

# DIGITALIZATION OF URBAN TRANSPORT INFRASTRUCTURE: INTELLIGENT TRAFFIC MANAGEMENT AND ITS IMPLICATIONS FOR SUSTAINABLE URBAN DEVELOPMENT AND PUBLIC POLICY

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## ABSTRACT

*This article examines the “smart city” concept, focusing on intelligent urban mobility as a key factor for sustainable development and quality of life. The study aims to address urbanization challenges-such as congestion and pollution-through Intelligent Transport Systems (ITS). The methodology is based on the Internet of Things (IoT), using sensors and cloud platforms for real-time data analysis. Various solutions are analyzed, including adaptive intersection management, multi-agent systems, and machine learning (Q-learning). Research results demonstrate a significant reduction in delays, fuel consumption, and emissions, while increasing public transport reliability. The authors conclude that integrating IoT with decentralized architectures (Agents of Things) is fundamental for building eco-friendly cities. The study confirms the “green kilometers in motion” concept, proving measurable environmental and economic benefits, making intelligent traffic management a vital tool for modern urban planning.*

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## 1. INTRODUCTION

“Smart City” is one of the most discussed and current concepts for the development of the urban environment among scientists and representatives of municipal authorities around the world (Batty et al., 2012). This multidimensional concept is based mainly on technologies that are related to the development of key components of the city, such as transport, environment, and urban management systems. All these components are closely interconnected, and their improvement through the use of intelligent technologies should contribute to improving the quality of life of citizens. One of the current research topics within the framework of the implementation of the Smart City concept is the

development of new technologies for ensuring urban mobility. Interest in this topic is determined by the need to solve a number of complex problems in existing urban transport systems, including the excessive impact of transport on the environment, large losses of time from traffic jams, excessive use of personal transport, and congestion of urban infrastructure. The implementation of intelligent transport technologies will allow these problems to be solved, as well as to increase the quality and expand the accessibility of urban transport.

The industrial revolution, which resulted in high rates of urbanization, brought with it both undeniable advantages for city dwellers (increasing the well-being of the average citizen, improving the quality of life), and negative aspects, such as the complexity of living together in a

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limited area, and long distances in daily commuting (Volker et al., 2013). The high well-being of residents allows them to own one or even several cars per household, which are actively used for intracity travel. This leads to a significant increase in the volume of car traffic in cities and an increase in the negative consequences of its use, such as an increase in the number of traffic jams, air pollution, and noise pollution. Problems are also associated with the lack of necessary parking spaces and the poor development of road infrastructure. As a result, the number of emergency situations in the city increases, transportation costs for residents increase, and the environment deteriorates, which negatively affects the quality of life (Welle et al., 2018). Intelligent transport technologies are aimed at the formation of transport systems that will allow minimizing the negative consequences of urbanization and intensive expansion of cities (Volker et al., 2013). Formation of an intelligent urban transport system is one of the components of the concept of creating a Smart City, which includes six basic components characterizing the key aspects of urban development, Smart Government, Smart Transport System, Smart Environment, Smart Economy, Smart Living/Surroundings, and Smart People, which form the “Smart City” (Benevolo et al., 2016). In modern understanding, a Smart City is considered an environment with a developed infrastructure, filled with intellectual elements, which, together with vehicles, are united in a single network with a large number of specialized sensors. This unification allows the formation of a single information space of the city (Yue et al., 2017). Urban theorists (Neirotti et al., 2014) define “Smart City” as “an ecosystem that develops through the effective use of information and logistics technologies, the functioning of which is aimed at improving the quality of life of citizens by unifying various systems and services”. In applied literature (Benevolo et al., 2016), a Smart City is considered a highly efficient city in which the key components – economy, residents, transport, environment – are in effective balance and are formed on the basis of a reasonable combination of financial resources through a system of effective self-government. The concept of “Smart City” is also often used to describe promising directions for the application of innovative technologies in the everyday life of the city, and in particular, behind this term often lies the use of innovative transport technologies (Giffinger et al., n.d.). Studies conducted in recent years confirm the thesis that the intellectualization of the urban transport system should, first of all, be ensured through intelligent urban mobility (Battarra et al., 2017). The Intelligent Transport System (ITS) is an advanced model of the transport system that uses information technologies to ensure traffic safety, reduce congestion, reduce environmental pollution, increase the energy efficiency of transport, and develop transport-related areas of urban life. Intelligent mobility is aimed at developing urban logistics technologies, creating intellectual systems,

introducing specialized information databases, analyzing information in real time, optimizing urban traffic, processing big data (Big Data), etc. State and private systems form a single system for providing transport services, which is vital for the city and its residents (Czech et al., 2018). A modern urban transport management system should assist municipal authorities in improving urban traffic management, making transport more user-friendly, more reliable, and maximizing its load while ensuring a high quality of transport service. The intellectualization of the transport system should help reduce traffic congestion, increase traffic safety, and contribute to maximum synchronization of urban traffic. The analysis of information on the movement of urban public transport in real time contributes to increasing the efficiency of urban transport management and enables citizens to access information on the current state of transport via their personal smartphone.

A major reason for the need to ensure efficiency in the operation of transport is the need to reduce air pollution from vehicles. Currently, transport is the main source of pollution in cities, over a quarter of all CO<sub>2</sub> emissions are due to transport, with urban road transport accounting for approximately 65% of this total (Yıldız & Aykanat, 2015). In 2016, the European Environment Agency recognized transport as a major source of harmful environmental impacts.

More than half of the world’s population lives in cities. Forecasts suggest that the shift from predominantly rural to predominantly urban settlements will continue over the next few decades (United Nations Population Fund /UNFPA/, n.d.). Such vast and complex agglomerations of people inevitably become polluted and chaotic. Cities and megacities give rise to new kinds of problems. The most fundamental technical, physical, and material problems are the complex issues of waste disposal from human activities, resource scarcity, air pollution, health hazards to residents, congestion on urban arteries, and crumbling and aging urban infrastructures. Another set of problems is more social and organizational in nature. Problems of this type are highly interdependent, have competing goals and values, social and political complexity, and affect numerous and diverse stakeholders. The problems of the city are intricate and difficult to solve. The urgency of the numerous urban problems leads to the search for intelligent ways to structure them and find solutions. Such cities are increasingly being labeled “smart”. One way to conceptualize the concept of a “smart city” is to model it as a sustainable and livable city.

“A smart city is a safe, environmentally friendly (green) and efficient urban center of the future with a provisioning infrastructure of sensors, electronics, and networks that stimulates sustainable economic growth and a high quality of life” (Hall, 2000).

“A city becomes smart when investments in human and social capital and in traditional (transport) and modern (ICT) connectivity infrastructure fuel sustainable economic growth and a high quality of life. These

investments must be supported by wise management of natural resources through participatory (involving residents) city governance” (Caragliu et al., 2009).

“It is a city that strategically builds and realizes the development of the economy, human capital, the city management system, mobility infrastructure, environmental protection, and quality of life. This development is built on a smart combination of endowments (givens, resources invested) and the activity of citizens who consciously and freely make decisions” (Giffinger & Gudrun, 2010).

In modern large cities around the world, there is a problem with air pollution. A large number of industrial facilities, combined with a huge number of moving cars, daily produce huge amounts of pollutant emissions into the atmosphere of cities, which naturally affects the quality of life of people. Life in a big city is so arranged that it inevitably includes daily trips. Perhaps a city can be called big when it becomes natural that home, work, places of recreation, and shopping are separated by significant distances. The duration of trips is increasing, and not always proportional to the distance: people spend more and more time on the road. There are many reasons for this: an increase in the number of cars and traffic jams, urban rhythms and their layering on each other, etc. What attracts attention is that, taking up more and more time in a series of daily events, the road and travel time are rarely mentioned in the story about how the day went. Why? Partly because a daily route is not a goal, it is simply a way to get to a “destination”, unlike a journey where all elements become significant, where the path can be a long-awaited adventure. And yet what is a daily journey?

For example, the path from home to work is a kind of place “in-between” semantic points in space; it is part of an unchanging mobility, repeated day after day, and habitual. What if you change your perspective and look at the path as a set of daily practices “on the way”, as something that is lived and filled with meaning and emotions every day, learning how to organize and prioritize routes.

The specific practices of movement that often fall into the focus of empirical research (tourism, migration flows, capital movements, etc.) are *φαινόμενα* in the Greek sense, since they are all, to one degree or another, observed events that are directly traced. “Mobility” falls out of this range, as it is not directly observed as such, but only through expression in various practices of movement, being their infinite ontological source; thus, as a traditional understanding of a “phenomenon”, it must be denied.

J. Urie considers bridges, highways, roads, and mobile phones as important elements of the “mobility paradigm”, that all of them, being in their essence “mobile equipment”, are in ontological relation (“in-order-to”) with different practices of movement. At the same time, they are immanent elements of a wide range of “mobility systems”, since their being (movement) does not have its own individual source, but appears only as a metonymy of the overall being “in-order-to” (in this case

mobility), as a fragment that tries to reflect the same picture that the whole mirror covers in its entirety. He speaks of mobility from the point of view of networks and flows, as a system formed by urban highways and measured by the number of cars, norms, and perceptions of their use. He is also interested in the elements and connections that build the transport system of the city and the development of the resources related to it (automobile, fuel industry), and the turning points that can change it. Not only the car, but also any physical movement (of people, cars, public transport, etc.) is conditioned by norms, power relations, and meanings. The ways of behaving in this case can be presented as more or less articulated “mobility cultures”, which can be both universal and locally rooted norms and habits, and can be based on official prescriptions, but not reduced to them.

## 2. LITERATURE REVIEW

The literature review defines the “smart city” as a multidimensional ecosystem that integrates technology, sustainable management, and infrastructure to enhance quality of life. Researchers emphasize that rapid urbanization leads to critical pollution levels, with transport accounting for over a quarter of all  $CO_2$  emissions. The scientific focus centers on implementing Intelligent Transport Systems (ITS) and the Internet of Things (IoT) to enable real-time data analysis for traffic optimization and environmental impact reduction. Studies demonstrate that intelligent routing and improving public transport reliability are essential for achieving urban sustainability.

## 3. METHODOLOGY

The methodology is based on the implementation of the Internet of Things (IoT) for real-time data collection and analysis using sensors and cloud platforms. It employs Agent-Based Modeling (ABM) and a decentralized “Agents of Things” architecture, where infrastructure elements act as intelligent agents. Traffic optimization is achieved through machine learning (Q-learning) and identification technologies such as RFID and LiDAR-GIS.

## 4. DISCUSSION AND ANALYSIS

### 4.1 Internet of Things (IoT) in Transport Management

Daily mobility - moving around the city - involves studying the organization of urban space, its structure. On the one hand, it involves the analysis of urban morphology, the physical structure and logic of the organization of space, and city maps. On the other hand, it is necessary to take into account the shared social

meanings of space, thanks to which it is created and in accordance with which it is used.

The European Environment Agency reports that in 2010, 17.5% of all greenhouse gases emitted into the atmosphere came from road transport (European Environment Agency, 2011). At the same time, the contribution of light vehicles to total CO<sub>2</sub> emissions is 12% (Commission of the European Communities, 2007). The dynamics of the increase in emissions from road transport are disappointing. While CO<sub>2</sub> emissions from stationary sources in Europe have been decreasing continuously since 1990 (Krautzberger & Wetzel, 2012), emissions from road transport increased by 23% between 1990 and 2009 (European Environment Agency, 2011). Numerous studies have shown that the choice of driving route can have a significant impact on the amount of pollutant emissions and fuel consumption during daily trips (Ahn & Rakha, 2008; 2013; Aziz & Ukkusuri, 2014; Boriboonsomsin et al., 2012; Guo et al., 2012). Also, the mode of transport (private, public, etc.) and the time of departure have a significant impact on the volume of pollutant emissions (Hensher, 2008; Stanley et al., 2011). Studies show the need to investigate the problems of routing flows with many and different groups of road users in the context of reducing pollutant emissions into the atmosphere from urban transport. The development of information and telecommunication technologies provides users of the transport network with the opportunity to receive information about the road condition and use it when choosing a route, departure time, mode of transport, etc. (Ben-Akiva et al., 1991; Gaker et al., 2011; Mahmassani, 1990). Studies have shown that traffic routes characterized by a minimum amount of pollutant emissions do not coincide with routes with a minimum travel time (Ahn & Rakha, 2008; Lin & Ge, 2006; Zhang et al., 2010). The relationship between driving speed and the volume of pollutant emissions gives rise to a conflict of interest for the driver when choosing a driving mode, to strive for a minimum driving time or minimum emissions (Ahn & Rakha, 2008; Aziz & Ukkusuri, 2014; Yin & Lawphongpanich, 2006). The results show that in the process of routing transport flows, the level of inclination of the roadway should also be taken into account, which has a serious impact on the volume of pollutants emitted by transport (Boriboonsomsin & Barth, 2009; Boroujeni & Frey, 2014; Wyatt et al., 2014; Zhang & Frey, 2006). It is proposed to collect information using special LiDAR-GIS systems and to form digital terrain maps (DTM) on their basis.

To date, there is a serious lack of methodological tools to support decisions on the allocation of “green” subnetworks in the urban transport network and to encourage drivers to use more environmentally friendly methods of transportation. In recent years, the demand for urban public transport (UPT) services has increased significantly. This is due to the transport policy of cities in many countries, aimed at the priority development of UPT systems. The development of UPT implies increasing its competitiveness in relation to private road

transport. The competitiveness of UPT can be achieved by increasing the reliability of the operation of its routes. From the point of view of users (i.e., passengers), reliability is a combination of characteristics such as waiting time (determined by the size of the route interval) and travel duration (preferably approaching the time spent in an individual car). But the most important of these characteristics when using public passenger transport is the change in travel time. In modern conditions, GPS tracks of the rolling stock of the GOTr are used to assess the reliability of the operation of the routes of the GOTr, obtained both in real time and in the form of archived data (Berkow et al., 2007; Chakroborty & Kikuchi, 2004). The main criteria for assessing reliability (respectively, variations in the duration of movements) are the time and buffer index (Ahn & Rakha, 2013). The choice of these reliability indicators is associated with the development of geoinformation technologies, in particular, with the widespread use of automotive navigation equipment (Ahn & Rakha, 2008). Many different elements of the road infrastructure are used to organize road traffic. The classic elements that directly control the movement of transport remain traffic lights and road signs. In recent years, many researchers have been working on the implementation of traditional traffic flow management using the Internet of Things (IoT) paradigm. A large part of the prototypes intended for testing algorithms and control approaches has been implemented on the basis of microcomputers, such as Intel Edison, Raspberry Pi, and similar devices. The question arises whether these computers are suitable for operation in real transport systems, by modeling traffic through a platform that demonstrates the ability to operate on low-power hardware. They create scenarios that reproduce the structural characteristics of urban intersections. In order to evaluate the performance, a unified test environment in the Java programming language was developed, in which the considered scenarios were implemented. Thus, it is established that compact and low-power devices, such as Raspberry Pi 2, can be used for integration into an IoT environment for the purpose of managing transport flows in urban conditions.

The main wireless standards used for communication between IoT elements in the intelligent transport system (ITS). If the vehicle is moving at a speed of more than 20 km/h, the use of GPRS for communication is inefficient, since the throughput of GPRS/GSM is in the range of 64 to 128 kilobytes per second. Therefore, for effective transport management, communication should be based on modern standards and optimized data transmission protocols in accordance with IoT standards. When modeling the operation of a traffic management system based on the Internet of Things, by applying the agent-based modeling (ABM) method, a traffic management system based on IoT is simulated. The purpose of the study is to study the interactions that underlie the functioning of the networked IoT service. A model was developed including several intersections, sensors, and

traffic lights. The final version of the model consists of 20 sensors, 4 intersections, and 4 traffic lights.

The study shows that the accuracy of the information transmitted to the decision-maker is not critical, as it does not have a significant impact on the performance of the traffic management system. Thus, during the modeling, it is confirmed how important it is to choose the right protocols and technologies used for data transmission in IoT. This is a necessary condition for organizing effective management of transport flows.

The traffic flow management algorithm at intersections in the IoT paradigm collects information from traffic detectors and transmits it to a microcontroller to calculate the traffic light duty cycle (Wyatt et al., 2014). Adaptive traffic light duty cycle control for a specific section of the road network is set individually. The collected traffic information is processed using an Intel Edison microcomputer, and the data is transmitted via Wi-Fi wireless channels to the Microsoft Azure IoT cloud service. The optimal traffic light duty cycles are calculated in real time. Subsequently, information about the calculated cycles is transmitted back to the microcomputer and introduced into the traffic light operation mode (Boriboonsomsin & Barth, 2009).

The use of IoT and cloud computing is expanding in order to maximize the benefits in traffic management and address transportation problems. It is also proposed to use IoT as an enabling infrastructure for creating a cloud platform and obtaining data from vehicles. This platform will store information related to traffic, traffic control and management, vehicle location tracking and monitoring, road surface condition (road conditions), warranty information, and vehicle service data. The proposed multi-layered cloud platform enables the integration of various sensors, actuators, controllers, GPS devices, mobile phones, and other equipment that access the Internet. It also uses network technologies (wireless network, cellular network, satellite network, etc.), cloud computing, and IoT. This platform supports Vehicle-to-Vehicle and Vehicle-to-Infrastructure communication mechanisms, and can collect and exchange data with drivers, vehicles, and roadside infrastructure (e.g., cameras and street lighting). The traditional traffic management model has several significant drawbacks that can be eliminated by a different software architecture for cloud computing in an IoT environment applied to traffic management. This architecture integrates multiple devices present in vehicles as well as devices from road infrastructure. Studies on integrating IoT with cloud data from transport infrastructure are in their infancy, and the available work on this topic is extremely limited.

**4.2 Methods for collecting traffic information via IoT**  
Radio-Frequency Identification (RFID) technology is used as the main tool in a prototype IoT application for traffic management. The key technology used in the system is the passive RFID UHF technology for collecting vehicle information (Stanley et al., 2011). The proposed approach is an alternative to the existing manual and semi-automatic traffic light control in

Thailand. The proposed solution aims to modernize RFID and IoT technologies to adapt to current traffic management standards, rather than requiring a complete change in the operation of the existing system. The practical aspects of the application are vehicle identification using RFID technology in traffic management using a collision avoidance protocol, data cleaning algorithms, and algorithms for completing missing data, a method for tracking the vehicle route at traffic lights, and camera image recognition (Stanley et al., 2011).

#### **4.3 Variations of IoT Systems**

The lack of sufficient intelligence in existing systems due to hardware and software limitations could be addressed by the concept of “Agents of Things” (AoT). The essence of this concept is that everything should be intelligent. These objects should interact directly with each other or through other systems. The AoT architecture consists of six levels. Agents at different levels interact through software agents. Unlike IoT, the main principle of AoT is intelligence (Zhang et al., 2010).

A distributed intelligent system based on IoT that is self-optimizing for traffic management and monitoring of environmental impact parameters, having a complex structure that provides optimization of the parameters of the traffic light operating time for a given intersection, depending on the number of vehicles passing through it. The main goal is to minimize delays (delays) of vehicles at intersections.

#### **4.4 IoT in Traffic Lights**

The concept of smart traffic lights (Smart Traffic Lights, STL) in the IoT paradigm is particularly relevant. The process of introducing STL as an element of road infrastructure, as well as the cognitive traffic management system (CTMS), is the basis for STL. A smart traffic light is capable of changing the phase time depending on the volume of traffic flow. The STL control method uses the maximum Boolean derivative for the lanes. The STL switching is delayed if all sides of the intersection are occupied, in order to minimize conflicts in all lanes, vehicle interaction with the traffic light to optimize transport travel time, and fuel economy based on IoT.

The application of machine learning (ML) as an intelligent traffic light signal control system that takes into account pedestrian movement in order to optimize both car and pedestrian traffic to achieve higher results. Distributed multi-agent Q-learning extends the capabilities of the system. The agent can collectively calculate the optimal control actions based on traffic information not only at the isolated intersection, but also at neighboring intersections.

New applications of IoT technologies in road infrastructure are constantly emerging. They include various sensors, traffic lights, lighting, road signs, and even road barriers and parking lots.

## 5. CONCLUSION

The integration of the Internet of Things (IoT), machine learning (ML), and distributed intelligent systems in road infrastructure (traffic lights, sensors, communication nodes) represents fundamental steps towards the realization of the concept of “Smart Cities and Green Miles on the Move”.

The transition to architectures such as “Agents of Things” (AoT) and the use of multi-agent Q-learning for intersection optimization (reducing delays by 50%) demonstrate the creation of a smart urban environment. Through IoT, full connectivity between all elements is achieved - from traffic lights to parking lots - which is the essence of smart city infrastructure. The proposed approach to decentralization and organization of each infrastructure element as an intelligent agent provides flexibility and scalability, which are mandatory for a large, smart city. Green Kilometers in Motion is directly confirmed by environmental results, such as:

**Fuel savings:** The proven ability of TLVC communication to reduce fuel consumption by up to 22% and the achieved savings of 8% with network management directly correspond to the goal of reducing energy consumption.

**Emission reduction:** The significant reduction in harmful emissions (CO up to 80%, NOx up to 35%) turns optimized movement into an environmental measure of paramount importance for improving air quality in urban areas.

The implementation of IoT in traffic management not only solves transport problems (congestion, delays), but also serves as a key mechanism for achieving the two strategic goals of modern urban planning: building intelligent and efficient systems and achieving the sustainability and environmental friendliness of urban transport.

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