

IMPACT OF INTELLIGENT TRAFFIC MANAGEMENT SYSTEM IN THE MAKING OF SMART CITIES: A CASE OF PATNA

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Abstract

This paper explores the impact of the Intelligent Traffic Management System (ITMS) in Patna. Rapid urbanization in Patna has intensified traffic congestion, safety risks, and enforcement challenges, necessitating the adoption of an advanced traffic management solution. The Intelligent Traffic Management System (ITMS) integrates Adaptive Traffic Control Systems (ATCS), Red-Light Violation Detection (RLVD), Automatic Number Plate Recognition (ANPR), and Speed Violation Detection (SVD) to optimize intersection efficiency and regulatory compliance. This study evaluates the system's impact using a combination of traffic performance data, violation trends, congestion indicators, and preliminary environmental proxies. Key findings reveal that ITMS has led to a substantial increase in automated violation detection, a notable reduction in traffic congestion and average travel time and improved administrative efficiency at the Integrated Command and Control Centre (ICCC). The results demonstrate that ITMS provides measurable operational and economic benefits, making it a scalable, replicable, and policy-relevant model for improving urban mobility, traffic governance, and road safety in rapidly growing Indian cities.

Keywords: Adaptive Traffic Control System (ATCS); Automatic Number Plate Recognition (ANPR); Red Light Violation Detection (RLVD); Speed Vehicle Detection (SVD)

Introduction

India is home to one-third of the global South population, and the cradle of the ambitious Smart Cities Mission. A major part of this mission-the intelligent traffic management system (ITMS)-is one of the advanced solutions in the smart city mission to address the congested traffic conditions faced by many cities. As a result of rapid industrialization and urbanization, many cities face

an increased population volume, resulting in an unplanned city infrastructure including road and junctions. An increasing population requires a multi-mode transport system for seamless daily commuting. Because of the unplanned city infrastructure, heavy traffic congestion, traffic violations, road accidents, and a disconnected transport system become a curse to the growing

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population. ITMS is revolutionizing how we move people and goods using modern technology, data, and communication tools to make transportation networks more efficient, safe, and eco-friendly. ITMS relies on advanced information and communication technologies to improve various aspects of transportation, such as traffic control, vehicle operation, and public transit systems. With the help of real-time data, sensors, and smart algorithms, ITMS aims to ease traffic congestion, shorten travel times, boost safety, and reduce environmental impact (Elassy *et al.*, 2024).

A smart transportation system uses advanced technology to improve various transportation-related applications and systems. When applied to traffic management, it gathers precise information about roads, traffic conditions, and accidents, helping to make better decisions. By quickly identifying routes, destinations, road conditions, and traffic levels, smart transportation systems help reduce delays for travellers. They can suggest alternative routes and accurately understand user needs, making travel smoother and more efficient. Overall, smart transportation systems enhance the reliability and effectiveness of traffic management, making our road networks function better and more predictably (Manimurugan and Almutairi, 2023).

The transportation sector in Indian cities is a significant contributor to greenhouse gas emissions, primarily from vehicles using fossil fuels. For a city like Patna, which has rapidly increasing vehicle ownership and traffic congestion, transportation would similarly account for a substantial portion of emissions. Like major global cities, Patna also faces considerable traffic congestion, leading to significant economic losses due to wasted time and fuel (Liu *et al.*, 2024). Smart sensors and advanced algorithms to manage traffic flow more effectively reduce congestion in increasingly complex urban environments. Unlike traditional traffic signal methods which rely on fixed durations or basic adaptive controls that can't easily adapt to changing traffic patterns, intelligent systems leverage real-time data from smart sensors placed at intersections and along roads. These sensors can detect various factors such as traffic volume, vehicle speed, pedestrian movement, and even weather conditions.

By analyzing this data continuously, ITMS can make dynamic decisions to optimize traffic light timings, adjust signal phases, and prioritize certain lanes or routes based on current traffic conditions (Singh, 2017). For example, if sensors detect heavy traffic build-up in one direction, the system can extend the green light duration for that direction to ease congestion. Similarly, in low-traffic conditions,

it can reduce unnecessary wait times, improving overall traffic flow efficiency.

These systems can also predict traffic patterns using machine learning algorithms, enabling proactive measures to prevent congestion before it occurs. Smart traffic lights can communicate with each other and coordinate their operations to create a "green wave" that allows vehicles to pass through multiple intersections without stopping. Additionally, smart traffic management systems can provide real-time information to drivers through navigation apps, suggesting alternative routes to avoid congested areas. Overall, by utilizing smart sensors and data-driven decision-making, intelligent traffic management systems help to reduce congestion, decrease travel times, lower fuel consumption, and minimize emissions, contributing to a more efficient and sustainable urban transportation network (Huang, 2024).

The traffic signal control system plays a critical role in urban traffic management by regulating and directing the flow of vehicles through controlled signal changes. This system not only enhances road traffic efficiency but also helps reduce congestion and improve overall safety (Khan *et al.*, 2023). In recent years, the development of an adaptive optimal control model for traffic signals based on reinforcement learning has emerged as a promising option in intelligent transportation systems. The core concept of this approach involves leveraging reinforcement learning algorithms to dynamically adjust traffic signal control strategies in response to real-time traffic conditions and environmental variables. This enables adaptive optimization of traffic lights, leading to more efficient traffic flow management. The integration of such intelligent, data-driven models in traffic signal control offers a forward-looking solution, poised to significantly improve the performance of urban traffic systems.

Literature Review

The ITMS plays an integral role in urban traffic management by streamlining traffic flow, reducing congestion, curbing environmental pollution, and enhancing road safety. By leveraging advanced technologies, ITMS not only decreases the occurrence of traffic violations and accidents but also promotes efficient use of multi-modal transportation systems. The system's impact is observed across four major areas: Area-Based Development (ABD), Redevelopment, Greenfield Development, and Pan-City Initiatives. ABD focuses on creating a more orderly traffic environment by enforcing traffic laws and

prosecuting violators, ultimately making existing urban areas more efficient and liveable. In contrast, Redevelopment modernizes infrastructure by integrating technological solutions that offer real-time data on traffic conditions, which helps to improve situational awareness and response. Greenfield Development introduces intelligent traffic systems in newly developed or previously unused areas, facilitating real-time traffic analysis and enabling proactive traffic management. Additionally, Pan-City Initiatives extend these smart solutions across the entire city, encompassing areas such as traffic management, water conservation, and waste management to create a cohesive urban ecosystem (Sahay and Ranjana 2024).

In terms of practical application, cities like Ahmedabad, Bhubaneswar, and Pune have implemented similar smart city initiatives. Ahmedabad's ITMS enhances traffic efficiency and reduces bottlenecks, while the city also uses smart water meters and a robust waste management system to ensure efficient resource utilization. Bhubaneswar has established a Smart City Operations Centre to monitor services in real-time, coupled with the integration of intelligent public transport and safety solutions. Pune has focused on innovative transport initiatives such as public bicycle-sharing systems and smart parking, while also employing smart grid technology for more effective energy management. These examples demonstrate how the application of ITMS and related smart city initiatives can transform urban infrastructure, improve service delivery, and promote sustainability across a wide range of urban environments.

ITMS in Patna has led to significant improvements in urban mobility, road safety, and overall quality of life for its residents. One of the most prominent outcomes has been the reduction in traffic congestion, as the Adaptive Traffic Control System (ATCS) ensures smoother traffic flow by adjusting signal timings based on real-time conditions. This dynamic control has minimized delays, particularly at busy intersections, leading to a noticeable decrease in commute times for citizens. Additionally, with the integration of the Red-Light Violation Detection (RLVD) and Speed Violation Detection (SVD) systems, traffic violations have decreased, resulting in safer roads. The automated issuance of e-challans has enhanced law enforcement's ability to manage traffic violations efficiently and generate revenue for the city (Khan *et al.*, 2023).

ITMS are integral to the smart city framework, enhancing urban mobility, reducing congestion, and contributing to sustainable infrastructure

development. This literature review explores the impact of ITMS within smart cities, particularly focusing on sustainable development facilitated by integrated command and control centers (ICCC).

ICCCs are pivotal in managing urban resources efficiently, enhancing the quality of life, disaster response, and urban security while conserving natural resources. These centers integrate various urban management systems, including ITMS, to create a cohesive urban management strategy. The systematic review highlights the role of ICCCs in ensuring sustainable urban development by integrating data from multiple sources to optimize urban services and infrastructure management (Belli *et al.*, 2020).

Sustainable development within smart cities is a complex, multidimensional concept that involves integrating economic growth, social well-being, and environmental responsibility. This approach focuses on improving the quality of life, offering better employment opportunities, and ensuring efficient service delivery while addressing critical environmental challenges through innovative, technology-driven solutions (Attaran *et al.*, 2022). The implementation of ITMS within smart cities is one such solution that aligns with these broader sustainability goals. By optimizing traffic flow, reducing vehicle emissions, and enhancing urban mobility, ITMS contributes significantly to the environmental sustainability of cities while improving the overall efficiency of urban transportation systems (Trindade *et al.*, 2017). The integration of sustainable design principles and the Internet of Things (IoT) further strengthen the smart city framework. Sustainable urban environments can be significantly enhanced through the balance of human-environment-society-economy systems. By leveraging City Information Modelling (CIM) platforms, urban planners can take a holistic approach to spatial planning and management, focusing on addressing the needs of citizens while promoting ecological efficiency. ITMS plays a vital role in this vision by providing real-time data analytics and adaptive traffic control measures, which improve traffic flow and contribute to reduced pollution levels. Urban planning in smart cities must also incorporate resilience to address the increasing complexities brought about by urbanization and the growing demand for resources. The integration of ITMS within urban planning frameworks enables cities to mitigate traffic congestion, reduce environmental impacts, and enhance their overall resilience to rapid urban growth. Cities like Amsterdam and Copenhagen have demonstrated this through the successful deployment of advanced traffic management systems, using real-time data and IoT to improve

the efficiency of urban mobility and reduce emissions. These systems represent practical applications of ITMS in supporting sustainable development goals. Despite the notable advantages, the implementation of ITMS presents challenges such as high infrastructure costs, data privacy concerns, and the need for robust cybersecurity measures. The integration of ITMS with existing urban infrastructure requires detailed planning and coordination among stakeholders. Additionally, managing the vast amounts of data generated by ITMS systems poses challenges in terms of storage, analysis, and privacy. Nonetheless, by addressing these challenges and focusing on further research in areas like cost-effective solutions and interoperability, ITMS will continue to play a key role in the evolution of smart and sustainable cities.

The ITMS in Patna incorporates multiple privacy safeguards to protect citizen data while ensuring effective traffic management. Vehicle and commuter data captured by ANPR cameras and surveillance systems are anonymized before storage and analytics to prevent personal identification. Access to raw data is restricted to authorized personnel through role-based authentication, and secure encrypted channels are used for real-time data transmission to the ICC. The system adheres to relevant national guidelines for data protection in smart city projects, including compliance with the Digital Personal Data Protection Act (Ministry of Law and Justice, 2023) and Smart City Mission privacy frameworks. These measures ensure that operational efficiency is achieved without compromising individual privacy, providing a model for secure and responsible deployment of intelligent urban traffic systems.

ATCS is one of the important ITMS components in restructuring the issues about city traffic. ATCS focuses on how to improve the free flow of traffic in the city with the help of technological intelligence. ATCS to be deployed at 30 strategic locations, covering all important junctions of Patna city that is designed to dynamically respond to rapid variations in traffic conditions. It is an advanced system that can use data from several detectors and optimizes the traffic signal timing in real time. Adaptive algorithms in ATCS identify the critical junction in each corridor or region and determine the cycle time for all the junctions in the corridor or region based on the optimal cycle time for the critical junction. The architecture of ATCS is presented in Figure 1.

Conventional traffic signal systems operate on a fixed timing principle where traffic controllers at each intersection are pre-programmed with a set duration for red, green, and amber light phases. This fixed timing system is applied to all directions at the junction, regardless of the real-time traffic conditions. While this method once provided an effective means of managing urban traffic, it has become less efficient with the exponential growth in vehicle numbers due to increasing populations. As more vehicles fill city roads, the limitations of a rigid traffic control mechanism become more apparent. Vehicles are required to wait for a predetermined time, regardless of the traffic volume, leading to extended wait times at intersections. This can cause a cascade of negative effects, including increased fuel consumption, elevated emissions, and heightened air pollution levels, which ultimately contribute to public health concerns.

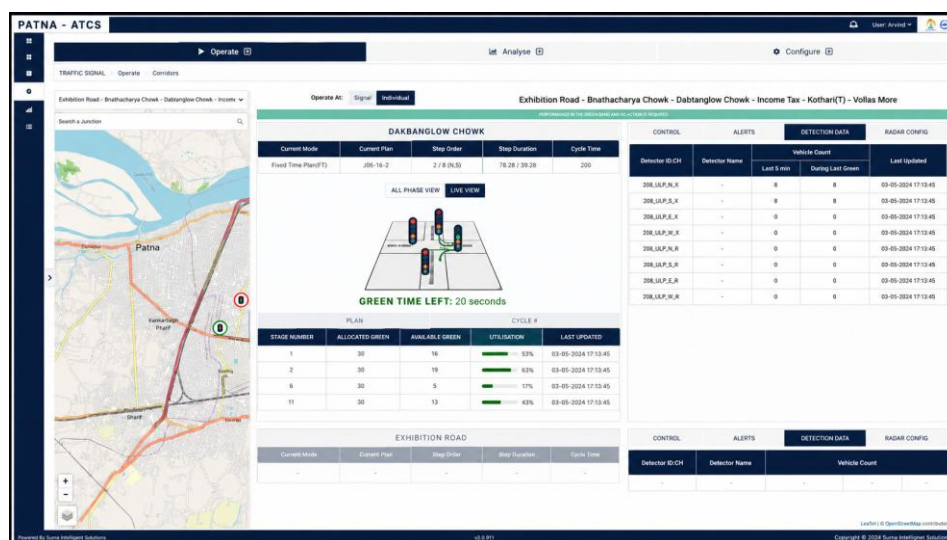


Figure 1. Architecture of the Adaptive Traffic Control System (ATCS)

One of the primary issues with conventional traffic control systems is their inability to adapt to fluctuating traffic volumes. Traffic controllers cannot modify signal durations based on real-time traffic flow, meaning that during periods of low traffic, vehicles may still face unnecessarily long wait times. Conversely, during peak hours or heavy traffic, the fixed timings fail to alleviate congestion efficiently, resulting in extended queues and further delays. The longer vehicles remain idle at traffic lights causing more fuel consumption and directly contributing to increased environmental pollution.

This inefficiency not only affects individual commuters but also adds stress to public health systems by contributing to respiratory issues caused by pollution. In addition to fixed signal timings, conventional systems also lack the capability to inform drivers or authorities about traffic congestion levels at any given intersection.

Without a real-time feedback loop, it becomes nearly impossible to re-route vehicles to alleviate congestion in specific areas. This absence of adaptability and feedback means that drivers remain unaware of alternative routes that could reduce their travel time and ease the overall burden on the road network. This inability to dynamically respond to congestion aggravates traffic situations, making traditional systems increasingly obsolete in modern, densely populated urban areas. Several studies have attempted to improve upon the conventional traffic system by introducing more dynamic methods of traffic control. For example, fuzzy logic-based controllers have been proposed to minimize queue lengths and waiting times at intersections by using variables like vehicle counts and waiting times to adjust the duration of green light phases. This approach offers an improvement over fixed-timing systems by attempting to match signal times to real-time conditions. However, such solutions still fall short in one critical area: they do not incorporate re-routing mechanisms. While these fuzzy logic systems manage to reduce congestion at intersections by controlling stop-and-go traffic more efficiently, they do not prevent congestion altogether, as they merely manage vehicles within the limited space of the intersection without addressing larger traffic flows throughout the city.

In essence, while conventional traffic signal systems once served as the backbone of urban traffic management, their rigid, pre-programmed nature now presents a significant barrier to efficient traffic flow. The need for more adaptive, real-time systems that can adjust signal times and provide dynamic routing information has become crucial in managing traffic congestion effectively in modern cities. Innovations in traffic management systems, which integrate advanced technologies like AI, IoT, and

real-time data analysis, are now being seen as the way forward in overcoming the limitations of traditional traffic systems (He *et al.*, 2024).

The implementation of the Adaptive Traffic Control System (ATCS) in Patna Smart City has successfully addressed the major drawbacks of conventional traffic signal systems. Unlike traditional methods, which operate on pre-set, rigid timings for red, green, and amber lights, ATCS is designed to be fully dynamic and responsive to real-time traffic conditions as shown in Figure 2.

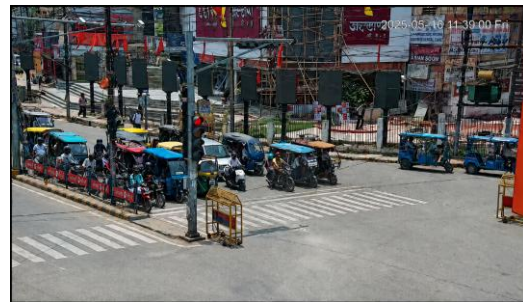


Figure 2. ATCS infrastructure

The system leverages specialized Machine Learning (ML) algorithms to intelligently capture and process traffic volume data from multiple approaches at each intersection. This data is then transmitted to a central server equipped with an Artificial Intelligence (AI) engine, which integrates inputs from various junctions across the city. By continuously processing this data feed, the AI engine can adaptively determine the optimal duration for traffic signals at each junction, ensuring efficient traffic flow and minimizing congestion throughout the urban road network.

The dynamic adjustment of signal timings represents a major departure from the fixed-timing approach of conventional systems. The ATCS system's ability to adapt in real time not only reduces waiting times for vehicles at intersections but also addresses the root causes of traffic congestion by optimizing vehicle movement across the entire city. This results in a more balanced distribution of traffic loads, reducing bottlenecks and improving overall traffic efficiency. The use of ML algorithms further enhances the system's capability, allowing it to learn and adapt to evolving traffic patterns over time. By considering historical data and real-time inputs, the system ensures that traffic signals operate at peak efficiency under a wide variety of traffic conditions.

Building on these advancements, the implementation of ATCS in Patna has led to significant improvements in key metrics such as travel time reliability, fuel consumption, and

vehicular emissions. The system has demonstrated the ability to significantly reduce idle time at intersections, contributing to a marked decline in fuel wastage and air pollution levels. For instance, the system's data-driven optimization of signal timings has resulted in smoother traffic flow, which directly correlates with lower emissions of greenhouse gases and particulate matter.

Moreover, the integration of ATCS with the city's ITMS has further enhanced its operational efficiency. The centralized control room receives real-time traffic data from ATCS and integrates it with inputs from other smart traffic management systems, such as RLVD and ANPR. This seamless integration enables a more comprehensive approach to traffic management by addressing violations, improving enforcement, and streamlining vehicle movement.

The architecture of the adaptive traffic solution is presented as Figure 3. In addition to addressing traffic congestion, the deployment of Automatic Number Plate Recognition (ANPR) systems across 29 strategic locations in Patna adds another critical layer of functionality to the city's traffic management strategy. The ANPR system automatically captures the license plates of vehicles entering, exiting, or passing through key points within the city, regardless of the type of vehicle as shown in Figure 4.

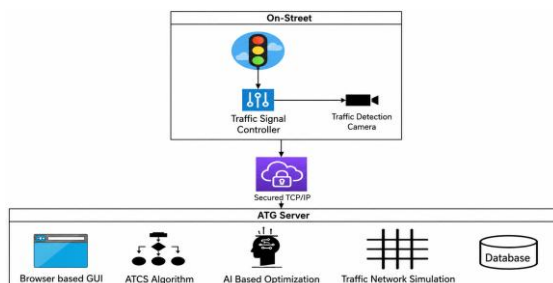


Figure 3. Architecture of the Adaptive Traffic Control System (ATCS) solution

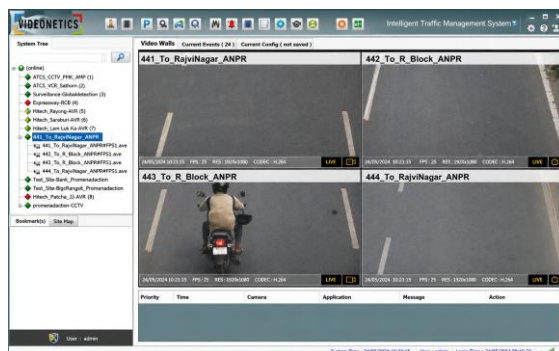


Figure 4. Vehicle detection process

This data is stored in a central database, allowing authorities to retrieve vehicle information, along with video footage, at any later point. The ANPR system enhances the enforcement of traffic regulations by providing a comprehensive record of vehicle movements, aiding in the identification of traffic violators and improving overall road safety.

The integration of ATCS and ANPR not only provides a more efficient traffic management framework but also creates a smarter, more connected urban environment. The real-time traffic data processed by the AI engine is used to optimize signal timings, reducing vehicle idling and contributing to lower emissions. Meanwhile, the ANPR system ensures that the city's roads are safer by enabling effective monitoring and enforcement. Together, these systems form a robust solution that not only addresses the shortcomings of conventional traffic management but also contributes to the broader goals of sustainability, safety, and livability within Patna Smart City.

By using these advanced technologies, Patna Smart City's traffic management system effectively enhances urban mobility, reduces environmental impact, and strengthens the city's capability for proactive traffic enforcement. The adaptive nature of ATCS and the strategic deployment of ANPR demonstrate how cutting-edge innovations can resolve traditional traffic challenges, paving the way for a more resilient and efficient urban future.

The integration of Optical Character Recognition (OCR) technology within Patna's ITMS plays a critical role in enhancing automated enforcement and real-time traffic monitoring. The ANPR system utilizes OCR to identify and read vehicle license plates by analyzing captured images from strategically positioned cameras. The software, powered by OCR, processes the characters on the license plate and automatically displays the number on the system's interface. This enables seamless data collection and storage, ensuring that vehicle details can be retrieved for law enforcement purposes when necessary. By automating the process of identifying vehicles, the ANPR system significantly reduces the manual effort required for traffic regulation and improves the accuracy of monitoring.

Complementing the ANPR system, the Red-Light Violation Detection (RLVD) system has been deployed at 30 key intersections across Patna. This system is designed to capture real-time evidence of vehicles running red lights using both detection and evidence cameras. The detection camera monitors the vehicle's position, while the evidence camera simultaneously captures both the vehicle and the state of the traffic light

(Chettry, 2024). This dual-camera setup generates a set of five screenshots as evidence, along with video footage, which is stored in a centralized database. The ANPR system decodes the vehicle's license plate, providing crucial data for law enforcement to pursue violations. The RLVD system represents a significant advancement over conventional traffic enforcement, offering irrefutable evidence that can be used to issue fines and penalize offenders, thus improving compliance with traffic rules.

In addition to the RLVD system, the Speed Violation Detection (SVD) system has been deployed at five critical locations in Patna, including the high-traffic Ganga Path and Atal Path (Liu *et al.*, 2024). The SVD system is equipped with speed-detection cameras that monitor vehicles exceeding the speed limits within the field of view (FOV). As with the RLVD system, the SVD captures the license plates of speeding vehicles, stores the data, and records video footage for future reference. This system plays a crucial role in reducing speeding-related accidents and enhancing road safety by automating speed enforcement in high-risk areas (Thahir *et al.*, 2024). The use of real-time data, coupled with automatic violation detection, makes the SVD system an essential component of the ITMS, helping to create safer roads and deterring reckless driving.

Once violations are identified through the ANPR, RLVD, or SVD systems, the E-Challan system automates the issuance of fines to the vehicle owners. Violations, such as speeding, red light violations, triple riding, wrong-way movement, and riding without a helmet, are recorded on the central server. The system automatically generates and sends a challan (fine ticket) to the vehicle owner via SMS, detailing the offense along with evidence from the video footage and screenshots. This seamless integration of multiple systems within the ITMS ensures that traffic violations are addressed promptly and efficiently while reducing the manual burden on traffic enforcement officers.

Together, these automated systems ANPR, RLVD, SVD, and E-Challan form a robust framework for intelligent traffic management in Patna (Wen, 2010). They address longstanding challenges related to manual traffic enforcement, such as human error, inefficiency, and limited coverage, by introducing technology-driven solutions that enhance accuracy, reliability, and timeliness. The ITMS not only optimizes traffic flow and improves road safety but also fosters greater adherence to traffic laws through consistent and automated enforcement. This holistic approach to traffic management supports Patna's broader smart city initiatives, contributing to the city's

livability, sustainability, and resilience by leveraging advanced technologies for urban governance.

Problem Management

Patna, the capital city of Bihar has been witnessing rapid urbanization in recent years. The city has experienced significant population growth and infrastructural development, resulting in expansion of the urban areas and increased demand for urban services. The urban population of Patna district was 1,825,000 in 2011, and it is estimated to be 2,529,000 in 2023. The urbanization rate of the Patna district was 11.3% in 2011, and it is estimated to be 15.3% in 2023.

Patna, Bihar was facing challenges like inadequate transportation infrastructure, unreliable public transportation, traffic congestion, and environmental pollution (Chan *et al.*, 2021). The inadequate transportation infrastructure and unreliable public transportation systems result in long commuting hours, delays, and overcrowded vehicles. This not only causes inconvenience to the citizens but also wastes valuable time, affecting their productivity and quality of life. The traffic congestion in Patna leads to increased travel time, pollution, and respiratory health issues for the citizens. Prolonged exposure to polluted air can have long-term health impacts and reduce the overall quality of life.

An article published on 6th May 2022 by The Times of India, reported that as per the data collected from the Integrated Road Accident Database (IRAD), 2,375 road accidents occurred in Bihar out of which 1961 people have lost their life. Further, the reports say that the number of road accidents in the first three months of the year (January to March) has declined by 7.73% in the state when compared to the same period in 2021. This has been achieved by manual helmet-checking drive, stopping drivers from using cell phones at the time of driving, and traffic awareness programs. However, these manual steps taken against the prevention of road accidents were not enough to bring casualties to zero.

Hence, it has been proposed to adopt and implement the Smart Traffic Management System under the Patna Smart City Project that can bring casualties due to road accidents to zero and help in traffic management, smooth traffic flow, and reduce traffic congestion.

With the advent of ITMS, how Patna Smart City adapted to handle the shortcomings of conventional traffic systems, particularly concerning real-time traffic flow management and

congestion reduction will be highlighted. The aim of this study is to bring forth the impacts of implementing the ITMS on the overall scenario of smart Patna city.

Methodology

The methodology is built around the deployment of an Adaptive Traffic Control System (ATCS) for the city of Patna, aimed at optimizing traffic flow in real-time by dynamically adjusting signal timings based on traffic volume and other parameters. The system consists of a two-tiered structure: a tactical traffic control layer and a strategic traffic control layer, each of which plays a crucial role in achieving the goals of seamless traffic management.

The study aims to provide a nuanced understanding of how this technology-driven system has influenced traffic behavior and road safety. The tactical traffic control layer, which operates on a second-by-second basis, receives real-time data from vehicle detectors at intersections. The data feeds into a central server equipped with ML algorithms and AI to predict traffic flow and optimize signal timings (Boukerche *et al.*, 2020). This system effectively captures traffic volume at various junctions and adjusts signal timings based on traffic conditions, ensuring minimal delays and avoiding congestion. The adaptive capabilities allow the system to respond to varying traffic loads at different times of the day, making it a highly responsive solution for the challenges of urban traffic. Road accidents have long been a major concern in Bihar, with fatality rates much higher than in developed countries. The increasing number of motor vehicles on the road has escalated the risk of accidents, making road safety a critical issue. The identification of black spots, and areas where accidents frequently occur, has been crucial for understanding and mitigating accident risks. Before the implementation of the ITMS in cities like Patna, Bihar had seen a steady increase in road accidents, particularly in black spot areas. The lack of real-time traffic management and enforcement mechanisms resulted in chaotic driving conditions, where the primary causes for accidents like over-speeding and reckless driving, violations of traffic signals and road rules, poor road infrastructure and geometric design flaws.

Lack of awareness regarding safety precautions like helmets and seatbelts. Despite the efforts of local traffic police, manual enforcement was limited, making it difficult to manage the growing number of vehicles and road users effectively.

The road accident rate was alarmingly high, with fatalities often occurring in high-traffic zones due to the absence of technological interventions.

The strategic traffic control layer works at a macro level, providing a framework for long-term traffic management by running simulations and “what-if” analyses. Using state-of-the-art traffic modeling tools such as SUMO (simulation of urban mobility), the system can simulate different scenarios, such as emergencies or special events, and predict their impact on traffic. This layer enables traffic managers to implement interventions at key points in the network, further improving traffic flow and minimizing disruptions. The central control system enables integration with external data sources, such as ANPR, GPS devices in buses and emergency vehicles, and even CCTV (closed circuit television) footage. The integration of these subsystems enhances real-time decision-making and provides predictive capabilities that improve the accuracy of traffic management (Gan *et al.*, 2024).

At the heart of this methodology is the Intelligent Traffic Signal Controller (ITSN), deployed at each intersection. The ITSN is designed with several critical modules that make it both adaptable and reliable. The signal control ensures that the ATCS remains operational and effective, even under challenging conditions. The system also incorporates advanced vehicle detection technologies, utilizing video-based detectors instead of traditional inductive loops, which are ineffective in India’s heterogeneous and undisciplined traffic conditions (He *et al.*, 2024).

Figure 5 further shows the lane wise vehicle detection. Virtual loops defined within the cameras trigger vehicle detection, feeding real-time data back to the ATCS server for signal optimization. The methodology thus overcomes the limitations of conventional vehicle detection systems, allowing for greater accuracy in vehicle count and presence detection under all light and weather conditions.



Figure 5. Lane-wise vehicle detection

A major feature of this system is the green corridor functionality, which prioritizes certain

vehicles, such as ambulances and VIP vehicles, by adjusting the traffic lights along their routes. Using GPS data from the priority vehicles, the system can estimate arrival times at each signal and adjust the signal timings accordingly to ensure these vehicles face minimal delays (Ouallane *et al.*, 2022). This feature is critical in emergency response scenarios and significantly enhances the system's utility.

In addition to its core traffic management functions, the ATCS integrates with external systems such as Variable Message Signs (VMS) and Public Address (PA) systems. These systems allow traffic managers to provide real-time updates to commuters regarding traffic conditions, roadwork, or events affecting traffic.

This holistic approach to traffic management ensures that the system is not only reactive but also predictive and communicative. Finally, the ATCS software operates on an open-source platform with a robust database that tracks historical traffic data, system performance, and fault reports. The system's analytical tools offer traffic managers comprehensive reports on junction performance, signal timing, and congestion levels, facilitating ongoing optimization and strategic planning (Balakiruthiga and Deepalakshmi 2021). The modular nature of the software enables customization, ensuring the system can evolve and improve as needed to meet the growing demands of Patna's urban environment. This methodology represents a highly advanced, integrated approach to urban traffic management, leveraging the power of AI, ML, and real-time data analysis to create a flexible, scalable, and efficient system that addresses the complex challenges of modern city traffic.

ITMS play a crucial role in the Smart Cities Mission, which is designed to address the multifaceted challenges faced by Indian cities through smart solutions. The core objective of this mission is to enhance urban governance, infrastructure, mobility, environmental sustainability, and social inclusion by employing cutting-edge technology, including ITMS.

The ITMS solution exemplifies the transformative potential of smart city technologies by providing a robust framework for traffic management. In cities like Patna, this system utilizes real-time data collection, analytics, and automation to reduce congestion and improve road safety, contributing to the city's long-term sustainability. ITMS integrates various traffic control systems such as Adaptive Traffic Control Systems (ATCS), Automatic Number Plate Recognition (ANPR), Red Light Violation Detection (RLVD), and Speed Violation Detection (SVD), which operate in unison to manage and

monitor the flow of vehicles more efficiently (Rajan and Datta, 2024). The adaptive nature of these systems allows for real-time adjustments to traffic signals and interventions based on the evolving conditions of the road network.

The architecture of ITMS involves a multi-layered approach wherein traffic data from multiple detectors and cameras are aggregated to build a comprehensive picture of traffic flow (Penchalaiah *et al.*, 2024). The ATCS, a central component, dynamically adjusts signal timings based on real-time vehicle count data, helping to optimize signal efficiency and minimize delays. Table 1 presents the changes in average traffic waiting times before and after ITMS implementation.

Table 1. Traffic flow optimization before and after ITMS implementation

Location	Pre-ITMS avg wait time (sec)	Post-ITMS avg wait time (sec)	Reduction (%)
Exhibition Road	140	90	36 %
Dakbanglow Circle	150	110	27 %
Golghar Tiraha	115	60	48 %
Jagdeo path	100	60	40 %
Voltas More	60	45	25 %

This real-time feedback loop is crucial to improving the traffic conditions in high-density urban areas. ANPR systems, working in tandem with RLVD and SVD systems, further enhance traffic enforcement by automatically detecting violations, generating evidence, and transmitting e-challans to violators. The integration of these systems ensures not only traffic regulation but also revenue generation for the city through the collection of fines, which can be reinvested into other smart city initiatives.

The technical challenges include issues related to network connectivity fluctuations, calibration and synchronization of field devices (such as ANPR cameras, adaptive signal controllers, and surveillance units), and delays in hardware integration across multiple vendor systems. Challenges in real-time data communication between field equipment and the Integrated Command and Control Centre (ICCC) were also documented, primarily due to inconsistent power supply and limited redundancy in network infrastructure. Moreover, interoperability between new ITMS modules and existing traffic databases required iterative adjustments in data formatting and API configurations.

The ATCS forms a critical component of ITMS, enabling dynamic and efficient traffic regulation through advanced signal control

mechanisms. By leveraging real-time traffic data, ATCS optimizes parameters such as phase sequencing, cycle lengths, phase splits, and offsets across intersections. This study analyses the operational features and impact of ATCS in enhancing traffic flow, reducing congestion, and ensuring system resilience across varied urban traffic scenarios.

Phase Sequencing: The signal cycle is divided into defined phases (e.g., 1, 2, 3). Non-essential phases are skipped when no vehicles are detected, except for critical roads. This ensures minimal idle time and optimizes traffic flow. In isolated mode, the sequence is fixed per local controller settings.

Cycle Length is adjusted to maintain an ideal Degree of Saturation (DS) of approximately 0.9. The range is user-defined (20–255 seconds), ensuring optimal lane utilization and preventing over-saturation, thus maintaining smooth traffic operations. The degree of saturation is expressed as:

$$DS = \frac{q}{s} \quad (1)$$

q: Traffic demand (vehicles/hour)
s: Saturation flow rate (vehicles/hour)

As per Equation (1) DS indicates the efficiency of signalized intersections. A target value of $DS \approx 0.9$ ensures optimal traffic flow without oversaturation.

Phase Split Adjustment: Phase splits, expressed as a percentage of cycle time, are adjusted incrementally to balance DS across competing approaches. This dynamic allocation minimizes bottlenecks and ensures efficient intersection management. The optimal cycle length C is expressed as:

$$C = \frac{(1.5 L + 5)}{(1 - Y)} \quad (2)$$

C: Optimal cycle length (seconds)
L: Total lost time per cycle (seconds)
 $Y = \sum(q/s)$: Flow ratio for all critical movements

As per Equation (2) C determines the optimal cycle time to minimize delays at an intersection. Effective green time g is expressed as:

$$g_i = \frac{Y_i}{\sum Y} * (C - L) \quad (3)$$

g_i : Effective green time for phase i (seconds)
 Y_i : Flow ratio for phase i

As per Equation (3), g_i allocates green time across competing approaches based on their respective traffic volumes.

Offsets: Signal offsets are synchronized within and across subareas to improve coordination. While lower flow areas may not achieve optimal synchronization, well-defined cycle times can facilitate smoother flow across arterial networks. Offset time is expressed as:

$$O = \frac{d}{v} \quad (4)$$

O: offset time (seconds)
d: distance between intersections (meters)
v: average speed of vehicles (meters/second)

The offset time as per Equation (4) ensures synchronization between intersections, minimizing stops along arterial corridors. The average delay per vehicle is expressed as:

$$d = \frac{0.5 C (1 - \frac{g}{C})^2}{1 - \min(1, X)(\frac{g}{C})} + \frac{900 T (X - 1)}{C} \quad (5)$$

d: Average delay per vehicle (seconds)
C: Cycle length (seconds)
g: Effective green time (seconds)
X: Degree of saturation for the approach
T: Duration of analysis period (hours)

As per Equation (5) d quantifies the average delay experienced by vehicles, reflecting intersection efficiency.

Figure 6 shows that the dashboard is part of an Adaptive Traffic Control System (ATCS) used to monitor traffic signals at an intersection. It displays the junction layout, previous and current signal cycles, and the distribution of green time among different traffic phases. The bottom table compares the configured timings with the actual signal

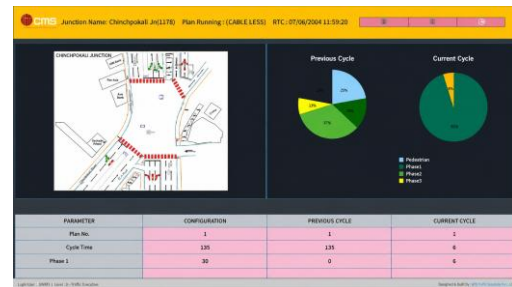


Figure 6. Traffic flow under the ATCS framework

timings. It helps traffic operators optimize signal timings and reduce congestion for smoother traffic flow.

ATC Mode: Adapts phase sequence and durations based on real-time traffic conditions while skipping unused phases to improve efficiency.

Sync Mode: Synchronizes adjacent signals using pre-determined plans, suitable for high-volume corridors with predictable traffic patterns.

Isolated Mode: Operates with fixed sequences and durations as per local controller settings, often serving as a fallback mechanism.

These mechanisms collectively enhance intersection throughput, reduce congestion, and ensure resilience in diverse traffic scenarios, establishing a robust framework for adaptive traffic management systems.



Figure 7. ATCS signal cycle operation

Figure.7 shows that ATCS (Adaptive Traffic Control System) is a smart traffic management system that adjusts traffic signal timings based on real-time traffic conditions using cameras and sensors. It reduces traffic congestion, vehicle waiting time, fuel consumption, and air pollution. It also improves road safety, supports emergency response, and enhances overall urban mobility in smart cities. In addition to traffic management, ITMS is part of a broader smart infrastructure network that includes public safety measures like CCTV surveillance and smart policing. This system also facilitates a greener urban environment by promoting smoother traffic flow, reducing vehicle idling times, and subsequently lowering emissions, thus contributing to air quality improvement. This is part of the broader environmental focus of the Smart Cities Mission, which aims to make urban spaces not only technologically advanced but also environmentally sustainable.

Smart city projects are inherently multidisciplinary, encompassing various sectors such as energy, water management, and urban mobility. In the context of energy management, smart grids and renewable energy sources are

employed to ensure efficient energy distribution (Praharaj *et al.*, 2018), while ITMS helps streamline public transportation, making urban mobility more fluid and reducing the need for individual vehicle use. Public safety and social infrastructure also benefit from the implementation of smart systems that ensure better law enforcement and emergency response times, facilitated by ITMS's capacity to provide real-time data to relevant authorities.

The implementation of ITMS and other smart city technologies faces several challenges (Tien, 2022). Financial constraints remain a significant barrier to widespread adoption, necessitating strategic partnerships with private entities through public-private partnerships (PPP). Technological integration also presents difficulties, particularly in terms of ensuring interoperability between different systems, which is critical to maintaining the cohesion and effectiveness of the entire smart infrastructure network. Furthermore, comprehensive urban planning and management are essential to prevent unplanned sprawl and ensure that smart infrastructure is maintained and optimized.

Citizen participation is another key factor in the successful implementation of smart city projects, including ITMS. Public awareness and engagement are necessary to ensure widespread compliance with traffic rules, as well as to foster a sense of ownership over the improvements made to the urban environment. The success of ITMS in cities like Patna will depend not only on technological sophistication but also on the active participation of the city's residents in embracing the new system, adapting to its functionalities, and recognizing its benefits in reducing traffic congestion and improving safety (Prasad and Alizadeh, 2020).

In summary, ITMS represents a critical solution in the broader context of smart city development, providing the backbone for smarter governance, infrastructure, and mobility in rapidly urbanizing environments. The system's ability to optimize traffic management in real-time, combined with its potential for integration with other smart city technologies, makes it a pivotal tool for achieving the objectives of the Smart Cities Mission. Nevertheless, addressing financial, technological, and participatory challenges will be vital to ensuring the long-term sustainability and success of ITMS and the larger smart city framework.

The implementation of the e-challan system in Patna Smart City, facilitated by the Intelligent Traffic Management System (ITMS), represents a sophisticated approach to managing and enforcing traffic regulations. The process begins with the deployment of high-resolution cameras strategically

installed throughout the city (Kapucu *et al.*, 2021). These cameras, equipped with advanced automated recognition software, are pivotal in monitoring and documenting various traffic violations. These violations include speeding, running red lights, incorrect lane usage, helmet-less riding, triple riding, and other infractions under the Patna Smart City Project's purview. Upon detecting a traffic violation, the ITMS system captures detailed images and videos, providing crucial evidence such as the vehicle's license plate, the nature of the violation, the location where the infraction occurred, and the precise timestamp. This evidence is initially processed by the system's automated components. However, to ensure the accuracy and validity of the recorded violations, the data undergoes manual validation by the Patna traffic police department. This step is critical in confirming that the recorded violation meets legal standards and is accurately represented (Praharaaj, 2020).

Following this validation, the details of the violation are integrated into a centralized database, which cross-references the data with the vehicle's registration information. This integration ensures that the violation record is correctly associated with the vehicle's registered owner. The validated violation is then uploaded to the ITMS Challan portal, where it undergoes final approval before the issuance of the e-challan. This digital document includes comprehensive details about the infraction, such as the nature of the violation, the amount of the fine, and the deadline for payment (Zeng *et al.*, 2022). Figure 8 depicts the process of E-challan generation. Once the e-challan is generated, it is sent electronically to the registered mobile number of the vehicle owner via SMS, ensuring that the owner is promptly notified. To facilitate compliance, Patna Smart City offers both online and offline payment options. Vehicle owners can settle their fines through an online portal or at designated counters.

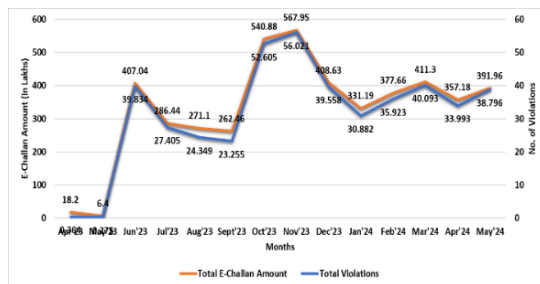


Figure 8. System-generated e-challan for the financial year 2023-24 (Apr-23 to May-24)

The ITMS database meticulously maintains records of all e-challans, encompassing both paid

and unpaid violations. This system ensures a thorough and transparent tracking mechanism, supporting future enforcement actions and providing a comprehensive overview of traffic violations within the city. Through this integrated approach, Patna Smart City effectively enhances its traffic management and enforcement capabilities, contributing to improved road safety and regulatory compliance. The Central Control Room for the ATCS system is designed to be the operational heart of traffic management, equipped with comprehensive hardware and software infrastructure essential for overseeing and controlling the traffic signal network (Joshi and Badola, 2024). This central hub maintains continuous communication with all traffic signal controllers distributed throughout the city. A critical component of this setup is the Application Programming Interface (API) provided by the ATCS, which delivers near real-time data on network status and system-generated alerts. This API, hosted on the control room's servers, facilitates seamless integration with other systems and supports the development of third-party mobile applications, thereby enhancing the overall connectivity and functionality of the ATCS. The communication network underpinning the ATCS is robust and secure, ensuring reliable data transmission between the field hardware and the central control software. Real-time data, including vehicle detection statistics, stage timings, operational modes, and event alerts, are transmitted through a stable communication network (Almihat *et al.*, 2022). This data exchange relies on the industry-standard UTM/UG405 protocol, which governs the interaction between the ATCS central application, and the traffic signal controllers installed at various junctions. The ATCS central application is designed for integration with central command and control software, facilitating a comprehensive management approach. Key parameters of the ATCS system, such as operational availability, current mode, and performance metrics, are communicated to the Command Center using UTM/XML APIs. These APIs, which can be customized to meet specific city requirements, play a crucial role in maintaining system transparency and enabling effective network management.

In addition to standard traffic management functions, the proposed solution incorporates advanced model-based optimization techniques to enhance traffic control efficiency. The system can generate detailed traffic counts, classify vehicle types, and estimate queue lengths, which provide valuable insights for dynamic traffic management (Pradhan, 2019). The high level of customization available allows for the testing and refinement of various control strategies, ensuring that the system

can be tailored to deliver optimal performance for Patna.

The ATCS control room application further enhances operational efficiency by eliminating the need for on-site manual adjustments. Instead, it offers a manual control option from the control room, which can be accessed through a role-based login system that ensures secure operation. This capability is complemented by features designed to prioritize specific types of traffic, such as emergency vehicles, VIPs, and public transport buses, thus improving overall traffic flow and response times. Additionally, the proposed system includes a mobile application for emergency vehicles, which enables these vehicles to receive priority at traffic junctions (Cheng and Sun, 2024). This integration not only supports emergency response efficiency but also provides real-time traffic condition information to the public, thereby promoting transparency and improving citizen engagement with the traffic management system. Through these advanced features and integrations, the ATCS at Patna Smart City aims to establish a highly effective, adaptable, and user-centric traffic management solution.

The e-challan process represents a structured and automated approach to monitoring traffic violations and issuing fines. The steps involve: Vehicles under Evidence Camera: Traffic surveillance cameras, often referred to as “evidence cameras,” are installed at key locations such as intersections, highways, or restricted zones. These cameras continuously capture footage of vehicles passing through their field of view. This footage serves as the basis for identifying traffic rule violations, such as speeding, jumping traffic signals, driving in the wrong lane, or illegal parking. Real-Time Event Detection: The system automatically scans the footage in real-time, looking for potential traffic violations. It utilizes image recognition and machine learning algorithms to detect violations like over-speeding, red-light crossing, or improper lane changes. This stage involves initial processing where events are flagged as potential violations for further review. Event Validation: Once a potential violation is detected, the footage is sent for manual or semi-automated validation. In this step, a traffic enforcement officer reviews the footage from ICCV system to verify if the detected event is an actual violation according to traffic rules. If the system or officer finds the event invalid (e.g., due to false detection, or justified vehicle action), it is discarded, and the system looks for another event. Violation Approval: If the event is validated as a legitimate violation, it proceeds to the approval stage. Here, the violation is officially

recorded on the ITMS challan portal, and relevant details such as the vehicle’s registration number, time, location, and type of violation are verified in the system. The system ensures that all necessary information is accurately captured to avoid errors in the next steps. e-Challan Generated: Once the violation is approved, the system generates an e-challan (electronic challan), which is an official notice of traffic rule infringement. The e-challan contains details such as: Violation date and time, Vehicle registration number, Location of the violation, Images or video evidence of the violation, Fine amount to be paid, E-challan is then sent to the vehicle owner, typically via SMS, email, or postal service. Outcome: The recipient is required to pay the fine within a specified period, failing which further action, such as increased penalties or legal proceedings, may be taken. The entire process is designed to be efficient, reducing the need for manual enforcement on the ground and increasing accountability through digital records. The e-challan system automates much of the traffic enforcement process, making it faster, more accurate, and less prone to human error while promoting safer driving practices.

Impact Analysis

The graph in Figure 8 is prepared based on last financial year 2023-24 system generated e-Challan details under Patna Smart City Limited. The E-challan data for Patna City displayed a fluctuating pattern with both low and high points. The months of April and May saw relatively low numbers of violations and E-challan amounts as the ITMS system was newly deployed and citizens were not accustomed to it (Savithramma and Sumathi, 2023). However, as the system was fully implemented and awareness spread, there was a significant surge in violations and E-challan amounts in June and July. Subsequently, in October and November, during the festive season, there was a sharp increase in E-challans due to a higher number of people violating traffic rules. Finally, towards the end of the year, the numbers returned to a more normal pace, indicating a potential stabilization in the adherence to traffic rules by the citizens. This data provides valuable insights into the trends of traffic rule compliance among the populace.

The graph in Figure 9 is prepared on basis of the last financial year system generated e-Challan details under Patna Smart City Limited. The most common violations are riding without a helmet, triple riding, and wrong-way movement of the vehicle.

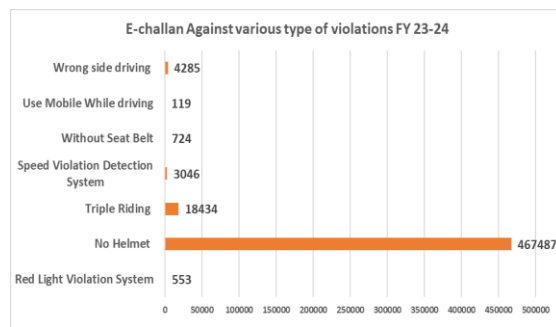


Figure 9. Distribution of e-challans issued for various traffic violations from April 2023 to May 2024

This comprehensive analysis delves into the intricate patterns of traffic violations in Patna Bihar before and after the implementation and integration of the e-Challan with ITMS.

At the early stage of the implementation of the ITMS e-challan, a huge surge in recorded traffic violations was recorded (Figure 9).

This phenomenon can be attributed to several factors: enhanced traffic enforcement system enabled authorities to efficiently issue challan against every single traffic violation, leading to a higher number of offenses being recorded. Little or negligible awareness about the same was also one of the reasons for the surge in recorded violations.

After the initial surge (Figure 9), a stabilization phase can be seen. During this period, the violation graph exhibited a plateau-like pattern. Because of adaptation to the new system, drivers and pedestrians gradually adapted to the presence of the e-Challan ITMS system, becoming more cautious in adhering to traffic regulations. Apart from this, fear of e-Challans and instant fines and digital evidence deterred individuals from violating traffic rules. But, still, most of them lacked awareness.

Following the stabilization phase, the violation graph demonstrated a consistent decline. Several factors played pivotal roles in driving this decline. As Patna Smart City Ltd started spreading awareness programs through news channels and digital media (YouTube) about the system's implementation, more citizens became aware of traffic rules and regulations (Mittal *et al.*, 2022).

Further, they started a special campaign to spread road safety messages via Variable Message Display (VMD) and public announcements related to traffic norms via Public Announcement (PA) installed in Pan City.

The implementation of the ITMS in Patna Smart City has had a profound impact on traffic management, contributing to enhanced road safety,

improved traffic flow, and increased efficiency in traffic law enforcement. One of the most significant outcomes of the ITMS is the introduction of the e-Challan system, which has automated the detection of traffic violations and issuance of fines. This digital mechanism has led to a noticeable improvement in traffic discipline and compliance among Patna's residents, with the system generating over 1,100 e-Challans per day. This volume of enforcement was previously unattainable through manual policing methods, indicating the transformative potential of ITMS in modern traffic management.

The e-Challan system, backed by high-resolution cameras and real-time data analysis, captures a wide array of violations, including speeding, red-light violations, wrong-way driving, and non-compliance with helmet and seatbelt laws (Barba *et al.*, 2012). The captured data is verified by the traffic police, ensuring accuracy before generating fines. This automated process has significantly reduced human intervention, decreased the likelihood of errors and corruption, while also promoted a more transparent and accountable system. Furthermore, the digital records provide irrefutable evidence of violations, streamlining the enforcement process and ensuring fairness in traffic law compliance.

In addition to its role in enhancing traffic discipline, the ITMS has also contributed to improved traffic flow across Patna. The system's capacity to manage signals dynamically based on real-time traffic conditions has reduced congestion and smoothed the flow of vehicles. This, combined with improved driver behavior due to the fear of automated fines, has alleviated traffic bottlenecks, making the city's roads safer and more efficient. Road safety has also benefited from the increased public awareness generated by ITMS, as citizens have become more conscientious about adhering to traffic rules to avoid penalties. The reduction in violations has directly correlated with a decrease in road accidents, contributing to a safer urban environment for all road users.

The ITMS has further demonstrated its capacity to support data-driven decision-making in traffic management. By collecting extensive data on traffic patterns, violations, and road use, authorities can make informed decisions about where to focus enforcement efforts and how to optimize traffic signal timings (Khalid *et al.*, 2019). This data also aids in long-term urban planning and infrastructure development, as it provides insights into traffic density and peak usage hours, helping to design more efficient transportation networks.

One of the key technological advantages of ITMS is its ability to integrate with other smart city

initiatives. For instance, the system's reliance on industry-standard protocols like UTM/UG405 ensures seamless communication between on-ground hardware and central control software, enhancing network reliability. This integration supports the remote management of junctions and ensures that real-time data is continuously fed into the system, allowing for prompt responses to traffic incidents and system alerts. The use of advanced optimization algorithms has enabled the system to provide additional functionality, such as classifying vehicles and estimating queue lengths, which are vital for maintaining smooth traffic flow.

The above Figure 10 shows a decline in violations against disobey of traffic signals from the month of July 2024 to Nov 2024 in and around Patna City.

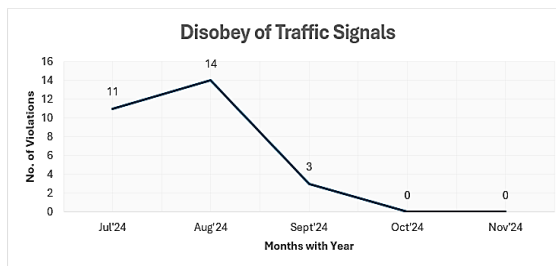


Figure 10. Monthly traffic signal violation cases from July to November 2024

From a financial perspective, the ITMS, particularly through the e-Challan mechanism, has provided a sustainable revenue model for the local administration. The fines collected from traffic violations are reinvested into the maintenance and expansion of the ITMS infrastructure, ensuring its long-term sustainability. Moreover, this revenue stream has contributed to the overall financial health of Patna Smart City, enabling it to fund further smart city initiatives and upgrades to its infrastructure.

In addition to improving efficiency and transparency, the ITMS has also reduced the environmental impact of traffic congestion. By optimizing traffic signals and reducing idling times, the system has contributed to lower fuel consumption and decreased vehicle emissions, aligning with broader goals of sustainability. The reduction in congestion not only benefits the environment but also improves the overall quality of life for Patna's residents, as less time is spent in traffic, and air quality is improved.

The above Figure 11 shows rise in violations against Penalty for not wearing protective helmet by motorcycle driver or pillion rider from the month of July 2024 to Nov 2024 in and around Patna City.

The above Figure 12 shows a decline in violations for not wearing seat belt from the month of July 2024 to Nov 2024 in and around Patna City.

The above Figure 13 shows rise and then further decline in violations against use mobile while driving from the month of July 2024 to Nov 2024 in and around Patna City.

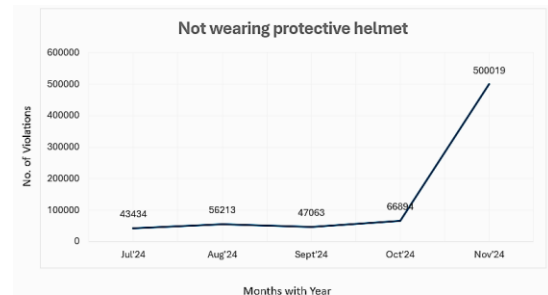


Figure 11. Monthly helmet violation cases from July to November 2024

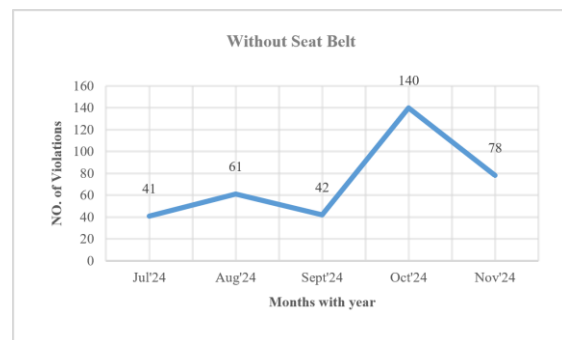


Figure 12. Monthly seat belt violation cases from July to November 2024

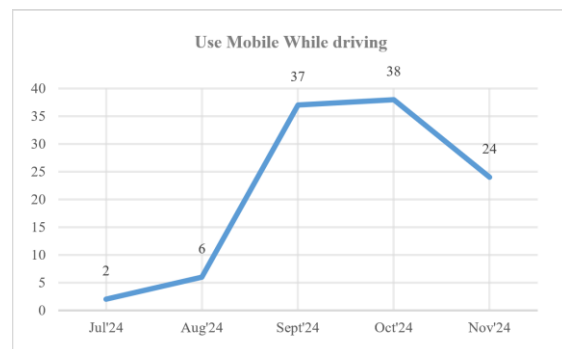


Figure 13. Monthly mobile phone use violations while driving from July to November 2024

The above Figure 14 shows decline in the end for violations against Triple Riding from the month of July 2024 to Nov 2024 in and around Patna City.

The above Figure 15 shows rise in violations against wrong side driving from the month of July 2024 to Nov 2024 in and around Patna City.

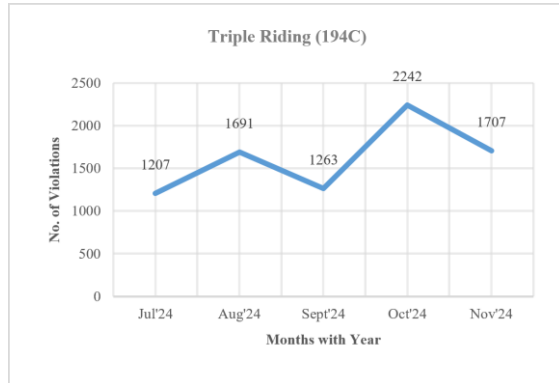


Figure 14. Monthly triple-riding violation cases from July to November 2024

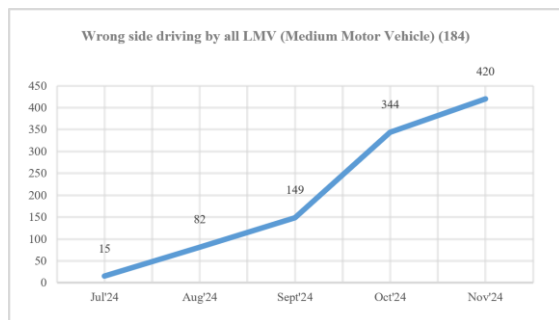


Figure 15. Monthly wrong-side driving violation cases from July to November 2024

The ITMS also incorporates advanced features aimed at enhancing equity and inclusiveness in urban transportation. The system is designed to prioritize emergency vehicles, public transportation, and VIP convoys, ensuring that critical services are not delayed due to traffic congestion. This prioritization is essential for maintaining access to lifeline infrastructure, such as hospitals and emergency services, especially during peak traffic hours or in the event of natural disasters. Furthermore, the system's ability to collect traffic data enables city planners to make transportation more inclusive by optimizing bus routes and schedules based on real-time conditions, thus improving access to public transportation for all residents.

The total investment for the Patna ITMS project amounted to ₹267 crore, covering hardware procurement (ANPR cameras, adaptive signal

controllers, network infrastructure), software development and integration, and recurring operational costs. Within just one month of operationalization, the system generated approximately ₹100 crore in e-challan revenues through automated enforcement, highlighting its immediate financial returns. Beyond revenue generation, the ITMS has contributed to measurable improvements in traffic flow, reduced congestion, and enhanced compliance with traffic regulations, which indirectly translate into time savings, lower fuel consumption, and reduced vehicular emissions. This rapid recovery of operational costs demonstrates the system's economic viability and underscores its potential as a scalable model for other Indian cities seeking smart, sustainable, and revenue-generating traffic management solutions.

The success of Patna's ITMS is a testament to the value of public-private partnerships in driving urban innovation. By collaborating with technology providers and traffic management experts, Patna Smart City has been able to implement a cutting-edge system that not only improves traffic conditions but also generates substantial economic, social, and environmental benefits. The public's growing awareness and compliance with traffic regulations, facilitated by the e-Challan system, reflect the positive behavioral shift fostered by the integration of technology into traffic management.

Limitations and Challenges of ITMS Implementation

Although the Intelligent Traffic Management System (ITMS) in Patna has played a significant role in improving traffic regulation, surveillance, and overall urban mobility, several limitations and challenges continue to affect its optimal performance. One of the major issues lies in data integration, as multiple subsystems such as Automatic Number Plate Recognition (ANPR), adaptive traffic signals, CCTV analytics, and e-challan modules operate semi-independently, with limited interoperability with legacy traffic databases. This lack of integration often results in data mismatches and delayed analytics, thereby reducing the system's real-time responsiveness.

Additionally, infrastructure and connectivity constraints pose recurring operational bottlenecks. Inconsistent network bandwidth and intermittent power supply frequently disrupt data transmission between field devices and the Integrated Command and Control Centre (ICCC), compromising the continuity of monitoring and control. The maintenance and calibration of sensors, cameras,

and signal controllers also remain challenging due to limited technical manpower and delayed vendor servicing, leading to temporary lapses in detection accuracy and traffic coordination.

Another persistent issue is user adaptation and enforcement efficiency. Despite technological advancements, public awareness of automated traffic enforcement remains low, and inconsistent follow-up on e-challans reduces the behavioral deterrent effect of the system. Furthermore, institutional coordination among key stakeholders such as the traffic police, transport department, and Patna Smart City Limited (PSCL) is still evolving, with occasional overlaps in jurisdiction and fragmented decision-making processes creating operational redundancies.

Finally, long-term performance data on parameters such as travel time reduction, emission control, and road safety improvements are limited, as the ITMS in Patna is still in its early operational phase. The absence of longitudinal datasets restricts comprehensive impact evaluation and comparative benchmarking with other cities. Addressing these challenges through enhanced data integration, robust maintenance frameworks, improved inter-agency coordination, and standardized performance monitoring will be critical to realizing the full potential of ITMS and ensuring its scalability and sustainability across other urban centers in India.

Conclusions

The implementation of the ITMS in Patna has demonstrated a transformative impact on urban traffic regulation, safety, and environmental conditions. The integration of advanced systems like ATCS, RLVD, ANPR, and SVD with digital platforms such as e-Parivahan has not only streamlined traffic enforcement but also enhanced compliance and transparency in governance. This study confirms the significant reduction in traffic violations, congestion, and emissions, alongside improved road safety metrics and citizen satisfaction. The findings underscore ITMS as a replicable model for smart city initiatives, emphasizing the critical role of technology-driven solutions in addressing urban mobility challenges. Future work should focus on further optimization of the ITMS framework by integrating real-time data analytics and machine learning algorithms to predict and prevent traffic bottlenecks dynamically. Expanding the system's coverage to more intersections and leveraging emerging technologies such as Internet of Things (IoT) devices, Vehicle-to-Infrastructure (V2I) communication, and artificial intelligence can enhance scalability and efficiency.

Additionally, the potential for generating revenue through e-challans, digital advertisements, and data-sharing agreements with private entities should be explored to ensure financial sustainability. Longitudinal studies assessing behavioral changes in traffic compliance and their correlation with technological interventions could provide valuable insights for policy formulation. These advancements will further solidify ITMS's role in fostering sustainable urban development and intelligent traffic governance.

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Author Contributions

Md Shamshad (Corresponding Author): Conceptualization, methodology, formal analysis, data curation, software, visualization, writing-original draft preparation, and manuscript editing. *Shambhu Sharan Mishra*: Supervision, validation, review and editing of the manuscript, and guidance in interpreting the research findings.

Ethics Statement

This manuscript is an original work of the authors. It has not been published previously, is not under consideration for publication elsewhere, and will not be submitted to another journal while it is under review by this journal. The authors have complied with all applicable ethical standards in the conduct and reporting of this research.

Declaration of Generative AI Use

The authors declare that no Generative AI tools were used in the preparation of this manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript. The authors have no commercial or associative interests that represent a conflict of interest in connection with this work.

Data Availability Statement

No new data were generated or analyzed in support of this research.

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