TRANSFORMATION OF CONVENTIONAL ROAD INFRASTRUCTURE INTO INTELLIGENT ROADS –TECHNOLOGICAL FRAMEWORK AND FUNCTIONALITIES

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Abstract

This paper explores the transformation of conventional road infrastructure into intelligent roadways through the lens of integrating modern information, communication, and cybernetic systems. The research focuses on the technological framework of Intelligent Transport Systems (ITS), structured through data acquisition layers, communication protocols, and centralized management. Key functionalities are analyzed in depth, ranging from advanced traffic flow analytics and automatic incident detection to dynamic user information systems. The study evaluates the multidisciplinary benefits of implementation, emphasizing economic efficiency through congestion mitigation, environmental sustainability via reduced greenhouse gas emissions, and the primary safety imperative directed toward achieving the "Vision Zero" strategy. Special emphasis is placed on regulatory harmonization with Directive 2010/40/EU and the Transport Strategy of the Federation of Bosnia and Herzegovina, defining the perspectives for the development of cooperative systems within the domestic road network. In conclusion, intelligent roadways are recognized as an essential foundation for creating a safer and more economically efficient transport ecosystem, where the synergy between driver, vehicle, and infrastructure redefines modern mobility.

1. INTRODUCTION

Road infrastructure, in the form we know it within the framework of contemporary engineering, is currently at a critical turning point of a complex evolutionary process that will fundamentally redefine its foundational function, architecture, and operational significance in modern society. Future development, design, and exploitation of roadways can no longer be viewed partially and exclusively through the traditional prism of construction expansion, asphalt works, and the physical expansion of the geometric parameters of the road network. The contemporary approach primarily implies a deep, multidimensional transformation of the entire transport system through the systemic integration of advanced information, communication, sensor, and cybernetic (ICT) technologies. In parallel with the process of designing new capacities, a key challenge and strategic priority is the systemic, phased upgrade and reconstruction of the existing, conventional road network. Due to pronounced technological obsolescence, a chronic deficit of modern control components, and inadequate throughput capacity, the existing infrastructure very often generates permanent bottlenecks and congestion. This directly causes a drastic drop in efficiency within modern transport and logistical flows, prolonged travel times, and a progressive increase in the total external and operational costs of transport entities, while simultaneously compromising the ecological integrity and the level of safety of the traffic system.

The purpose of this paper is reflected in a detailed theoretical deconstruction, systematic analysis, and scientific valorization of the complex concept of an intelligent roadway ("smart road"), along with a comprehensive critical review of contemporary engineering solutions and sophisticated execution methodologies that form the operational backbone of this system.

A special scientific and engineering emphasis will be placed on establishing an interoperable, real-time connection within the triangle formed by the three fundamental pillars of contemporary traffic: the driver as the cognitive decision-making center, the vehicle as the advanced technological subject, and the roadway as the intelligent infrastructural environment. This research aims to explain how such a synergy, supported by cooperative communication systems, can transform traffic from a reactive into a proactive system capable of predicting incidents, optimizing throughput, and minimizing ecological degradation, thereby directly contributing to the global goals of sustainable mobility.

2. TECHNOLOGICAL FRAMEWORK AND FUNCTIONALITIES OF INTELLIGENT ROADWAYS

In contemporary science and traffic engineering, an intelligent roadway is defined as a complex, highly integrated cyber-physical system in which conventional, static road infrastructure is systematically upgraded and infused with advanced information, telecommunication, and computing techniques. The primary goal of this technological synergy is reflected in the radical transformation of a classical, passive infrastructural object into an intelligent and highly dynamic environment. These operations primarily encompass real-time collection, processing, and distribution of critical information to end users, proactive and adaptive management of traffic flow capacity and speeds, as well as the complete automation of safety and emergency protocols. The aforementioned processes are realized through the implementation of specialized software applications, computational decision-making algorithms, and robust control subsystems, which directly minimize the possibility of human error, optimize the throughput capacity of the roadway, and raise the level of service to its technological maximum. The backbone of an intelligent roadway consists of the ITS (Intelligent Transportation System) information system, which can be divided into three key hierarchical levels.:

Data Acquisition Layer,

This segment of the intelligent roadway architecture encompasses a complex, highly distributed network of advanced peripheral units and authoritative hardware components, whose primary role is the permanent and non-invasive acquisition of data from the field. This sophisticated technological layer integrates a wide range of elements, including:

Piezoelectric and ultrasonic sensors,

Underground inductive loops for electromagnetic detection,

Microwave and radar speed and dimension detectors,

High-frequency LiDAR (Light Detection and Ranging) systems for precise 3D environmental scanning,

Multispectral and high-resolution cameras equipped with advanced ANPR (Automatic Number Plate Recognition) algorithms.

The aforementioned measuring and detection components perform fully automated and continuous real-time data collection on all relevant parameters of the traffic flow, primarily concerning current traffic volume (intensity), flow density, space mean speed, as well as vehicle classification and structure within traffic lanes. Parallel to traffic parameters, this network of peripheral units conducts constant monitoring and exact evaluation of the physical-mechanical condition of the pavement surface itself (detection of black ice, moisture levels, presence of water, or macro-damage), as well as microclimatic and meteorological conditions in the immediate environment of the roadway (visibility, wind gusts, air temperature, and precipitation). This creates a robust and reliable information base necessary for making strategic and operational control decisions within the broader intelligent transportation system.

Communication Subsystem,

This component of the intelligent roadway architecture represents a critical, bidirectional communication channel designed for continuous and ultra-reliable exchange of structured data between end users (encompassing conventional vehicles, autonomous transport entities, and the drivers themselves) and the central control system of the traffic network. The aforementioned communication subsystem is designed on the principles of high redundancy and utilizes robust, standardized telecommunication protocols adapted for operation in extreme and dynamic environmental conditions. Depending on the network topology and operational requirements, this layer employs advanced hybrid solutions that integrate fixed and mobile technologies:

High-capacity wired backbone infrastructure (primarily single-mode fiber-optic networks), which serves as a backbone for transmitting mass data from peripheral nodes to the central server,

Short- and medium-range wireless communication protocols (DSRC – Dedicated Short-Range Communications), designed for direct interaction based on V2I (Vehicle-to-Infrastructure) and V2V (Vehicle-to-Vehicle) architecture,

Fifth-generation mobile networks (5G and C-V2X technologies), which provide massive connectivity and support the operation of critical real-time applications.

The implementation of such a technological stack unconditionally ensures the maximum level of integrity and cryptographic protection for the transmitted information packets, while simultaneously achieving minimal, almost negligible network latency (ultra-low latency). This is of fundamental importance for the timely broadcasting of safety warnings, dynamic traffic flow management, and the prevention of incident situations across the network.

Control Layer (Central Processing System).

This layer of the intelligent roadway architecture represents the processing and operational hub of the system, which performs continuous ingestion, mass aggregation, and advanced analytical processing of heterogeneous data collected from peripheral detection nodes. Within this computing layer, unstructured data from the system is filtered, analyzed, and converted into authoritative traffic flow parameters in real time.

Based on strictly implemented mathematical algorithms, expert decision-making systems, predictive models, and valid traffic safety regulations, this subsystem automatically generates optimal control strategies. The generated decisions and commands are reflected on the ground without delay and in real time through a feedback loop. This is realized through dynamic changes in traffic signaling regimes, primarily via Variable Message Signs (VMS) portals, adaptive traffic lights at intersections, and systems for automatic speed management and lane restrictions. In this manner, the layer ensures the maximization of the roadway's throughput capacity and minimizes the risk of incidents and secondary traffic congestion.

The essential and fundamental difference between an intelligent roadway and a conventional (Čekada, 2017), classical one lies in the cognitive ability of the system to continuously learn, evolve, and make decisions based on the synergy of historical databases and structured information collected in real time. While traditional road infrastructure relies on statically calculated capacities and fixed regulation regimes, Intelligent Transportation Systems (ITS) (Ezgeta, 2013) apply advanced methods of analytics and machine learning. This high level of automation and digital integration enables a complete paradigm shift—namely, the transition from traditional, delayed, and reactive management (which acts only after a traffic incident or congestion has already formed) to advanced, proactive, and predictive traffic flow management.

By implementing proactive management strategies, the system is capable of anticipating potential bottlenecks and fluctuations in demand before they explicitly escalate across the network. (Ezgeta, 2013) This directly and measurably optimizes key throughput and level-of-service parameters (such as flow density, lane capacity, and travel time), maximizes the degree of active and passive safety for all traffic participants, and drastically reduces environmental degradation and pollution of the immediate surroundings. This ecological benefit is a direct consequence of systematically reducing traffic congestion, eliminating the "stop-and-go" driving phenomenon, and subsequently reducing the emission of harmful exhaust gases, soot, and greenhouse particles into agroecosystems and urban environments..

Within an automated roadway, specific subsystems are implemented whose functionalities encompass:

Advanced Traffic Flow Analytics,

Continuous measurement of intensity, vehicle classification by category, and in-depth analysis of speeds and headway between vehicles.

Video Analytics and Remote Surveillance,

The use of intelligent video surveillance for automatic incident detection and remote flow management during emergencies.

Automated payment,

Contactless payment via smart cards and on-board units (OBU), thereby eliminating delays at toll plazas.

Telecontrol and Vehicle Dimensioning Systems,

The use of lasers and light curtains (optical grids) for the automatic detection of vehicles whose dimensions violate the safety clearances of structures.

Tunnel Safety Engineering,

Integrated systems for visibility enhancement, early smoke and fire detection, and the automatic activation of fire protocols and suppression systems.

Meteorological Monitoring,

Precise telemetry of atmospheric conditions (air temperature, wind speed, precipitation) as a basis for preventive road maintenance.

Dynamic Information and Navigation,

Management of variable message signs (VMS) and information boards, and the provision of real-time recommendations on optimal route choices.

Energy Management.

Intelligent regulation and adjustment of lighting depending on traffic density and ambient conditions.

Modern roadway management includes the system's ability to learn from collected data, representing a transition from reactive to proactive automation. The key functionalities defining this level of intelligence include:

Flow Monitoring,

Traffic volume measurement, vehicle classification, and in-depth analysis of traffic flow parameters.

Active Surveillance and Control,

Video surveillance with the capability for remote traffic flow management and telecontrol of vehicle dimensions using lasers and light curtains (optical grids).

Facility Safety and Security Systems (Lindov, 2008),

A special focus on tunnels through telecontrol of smoke/fire detection, automatic activation of fire suppression systems, and visibility enhancement.

Environmental Management,

Telemetry of meteorological conditions (temperature, precipitation, wind) combined with the automatic regulation of lighting.

Dynamic Communication,

Management of variable message signs (VMS) and information boards, and the provision of navigation instructions regarding currently optimal route choices.

Economic Efficiency.

Automated toll collection via "smart" cards and electronic systems.

3. OPERATIONAL BENEFITS AND SOCIO-ECONOMIC EVALUATION OF INTELLIGENT ROADWAY IMPLEMENTATION

The systemic implementation of intelligent roadways generates multiple improvements within the transportation ecosystem, primarily reflected through the optimization of traffic network performance, increased safety, and the reduction of negative external effects.

More efficient management and adequate control of traffic flows achieve a significant mitigation of traffic congestion and the elimination of critical bottlenecks. This approach directly leads to a reduction in economic losses inherent to waiting in queues and unforeseen delays. Consequently, it results in a substantial shortening of travel times for passengers and freight transport, thereby increasing the overall throughput (flow) of the infrastructure. For transport operators, the availability of real-time data enables advanced optimization of transport routes (Kiso, 2010), a reduction in operational costs, and increased reliability of logistics chains.

From a traffic safety perspective, intelligent roadways drastically reduce the "surprise factor" for drivers. Additionally, integrated SOS systems within the road infrastructure allow for near-instantaneous detection of incidents and prompt deployment of emergency services, thereby minimizing the consequences of traffic accidents.

Traffic flow optimization through ITS (Ejubović&Mališević, 2026)has a direct positive impact on environmental parameters. Reducing congestion eliminates the inefficient "stop-and-go" driving regime, which is the primary cause of increased fuel consumption and elevated emissions of harmful gases. Special importance is given to the intelligent routing and monitoring of hazardous materials (ADR) transport. This type of surveillance enables proactive action and an efficient response in the event of incidents, thereby preventing potential large-scale environmental disasters, protecting human lives, and preserving biodiversity in the immediate vicinity of roadways.

4. PERSPECTIVES ON INTELIGENT INFRASTRUCTURE DEVELOPMENT IN BIH IN THE CONTEXT OF EUROPEAN STANDARDS

In accordance with the European regulatory framework and local strategic goals, the development of intelligent roadways in Bosnia and Herzegovina must be based on harmonization with Directive 2010/40/EU. This Directive establishes a strict framework for the coordinated deployment of Intelligent Transport Systems (ITS) (Ezgeta, 2013) across four key priority areas: the optimal use of road, traffic, and travel data in real time; the continuity of traffic and freight management services on international borders; the application of ITS road safety and security applications; and the technological linking of vehicles with the transport infrastructure (V2I)(Ezgeta,2013). The EU places a special focus on priority actions such as the interoperable eCall system for automated accident notification, information services for safe and secure parking places for trucks and commercial vehicles, and the provision of EU-wide multimodal travel information services. For these systems to be functional, they must satisfy the core principles outlined in Annex II, primarily interoperability, which enables data exchange regardless of the equipment manufacturer—and the continuity of services across the Trans-European Transport Network (TEN-T). Technical implementation relies on satellite infrastructure, such as precise positioning systems, and open in-vehicle platforms that support "plug-and-play" integration of new applications, alongside mandatory backward compatibility with existing legacy systems.

Complementary to these European aspirations, the Transport Strategy of the Federation of BiH clearly defines the need for ITS implementation as a crucial tool for drastically reducing the number of traffic accidents and raising the general level of safety. The Strategy foresees modernization through better control of traffic flows, precise recording and tracking of the transport of hazardous materials (ADR), and continuous monitoring of vital infrastructure. The accelerated advancement of information and communication technologies opens up direct perspectives for the establishment of modern SOS networks, initially on highways and successively on other main roads. This approach enables the transition from passive to active infrastructure, where the integration of sensor networks and smart signaling ensures more efficient incident management and higher-quality information distribution to all users. In this way, the strategic goals of BiH—from economic efficiency to the protection of lives—are directly linked with the principles of energy efficiency and environmental sustainability proclaimed by European legislation.

5. CONCLUSION

Intelligent roadways represent not only a technological leap forward, but a fundamental paradigm of the future of transportation systems. In an era of ubiquitous automation and digital transformation, transport infrastructure is evolving from a passive physical layer into a highly connected information system. The integration of advanced ICT solutions enables the establishment of a cooperative connection between vehicles, drivers, and the infrastructure itself, resulting in incomparably more precise surveillance and more efficient management of dynamic traffic processes. Although economic sustainability and return on investment play a significant role in planning such complex systems, the primary imperative of intelligent roadway development must remain the safety aspect. The implementation of ITS technologies directly contributes to achieving "Vision Zero," because the tragic outcomes of traffic accidents, such as permanent disability or loss of life, have no market value and must not be treated as mere statistical data. Technological solutions that minimize human error and enable prompt action in crisis situations represent a moral and engineering priority of modern society. Furthermore, intelligent roadways are a key instrument in the fight against global warming and the greenhouse effect. Optimizing traffic flows directly reduces the emission of harmful pollutants, whereby the transport sector actively contributes to decarbonization and environmental preservation. Finally, economic development and network connectivity, supported by sophisticated control centers, form the third pillar of sustainability. It can be concluded that intelligent roadways, although already implemented to a certain degree, are only at the beginning of their full developmental potential. Their further evolution is unquestionable, as they represent not just an option, but a necessity for creating a safer, greener, and economically more efficient society.

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