. Based on all this, it can be said that the sophisticated operation of sensor networks and the integration of data have become indispensable to the success of modern intelligent transportation systems, as they ensure dynamic and adaptive operation. Advanced data collection technologies thus enable the early detection of problems, their prevention when necessary, and more efficient traffic management, contributing to a safer, more sustainable, and more comfortable transportation environment.

Communication infrastructure and related devices

Communication infrastructure and devices play a fundamental role in the operation of SMART transportation systems, enabling data flow and connectivity between individual components. This includes state-of-the-art wired and wireless networks, such as fiber-optic, mobile (4G, 5G) and Wi-Fi networks, as well as V2X (vehicle-to-everything) technologies for communication between sensors and vehicles, traditional communication switching and addressing systems found in telecommunications equipment, and intelligent network protocols that ensure fast and secure flow of data. Of course, we must not forget mobile towers, routers, central data transmission units, IoT devices, and the unified standards and protocols (such as MQTT or DDS) required for connectivity, which enable efficient and secure sharing of data and connect vehicles with other elements of the infrastructure [8-10].

Based on this, vehicle management systems can be broken down into several levels:

- at the first levels, simpler, automated functions are implemented, such as speed control, adaptive cruise control, or lane departure prevention (**active safety**);
- at higher levels, automation handles complex decision-making processes that use biometric sensors to take into account the traffic environment, weather conditions, driver fatigue, inattention, or traffic congestion (**driver condition monitoring**).

These studies have found that smart devices installed along roads (RSUs-Roadside Units) and a central control system together form the brain of the system. Based on this, the system can be organized as follows [11-13].

- **Edge Computing:** low-latency data processing on-site for rapid decision-making.
- **AI Prediction:** forecasting accident hotspots and organizing traffic control based on historical data.
- **Digital Twin:** real-time simulation of urban traffic for risk analysis.

Materials and methods

In our study, we examined datasets on traffic conditions related to transportation development over the past decade and conducted a comparative analysis of these databases. The data used for the statistical analysis were provided to us by the Central Statistical Office. Building on methods used in the relevant literature, our analysis examined the regional relationships between SMART developments and traffic accidents, and, based on this analysis, we made recommendations for the future directions of sustainable transportation development. In our study, primarily:

- we analyzed domestic and international economic data and their forecasts at NUTS 3 and 4 levels, taking into account that, according to the Williamson-Kuznets hypothesis, as economic development increases, growing regional disparities begin to level off beyond a certain point;
- we conducted our demographic forecast based on the latest 2022 census data, broken down by age group and differentiated by region;
- we developed the motorization forecast by taking into account basic settlement statistics and using basic motorization development curves.

Results and discussion

In response to changes in the social and economic environment, several sector-specific strategic documents have been developed in Hungary, all of which prioritize modernizing transportation infrastructure and promoting sustainable transportation. These strategies primarily focus on strengthening north-south corridors, as Hungary joined the Baltic Sea – Adriatic Sea, Western Balkans – Eastern Mediterranean, and the Baltic Sea – Black Sea – Aegean Sea European transport corridors in 2024. The growing importance of east-west transport routes raises serious capacity issues, primarily in freight transport. As a result, it has become necessary to launch domestic projects to address current capacity shortages. The coordinated management of cross-border mobility needs remains an unresolved issue in cooperation efforts, necessitating the creation of additional management and development tools. Consequently, the sustainable development of transport safety has come to the forefront among development objectives.

Differences in the regional dimension examined showed a significant correlation with induced risk. Our findings clearly demonstrated the **Peltzman effect**, which forms the basis of the theory of risk compensation. Based on this theory, our findings indicate a correlation with the urban/rural divide: while SMART developments in cities can reduce the number of collisions and pedestrian accidents, on rural roads, an increased sense of safety can paradoxically lead to speeding.

With regard to Hungary, the analysis of SMART traffic safety systems has reached a new level by 2026: the focus has shifted from Budapest-centric approach toward Trans-European Transport Networks (TEN-T) and smart regions. Due to Hungary's geopolitical position, the safe management of transit traffic is a primary strategic interest. Based on all this, our analysis examined not a single city but the interconnections among domestic regional areas during the regional study. Expressway connections exist only between the major hubs of the outer urban ring and Budapest. Elements of the TEN-T network carry the decisive share of traffic volume; at the same time, it can be observed that, in the case of public roads, the secondary network serving these areas is also heavily burdened by long-distance heavy traffic.

Based on our research, it can be concluded that the road network in Hungary has a Budapest-centric, fundamentally radial structure, supplemented by border-oriented elements in accordance with the requirements of network integration. Based on our analyses, it can be concluded that the interrelationships and network of connections between the traffic flow, accident response times, and the cross-border mobility system are crucial for the future of sustainable transport development (Table 3).

Table 3

Regional network, impact and solution [9]

Criterion	Regional impact	SMART solution
Traffic flow	Urban traffic congestion affects the metropolitan area.	Regional, cloud-based traffic management.
Response time to accidents	Response times may be slower on rural roads.	eCall systems and automatic route planning for emergency responders.
Cross-border mobility	Different technological standards between neighboring regions.	Harmonized EU ITS protocols (e.g., the CROCODILE project).

The forecast of transportation demand, based on our analyzed database, was conducted in light of the expected trends in factors influencing the traffic demand (economic growth, population changes, fluctuations in energy prices, etc.). Based on this, we determined that demographic projections for passenger transport indicate a decline and aging of the population that can only be partially offset by the increase in individual mobility resulting from economic growth; thus, the development of smart transportation systems has become a critical task. Our study highlights that there is significant asymmetry among Hungarian regions in the area of digital infrastructure; thus, reducing the regional divide is a priority task in terms of SMART readiness (Table 4).

Table 4

Regional differences and the digital divide [8]

Region type	SMART readiness	Primary security focus
Central Hungary	High	Traffic calming, pedestrian safety (smart crosswalks), micro-mobility safety.
Western Transdanubia	Outstanding	Cross-border (Austrian-Hungarian) data exchange, integration of autonomous vehicles.
Eastern Hungary	Improving	Improving safety at intersections, SMART systems to prevent wildlife collisions.

Based on the above, it can be concluded that Hungary's sustainable transport future is closely linked to the European Union's transport policy objectives, which increasingly emphasize the use of low- and zero-emission vehicles, as well as renewable and low-carbon fuels, in road, rail, water, and air transport. Domestic transport policy must promote the development of environmentally friendly technologies, sustainable services, and innovation (R + D + I) in line with these objectives, particularly in the areas of vehicle manufacturing, the production of alternative fuels, and the development of the necessary infrastructure. At the same time, reducing emissions alone is not enough.

It is essential to promote a shift in transportation modes: rail, public transit, cycling, and walking must be prioritized over private vehicle use. Making everyday mobility more sustainable, especially in large cities and metropolitan areas, helps reduce air and noise pollution and traffic congestion while improving quality of life and supporting climate protection goals. During the sector's transformation, the land-use requirements of transport systems and the environmental impacts of transport modes throughout their life cycle must be taken into account. It is important that developments be coordinated with other sectors, particularly urban planning, energy management, and environmental protection, to promote the circular economy, protect biodiversity, and integrate green infrastructure [13]. Creating the conditions for sustainable transportation in Hungary is essential not only from an environmental perspective but also from economic and social standpoints.

Conclusions

1. Based on the results of our research, it can be concluded that **digitalization** has become an indispensable driving force behind the modernization of the entire transportation system, making it smoother and more efficient.
2. Based on our research, we have found that the strongest correlation occurs when a region allocates its GDP surplus to SMART developments. Wealth alone is not enough if it is coupled with aging infrastructure or uncontrolled speeds. Achieving "Vision Zero" (zero fatal accidents) is practically impossible without technological density given modern traffic volumes.
3. Taking into account the development of traffic safety systems along international transport corridors, it can be concluded that Europe - and within it, the regions of Central and Eastern Europe - must integrate digitalization and **transport automation** to further enhance safety, protection, reliability, and comfort, while also improving global competitiveness within the framework of efficient logistics chains.
4. Based on the above, it can be stated that the main **related developments** lie in intelligent transportation systems (ITS), real-time data collection and sharing, the development of new technologies and services, the development of smart infrastructure, the potential of artificial intelligence, integrated digital ticketing and payment systems, vehicle-to-vehicle communication in self-driving and automated vehicle systems, the development of cybersecurity and data security, blockchain logistics, and digital twins and simulation.

Author contributions

Conceptualization, L.B. Cs.T. and K.J.; Data collection and Methodology, L.B.; Formal analysis, K.J. Cs.T.; Investigation, L.B. Cs.T. and K.J.; Writing-review and editing, K.J. Cs.T.; Visualization, L.B. All authors have read and agreed to the published version of the manuscript.

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