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Using Smart Intersections to Reduce Traffic Congestion and Emissions in Urban Areas

Abstract

Growing urbanization and the frequent increase in motorization in urban areas cause significant traffic congestion and pollute the atmosphere by creating large amounts of harmful gas emissions. Smart intersections are based on adaptive traffic management systems, real-time data analysis, which is why they can optimize traffic flows in cities. This paper explores the effect of smart intersections in reducing traffic congestion and CO₂ emissions with a focus on the city of Rijeka. The research is conducted through a literature review and analysis of the effect of smart traffic lights that have been implemented in the automatic traffic management system of the city of Rijeka. Special emphasis is placed on the empirical results of smart traffic lights that have been installed in Asian cities with relevant information for the application of the same systems in the Republic of Croatia. The results show a reduction in travel time, an increase in traffic flow and a reduction in CO₂ emissions. The objective of this paper is to analyze the current state of installed smart traffic lights in the city of Rijeka, and to investigate the efficiency of the application of these modern intelligent transport systems.

Keywords: smart intersections, traffic congestion, CO₂ emissions, intelligent transportation systems, urban traffic

1. Introduction

The increase in urbanization and the increasing dependence on individual automobile traffic constitute one of the main challenges facing modern cities in Croatia and around the world. Problems that arise in large urban regions are the increase in the number of vehicles, which causes traffic congestion, lengthens travel times, reduces traffic safety and increases the negative impact on the environment and health of the population. Various studies have determined that road traffic has a major impact on

the generation of carbon dioxide (CO₂) emissions. It should also be noted that a good share of these emissions occurs during traffic jams and frequent stopping of vehicles at intersections. [1,2]

Critical points in the urban traffic network are intersections, as they are where the greatest congestion and time losses occur. Traditional traffic management systems at intersections are mostly based on adaptive time-limited or fixed traffic light plans. The biggest drawback of traditional management is that it relies on data that is predefined based on previous measurements of traffic capacity. On the other hand, traffic is a dynamic system subject to frequent changes in traffic conditions, and as such, the traditional approach is not suitable for it. Traffic events such as road works, sudden changes in traffic demand, traffic accidents or an increase in the number of vehicles due to the tourist season greatly affect the variability of the traffic itself. [3] In order to increase the efficiency of traffic management, Intelligent Transport Systems (ITS) have been developed in the last few decades. Intelligent Transport Systems interconnect information, communication and control technology in the transport system. The main goal of such systems is to improve the flow, sustainability and safety of traffic. [4]

Smart intersections represent one of the most significant applications of ITS in urban environments. They are equipped with advanced systems that enable real-time data collection and processing, thus addressing the main drawback of traditional intersection management systems.

One of the most significant applications of ITS in urban areas is smart intersections, or intersections equipped with advanced systems for collecting and processing traffic data in real time. [5] Smart intersections function by using various types of sensors that are installed in urban areas. Sensors are used to detect and monitor traffic flow in real time, and the most common are induction loops built into the roadway, video cameras that enable computer vision, radar sensors, and wireless detectors that enable communication with mobile devices or vehicles. The data that these sensors collect most often includes parameters such as traffic intensity, vehicle column length, vehicle speed, distance between vehicles, and waiting time at the intersection. Sensors and cameras can also detect traffic entities such as public transport vehicles or emergency services. [6]

The data collected from the sensors form the basis for adaptive traffic signal control and are sent via a communication network to the central control system. The central control system can be explained as the brain of the ITS traffic control operation. Its task is to process the data collected in real time using predefined algorithms or models using artificial intelligence. By analyzing the current traffic situation, the system makes a decision and adjusts the duration of the signal phase if necessary. The system can also adjust the length of the green phase and the priority of individual lanes if necessary. The advantages that such system provides are a quick response to changes in traffic conditions, which ensures adaptability, thereby increasing traffic flow and reducing vehicle waiting time at the intersection. [1,7]

Based on the collected data, smart intersections use adaptive signal management. Unlike traditional traffic light systems, adaptive systems are different because they

adjust the duration of the signal phase in real time to the current traffic congestion. This reduces vehicle delays and increases the absorption of the intersection. According to research by Ovaldo Santos et al., adaptive signal systems can reduce delays and average vehicle travel times by 10 to 30%, depending on the traffic flow. [7]

In addition to the positive impact on traffic flow, smart intersections reduce the negative environmental impacts of traffic. Vehicles consume the most fuel during numerous stops and restarts, which increases CO₂ and nitrogen oxide emissions. Research conducted by Kan Wu et al., based on microsimulation and emission modelling, confirms that implementing an adaptive signal plan at intersections leads to a significant reduction in emissions in urban environments. [2]

In recent years, smart traffic management systems based on the use of smart intelligence have become increasingly prominent. Numerous cities such as Barcelona, Singapore, New York, London, etc. have implemented smart systems in city networks thus receiving smart city status. [8] The Chinese city of Hangzhou can also be classified as a smart city. This city has implemented the City Brain system in its traffic network, which can process data from thousands of intersections, cameras, and sensors. The City Brain system is considered extremely advanced because it uses machine learning algorithms to optimally manage traffic flow across the entire city network. According to available research for the city of Hangzhou, a significant reduction in travel time and CO₂ emissions has been found. [2] This confirms the importance of implementing smart intersections for sustainable urban traffic management.

The installation of smart traffic light systems in the city of Rijeka appears to be relatively limited. The installation of smart traffic lights is mainly carried out through projects to modernize the transport infrastructure and promote sustainable urban mobility. Owing to such projects, the City Traffic Center was established in 2003, which represents the central point for monitoring and managing traffic in the city of Rijeka. [9] The technical solutions that have been implemented show significant financial savings. According to expert estimates, the automatic traffic management system in the city of Rijeka saved 55.7 million kunas for the period from 2002 to 2008 alone. [9] It should be noted that there is a need for further analysis of the actual impact of the implemented smart traffic lights. Also, the traffic management system in the city of Rijeka should be compared with systems that are implemented in larger urban areas. The goal of this research is to analyze the current state of smart traffic lights that are integrated into the automatic traffic management system in the city of Rijeka. This paper will explore the potential of these traffic lights for reducing traffic congestion and emissions in the city. A special focus will be placed on comparing traffic solutions implemented in other smart cities with the goal of potentially improving the traffic management system in Rijeka. In this way, this paper will contribute to understanding the function of smart intersections in the development of sustainable urban transport.

2. Analysis of implemented smart traffic light systems around the world

The development of smart intersections has become one of the most researched areas within intelligent transportation systems in the last few decades. Numerous studies have established that traffic lights, which are controlled by a fixed time cycle, cannot accommodate dynamic changes in traffic, especially in cities with large daily and seasonal fluctuations in traffic demand. [3]

The city of Hangzhou in China provides an example of how the successful implementation of intelligent systems can improve citywide management. The City Brain system was introduced by Alibaba Group in 2016. [10] City Brain collects data from traffic cameras, sensors and vehicle GPS into a centralized, AI-controlled system. Artificial intelligence analyzes traffic flows in real time and automatically adjusts signalized intersection schedules to increase throughput. This reduces traffic congestion and optimizes traffic flow. The City Brain system was first deployed in the Xiaoshan District. [11] According to available data, the average traffic speed has increased by approximately 15% in the cities of Hangzhou and Nanchang, indicating the success of the project. [2] Prior to the introduction of the City Brain system, Hangzhou was considered one of the most congested cities in China, which highlights the practical effects of automated signal management. Improved traffic flow is not the only recorded benefit. The system has also enhanced emergency response efficiency and increased the detection rate of traffic incidents, thereby reducing police and ambulance response times. One of the key advantages of the City Brain system over traditional systems is its integration of the entire traffic network comprising more than a thousand intersections, i.e. intersections are no longer managed individually. The improvement in road traffic in the city of Hangzhou resulted in the expansion of the City Brain system to other Chinese cities such as Shanghai, and nearby Kuala Lumpur in Malaysia. [12]

China is not the only Asian country that has decided to incorporate smart traffic light systems into its road system; similar systems can also be found in South Korea. In recent years, the Seoul Metropolitan Government has conducted pilot programs using cameras, LIDAR detectors, and artificial intelligence to adjust signal cycles to traffic conditions. [13] These systems have been implemented in locations with chronic traffic congestion, where they have improved vehicle flow, and consequently reduced CO₂ and other harmful gas emissions. The “Smart Intersection Construction Project” is currently the most significant traffic automation pilot project in Seoul. Its primary objective is to use artificial intelligence and Big Data analytics to collect data on traffic density, vehicle speed, and unpredictable road situations in real time. [14] The collected data are used to calculate optimal signal cycles, which are then applied in real time in the signal systems. This has increased the number of vehicles that can pass through the intersection during a single cycle, and unnecessary waiting at traffic lights has been reduced or, in some cases, completely eliminated. Analyses indicate that the Smart Intersection Construction project has significantly improved intersection efficiency. At some of the smart signalized intersections, the average delay has been reduced by

41%. In addition, due to greater signal flexibility and better vehicle detection, signal violations have been reduced by 36%. [15] With a 41% improvement in traffic flow, it could be concluded that exhaust emissions have also decreased, as fewer stops result in lower fuel consumption.

Apart from Asian countries, Intelligent Transport Systems and smart traffic lights are also widely implemented in Europe. Munich and Barcelona were among the earlier European cities to begin installing smart technologies aimed at reducing traffic congestion and CO₂ emissions in their city centers. Munich has the third-highest traffic volume in Germany, making the implementation of smart traffic lights inevitable. Prior to the introduction of intelligent systems, traffic congestion led to reduced road safety, deteriorating traffic flow, and increased environmental pollution. Research has found that the “Munich Traffic Control Centre” traffic management tool significantly improved traffic flow [16], while also mitigating negative environmental impacts. Additional benefits have been observed in the integration of public transport with automated signaling systems, where detected public transport vehicles are given priority to pass through the intersection. After a sensor or camera spots a public transport vehicle, the cycle of the traffic light is extended so that it can pass through the intersection. In the field of sustainable urban mobility, notable progress can also be observed in Barcelona. Although the city is widely regarded as one of Europe’s leaders in smart city development, it is interesting that it does not yet have a fully developed system of intelligent traffic lights comparable to those in Munich or Hangzhou. At the end of 2025, a decision was made to explore the application of artificial intelligence in smart traffic lights for integration into Barcelona’s traffic system. The project is being implemented in collaboration between the city of Barcelona and the Polytechnic University of Catalonia. [17] Its primary objective is to improve vehicle flow and optimize waiting times at intersections, thereby indirectly contributing to the reduction of harmful gas emissions. In addition to these initiatives, Barcelona has taken significant steps to enhance the energy and environmental efficiency of traffic lights. The former incandescent lighting system was replaced with light-emitting diode (LED) technology, resulting in substantial reductions in electricity consumption. The transition from conventional bulbs to LED lighting achieved energy savings of approximately 85%. The use of LED bulbs resulted in a reduction in daily electricity consumption from 46,000 kWh to 10,000 kWh, saving the city €65,000 per month. [18] The 85% reduction in electricity consumption has led to an annual decrease of 18 tons of CO₂ emissions, marking an important step toward the city’s decarbonization goals.

3. Analysis of the current state of smart transport infrastructure in the city of Rijeka

The city of Rijeka is an important transport hub in the northern Adriatic. Owing to its extensive transport network, the city represents a key node within the Mediterranean Corridor. The problem that arises from the overlapping of transit, urban, port and

tourist flows causes significant traffic congestion in the inner-city area. In particular, the connection between the Mediterranean Corridor and the Port of Rijeka places considerable strain on the urban road network and the surrounding area due to the high volume of freight traffic generated by port activities. In order to reduce traffic congestion, especially in areas where transit and urban traffic intersect, an automatic traffic management system (AUP) was introduced in 2003. Rijeka is regarded as the first Croatian city to implement smart traffic technology. Since the establishment of the AUP, the modernization of the city's network has been carried out in several phases, during which a substantial number of outdated traffic signals have been progressively replaced.

3.1. Analysis of traffic congestion in the city of Rijeka

In addition to replacing outdated traffic signals, Rijeka has, over the years, installed cameras, sensors, and traffic detectors throughout its road infrastructure. The signal plans were originally based on data collected from inductive loop detectors embedded in the roadway. Seven key locations, corresponding to the main entrances to the inner urban center, were strategically selected for the installation of traffic detectors (Figure 1). [19]



Figure 1. Areas where traffic counting is performed in the urban center in the AUP system

Figure 1 shows intersections where individual loop detectors are installed, marked with R. [19]

R6 Krešimirova (Public Health Teaching Institute of PGŽ)

R38 Vukovarska – V. Cara Emina – Cambierijeva – J. Završnika

R40–R41 V. Cara Emina – Prvog Maja – Manzonijeva – F. La Guardia

R46–R47 Laginjina – Pomerio – Žrtava fašizma

R24–R25 Titov trg – Školjić
 R20–R21 Strossmayerova – Križanićeva
 R89 D404 – A. K. Miošića

Detectors record each vehicle passing through an intersection and transmit data to a central database at 15-minute intervals. The main traffic computer, located in the city traffic control center, processes the collected data and selects the optimal signal plan for the traffic lights, subsequently sending appropriate commands to local devices. [9] In addition to individual loop detectors, strategic detectors were also installed at certain locations to classify vehicles based on their length. The reference categories recognized by the strategic detectors were: up to 6 meters, 6 meters to 9 meters, 9 meters to 12 meters, over 12 meters. However, inductive loop detectors do not provide information about traffic jams above the roadway, since they are built into the roadway. Although they are still used in some smart cities as a hybrid ITS system, they are now considered conventional rather than advanced smart technology. Consequently, inductive loop detectors in Rijeka were removed from their function in 2023. The city is currently transitioning to a system based on video analysis computers and cameras mounted directly on traffic signal installations. This system has already been implemented along Adamićeva Street and at the Orehovica intersection. The system is currently in the testing phase, and its benefits will be demonstrated in the near future. Traffic counting in the city of Rijeka is currently conducted using portable traffic analysis sensors which, unlike inductive loop detectors, provide data on vehicle speed and pavement temperature.

By analyzing data from portable sensors obtained from the TD Rijeka plus traffic center, a study was conducted to evaluate Rijeka's urban roads for the period from 15 to 21 September 2025. Traffic counting was carried out at two locations, namely the intersection R38 Vukovarska – V. Cara Emina – Cambierijeva – J. Završnika and R40–R41 V. Cara Emina – Prvog Maja – Manzonijeva – F. La Guardia. The counting lasted 7 days, from Monday to Sunday.

Table 1. Traffic count data for 2025 for R38 Vukovarska – V. Cara Emina – Cambierijeva – J. Završnika

R38	Mon.	Tue.	Wed.	Thu.	Fri.	Sat.	Sun.	Week total
Average Daily Traffic (ADT)	11124	10797	10916	10749	10721	6782	5339	66428
Vehicle speed (km/h)	35	35	36	35	36	41	42	/
Pavement temperature (°C)	29	26	26	28	29	30	30	/

The results indicate that, for R38, the highest traffic load was on Monday with 11,124 vehicles counted, and the lowest on Sunday, 5,339 vehicles. R38 has a high traffic volume with an average daily traffic of $\approx 9,490$. The afternoon peak hour is more dominant than the morning one and occurs consecutively every weekday between 3:00 PM and 4:30 p.m. The average vehicle speed during the peak hour varied from 20 to 25 km/h depending on the day. During the peak hour, on Monday between 3:30 p.m. and 4:30 p.m., 1,007 vehicles passed the section with an average speed of 21.3 km/h. The detector counted 261 vehicles in a 15-minute interval between 3:45 p.m. and 4:00 p.m., which was the absolute maximum of the entire seven-day period. The lowest speed recorded during peak hours is 18 km/h, which clearly indicates traffic saturation and the formation of queues. The average speed outside peak hours varies between 38 and 42 km/h, and at night and on weekends often exceeds 45 km/h. Compared to free flow, during peak hours there is a significant speed drop of 46.8%. Traffic is halved during weekends. The highest recorded pavement temperature reaches 48 °C, measured on Saturday between 1:30 and 2:30 p.m., and the lowest 19 °C on Wednesday between 1:00 and 6:00 a.m.

Table 2. Traffic count data for 2025 for R40–R41 V. Cara Emina – Prvog Maja – Manzonijeva – F. La Guardia

R40-41	Mon.	Tue.	Wed.	Thu.	Fri.	Sat.	Sun.	Week total
Average Daily Traffic (ADT)	5000	4738	4724	4561	4734	3350	2723	29830
Vehicle speed (km/h)	50	50	51	51	50	53	54	/
Pavement temperature (°C)	27	25	25	25	26	26	27	/

For the R40–R41 intersection, traffic count results indicate a significantly lower number of vehicles passing through the intersection compared to R38. One possible reason is the number of bus routes and the lower functional importance of this road section. The highest recorded traffic volume at R40–R41 was on Monday with 5,000 vehicles counted, while the lowest was recorded on Sunday, with 2,723 vehicles. The R40–R41 intersection has an average daily traffic volume of approximately 4,261 vehicles. The peak hour varies throughout the week but generally occurs between 2:30 p.m. and 4:00 p.m. Unlike R38, the peak hour with the highest load on the traffic network was measured on Friday, September 19. During the period between 2:30 p.m. and 3:30 p.m., 429 vehicles passed through the section. The detector recorded 123

vehicles within a 15-minute interval, which also represented the absolute maximum for the entire seven-day period. During the peak hour, the average vehicle speed was 50.4 km/h, while the lowest recorded speed was 42 km/h on Monday. The average free-flow speed was 54.8 km/h. Compared to free-flow conditions, a speed reduction of 8.1% occurs during peak hours. On weekends, the traffic volume decreases by 45.5%. The highest pavement temperature recorded during the seven-day observation period was 43 °C on Saturday between 1:45 p.m. and 2:00 p.m., while the lowest was 19 °C on Wednesday between 1:00 a.m. and 6:00 a.m.

3.2. Analysis of smart traffic lights in the city of Rijeka

In the Rijeka metropolitan area, 85 signalized intersections are currently registered and managed by the City Traffic Control Center. The technical equipment of the traffic center includes a central traffic computer and server unit (RMS), operator workstations, a video wall with multi-channel surveillance (up to 16 cameras), a communication server for GSM and optical connections, as well as a fault diagnostics and alert notification system. According to the data provided by the traffic control center, 74 out of 85 signalized intersections are integrated into a traffic-responsive control system, representing 87% of the total network. The remaining 11 intersections are still operated using predefined fixed-time signal programs. Traffic-responsive control operates through dynamic adjustment of signal cycles based on detected traffic demand. Each intersection within the system is assigned a unique identifier and is managed individually. Remote control functionalities provided by the traffic control center include switching devices to special operating modes (flashing yellow signal), device shutdown and reset, fault diagnostics, and partial traffic data collection. Each of the 74 signalized intersections has predefined signal plans, typically four per intersection. These plans are created in accordance with the design documentation of each intersection, and the selection of a specific plan depends on current traffic conditions.

An analysis of existing equipment revealed significant technical and temporal heterogeneity among traffic signal controllers. EC1-type controllers are the most prevalent, installed at 54 intersections, accounting for 64% of the total network. These devices belong to an older generation and were primarily installed between 2003 and 2009. The second most common are EC2-type controllers, installed at 20 intersections (23% of the network). Compared to EC1, EC2 represents an upgraded version and supports a higher number of signal groups and detectors. At eight intersections (10% of the network), outdated analog controllers of the PSV 1007 type are still in use. These devices have limited functionality and are incompatible with modern infrastructure. A major drawback is that faults cannot be detected remotely within the system and must instead be resolved on-site. The most recent controllers, ITC3-type devices installed in 2024, are currently present at only three intersections (3% of the network). These controllers are designed to collect data, communicate with the central computer, and perform basic local optimization. Similar devices have been deployed in Cambridge,

where they proved to be an effective solution for smaller intersections. While ITC3 controllers are compatible with smart infrastructure, they do not include built-in AI-based machine learning algorithms or predictive models, as found in the most advanced smart cities. Their “smart” functionality is achieved primarily through integration with the central control system rather than autonomous operation. All traffic signals in the city of Rijeka are equipped with LED signal lights, resulting in significant energy savings and reduced CO₂ emissions. In addition to environmental benefits, LED lights have a longer service life compared to incandescent bulbs, reducing maintenance frequency and minimizing the need for lane closures during servicing, which positively affects traffic flow continuity. From a safety perspective, LED signals also offer improved visibility under adverse weather conditions such as rain, fog, and strong sunlight, which are common in Rijeka.

4. Analysis of traffic intensity at selected intersections and discussion

Traffic counting locations selected in 2025 were chosen to enable comparison with inductive loop detector data from 2019 and 2022. Traffic count data for intersection R38 in 2019, 2022, and 2025 are presented in Figure 1, while the data for intersection R40–R41 are shown in Figure 2.

4.1. Traffic counts at intersections R38 and R40–R41

The data indicate that traffic patterns in 2019 were stable and balanced, with clear differences between weekdays and weekends. In 2022, a decrease in total traffic volume of 2.3% compared to 2019 was observed, which can be attributed to changes in travel behavior following the COVID-19 pandemic.

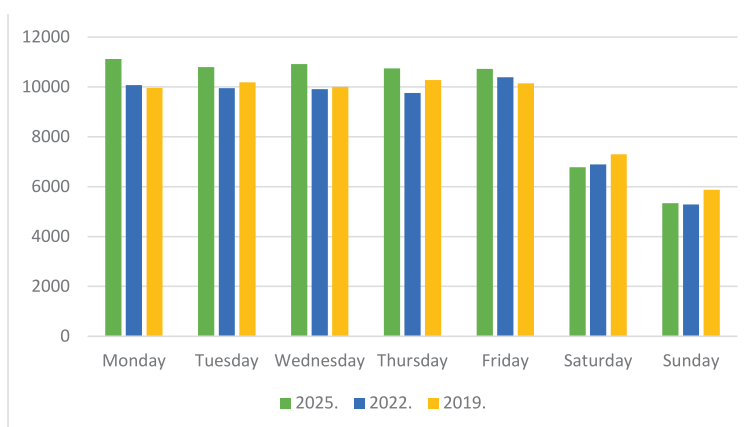


Figure 1. Traffic count data for intersection R38 for 2019, 2022, and 2025

In 2025, a clear recovery and increase in traffic volume is evident. Compared to 2019, traffic increased by approximately 4.2%, and by 6.7% compared to 2022. Traffic demand is higher on weekdays. Since weekend traffic shows no significant oscillations, it can be concluded that increased travel demand is not primarily driven by tourism but rather by urban and work-related trips.

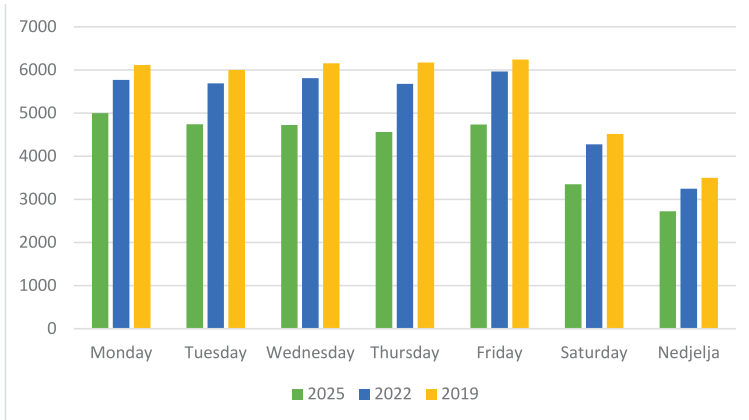


Figure 2. Traffic count data for intersection R40–R41 for 2019, 2022, and 2025

Intersection R40–R41 shows an opposite trend compared to R38, with a continuous decrease in traffic demand over the observed period. Total weekly traffic in 2022 decreased by approximately 5.8% compared to 2019. In 2025, the average daily traffic amounted to 4,261 vehicles/day, representing a significant decrease of 22.9% compared to 2019. These results suggest a redistribution of traffic flows toward alternative routes.

Data collected from portable sensors indicate that traffic congestion and travel times in Rijeka can be mitigated if signal control systems are capable of adapting to variable demand in real time. Analysis of Rijeka's smart infrastructure suggests that congestion reduction mechanisms primarily stem from traffic-responsive signal control. Increased intersection capacity during peak periods results from the selection of optimal signal plans. Data from intersections R38 and R40–R41 reveal a repetitive pattern where vehicle speeds decrease during peak hours and approach free-flow conditions outside peak periods. At intersection R38, where a substantial speed reduction relative to free-flow conditions was recorded, even minor optimization of signal cycles could significantly reduce delays by alleviating traffic saturation. Improved allocation of green time during peak hours enables clearance of congested traffic flow.

4.2. Analysis of results and future development trends

The research results indicate that Rijeka has established a functional ITS foundation but has considerable potential for further development. Compared to leading global and European smart cities, Rijeka remains at a lower level of technological maturity. Traffic-responsive systems that react to detected conditions cannot be directly compared with network-coordinated predictive systems based on artificial intelligence. When compared to smart cities such as Hangzhou and Seoul, Rijeka has already made an important step forward by integrating 87% of its signalized intersections into a traffic-responsive control system. However, the absence of AI-based traffic prediction capabilities remains evident. In advanced smart cities, intersections are not managed in isolation, as demonstrated by the City Brain system in Hangzhou, which operates at the level of the entire urban network, enabling more efficient traffic distribution. In Seoul, smart intersections function as part of a broader digital urban infrastructure, in which traffic data are integrated with meteorological conditions and incident monitoring. In both cities, key components include video analytics and centralized AI-driven data processing, whereas Rijeka continues to rely predominantly on local intersection control based on predefined signal plans.

From an infrastructure perspective, video-based detection systems capable of monitoring the entire network and collecting queue-length data will play a crucial role in future smart traffic management in Rijeka. The city should upgrade its network toward coordinated and predictive control. Expanding video analytics and standardizing detection across a greater number of intersections represents the next essential step. Cameras should be capable of reliably measuring vehicle queue lengths, not only traffic flow and speed. The analysis indicates that Rijeka's current system primarily reacts to traffic conditions rather than anticipating them. This highlights the need for AI-based support systems capable of predicting traffic conditions several minutes in advance, enabling preventive congestion management, particularly in the city center during peak hours or tourist seasons. In terms of energy efficiency, Rijeka has already made significant progress by equipping all traffic signals with LED lights, substantially reducing operational costs, as demonstrated by the example of Barcelona. However, the development of smart traffic infrastructure also presents challenges, including high investment costs, the need for specialized personnel, and reliable communication networks. Rijeka's limited financial and technical resources constrain rapid modernization, as reflected in the heterogeneous signal controller inventory. EC1-type controllers, which dominate the network, cannot be compared with technologies used in leading smart cities. Much of the existing equipment relies on outdated technology and requires upgrading, potentially supported through EU funding mechanisms. Furthermore, the deployment of advanced technologies raises concerns regarding data protection and cybersecurity. Investment in robust cybersecurity measures is therefore essential.

Based on the collected research results, a SWOT analysis of urban traffic development in the city of Rijeka was conducted and is presented in Table 3.

Table 3. SWOT analysis of urban transport development in the city of Rijeka

STRENGTHS	WEAKNESSES
<ul style="list-style-type: none"> ⇒ The city center is relieved by a network of national, county, and local roads, together with access to the motorway and bypass routes ⇒ 87% of traffic signals already operate under traffic-responsive control, providing a solid technical foundation for the development of more advanced systems ⇒ Replacement of conventional incandescent bulbs with LED signal lights contributes to sustainability ⇒ Centralized traffic monitoring enables traffic data collection and coordination of traffic signals, forming the basis for future modernization 	<ul style="list-style-type: none"> ⇒ The traffic management system lacks predictive algorithms and centralized coordination at the level of the entire network ⇒ Insufficient synchronization of traffic signals with public transport vehicles and emergency services reduces the efficiency of public transport and its competitiveness compared to private cars ⇒ Real-time traffic optimization is hindered by the heterogeneity of traffic detection technologies ⇒ Financial, technical, and human resources required for the development of advanced ITS solutions remain limited
OPPORTUNITIES	THREATS
<ul style="list-style-type: none"> ⇒ Availability of European Structural and Investment Funds to support ITS development projects ⇒ Implementation of predictive traffic management systems could improve signal performance and reduce delays ⇒ Promotion of cycling, walking, and electric vehicles may reduce dependence on private car usage ⇒ Deployment of 5G communication and Big Data analytics enables faster modernization of traffic systems 	<ul style="list-style-type: none"> ⇒ Continued growth in private car usage may lead to further congestion, particularly during peak hours ⇒ Expansion of digital systems and traffic data collection may compromise data privacy and cybersecurity if not properly addressed ⇒ Rijeka's specific topography and limited number of alternative routes hinder traffic redistribution in the event of congestion or road closures ⇒ Obsolete traffic signal equipment may reduce ITS reliability and complicate system upgrades

A review of the results of this research indicates that the city of Rijeka is currently in a transitional phase between a conventional traffic-responsive control system and an AI-driven, smartly interconnected infrastructure. Future development should focus on centralized data analytics, integration of public transport, and the expansion and

deployment of video-based traffic detection systems, alongside the gradual introduction of predictive algorithms. It is realistic to conclude that the city of Rijeka will face financial and technical constraints in achieving these objectives.

5. Conclusion

Based on the analysis of the literature and the collected empirical data, it has been determined that signalized intersections are the locations where the greatest delays, traffic congestion, and increased emissions of harmful gases occur in urban environments. For this reason, the modernization of intersection control represents one of the most effective solutions for improving traffic flow efficiency. A review of contemporary examples of system implementation worldwide, particularly in cities such as Hangzhou and Seoul, shows that advanced systems based on artificial intelligence and real-time data analysis enable predictive traffic management. These systems anticipate traffic demand and optimize signal plans at the level of the entire urban network. The results indicate a reduction in travel time, an increase in average travel speeds, and a decrease in CO₂ emissions.

The analysis further indicates that the city of Rijeka has already established the basic foundations of intelligent transportation systems through its traffic control center. Opportunities for reducing congestion and travel time lie in further investments in traffic detectors and smart traffic signals, the transition toward network-coordinated traffic control, and the implementation of AI support at the level of the entire network. Additionally, the installation of LED signalization represents an important technological advancement in reducing electricity consumption. However, the system remains relatively heterogeneous and is largely based on predefined signal plans, without advanced analytics and coordination at the network level. Traffic analysis was conducted at selected intersections, and the results showed that the greatest positive effects of smart traffic management can be achieved in the most heavily loaded intersections. Traffic count results at intersections R38 and R40–R41 indicate different traffic patterns. Intersection R38 proved to be significantly congested during peak hours, where traffic flow speed dropped to 21.3 km/h. Even minor optimization of signal cycles at this intersection could lead to a reduction in delays and fuel consumption savings. On the other hand, at intersection R40–R41, lower and more stable traffic demand was observed, resulting in less pronounced effects of smart signalization. This confirms that the potential of smart intersections largely depends on local traffic conditions and that the greatest benefits are achieved at critical points within the network. Smart intersections thus represent an efficient and sustainable tool for improving urban mobility in the city of Rijeka, particularly when applied in a targeted and systematic manner.

For the future development of smart systems in Rijeka, it is essential to focus on the expansion of video analytics, the introduction of a centralized analytical system, and the gradual implementation of traffic prediction algorithms. An important component

is also the stronger integration of public urban transport. By implementing priority systems for buses and emergency vehicles, the reliability of public transport would increase and dependence on private vehicles would be reduced. Nevertheless, further development is hindered by high investment costs, the need for specialized personnel, technical heterogeneity of equipment, and insufficient levels of cybersecurity and data protection. In addition, the topographical and spatial characteristics of Rijeka limit the possibilities for redistributing traffic flows. It can therefore be concluded that smart intersections represent an effective and sustainable tool for improving urban mobility in Rijeka; however, achieving their full potential will require significant additional financial investments if the city aims to keep pace with leading smart cities in the field of intelligent transportation systems.

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