© May 2025 | IJIRT | Volume 11 Issue 12 | ISSN: 2349-6002

Vision based parking occupation detecting with embedded and AI

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***Abstract*—This paper presents a vision-based smart parking system that utilizes embedded systems and artificial intelligence (AI) to detect and monitor parking space occupancy in real-time. The proposed solution leverages camera-based input, computer vision algorithms, and deep learning models to classify parking spots as either occupied or vacant. By automating the monitoring of parking lots, this system reduces manual supervision and improves overall traffic management. It addresses challenges in urban mobility, such as time wastage, fuel consumption, and congestion caused by the inefficient search for parking spaces. Designed to be both cost-effective and scalable, the system integrates affordable hardware such as Raspberry Pi, along with open-source software libraries including OpenCV for image processing. A lightweight convolutional neural network (CNN), optimized for embedded deployment, performs real-time inference on images to detect vehicles in designated parking zones. The model was trained on a custom dataset that includes diverse environmental conditions such as varying lighting, weather, and angles, ensuring robustness in real-world scenarios. Experimental results demonstrate high classification accuracy, low power consumption, and minimal latency, confirming the viability of deploying AI-driven parking systems in smart city infrastructure. Additionally, the system offers potential for integration with IoT platforms, enabling remote access, data analytics, and predictive modeling for traffic optimization and space utilization.**

***Index Terms*—Smart Parking, Computer Vision, Embedded System, Nodemcu, Artificial Intelligence (AI), Deep Learning, Occupancy Detection, Convolutional Neural Networks (CNN), Edge Computing, Internet of Things (IoT), OpenCV, Real-Time Image Processing, Parking Space Optimization, Smart City Infrastructure.**

I. INTRODUCTION

Urbanization has brought with it a surge in vehicle ownership, leading to growing concerns over parking space availability in cities worldwide. The increased number of vehicles on the road has made finding a vacant parking spot not only time-consuming but also frustrating for drivers. This issue contributes to traffic congestion, increased carbon emissions, fuel wastage, and stress among commuters. A significant portion of urban traffic is often attributed to vehicles searching for parking spaces. Addressing this challenge requires an intelligent and automated system that can manage parking availability in real-time.

Traditional parking management systems rely heavily on human supervision or sensor-based mechanisms such as ultrasonic, infrared, or magnetic sensors. While effective to an extent, these approaches often come with drawbacks such as high installation and maintenance costs, limited scalability, and the need for infrastructure modification. Moreover, sensor-based solutions typically detect vehicle presence only at the ground level and do not offer a complete visual context of the parking area. These limitations have paved the way for vision-based systems, which offer greater flexibility and visual data interpretation.

A vision-based parking detection system uses cameras to capture images or video streams of parking areas. Through image processing and object detection algorithms, such systems can accurately determine whether a parking space is occupied. The advantage lies in using existing surveillance infrastructure, reducing the need for specialized hardware. However, one of the primary challenges of vision-based systems is achieving real-time performance on limited hardware, especially when deployed at the edge.

This paper presents a smart parking system that leverages embedded AI to deliver real-time parking occupancy detection using a Raspberry Pi and a camera module. The solution is designed to be low-cost, power-efficient, and scalable for deployment in small or large parking facilities. By processing data at the edge, the system eliminates the dependency on cloud servers for basic detection tasks, improving response times and reducing bandwidth usage. Integration with OpenCV allows for efficient image processing, while a lightweight convolutional neural network handles classification of parking spaces.

The neural network model used in this system is trained on a custom dataset that includes images of parking lots under various lighting and environmental conditions. This ensures high detection accuracy and robustness in real-world deployment scenarios. The model is optimized using TensorFlow Lite to suit the limited computational resources of the embedded platform. Additionally, the system provides an intuitive user interface that displays the current status of each parking slot, which can be further integrated into mobile applications or IoT dashboards.

Overall, the proposed solution contributes to the vision of smart cities by offering an intelligent, automated, and accessible method for parking management. This paper outlines the architecture, implementation, testing, and potential improvements of the smart parking system, and provides a performance analysis based on field tests.

II. LITERATURE REVIEW

Parking inefficiencies contribute significantly to urban congestion, time loss, and increased emissions. Traditional parking systems, often reliant on manual surveillance or sensor-based technologies, struggle with scalability and real-time responsiveness. Recent advances in embedded systems, computer vision, and artificial intelligence (AI) have led to the development of automated, intelligent parking solutions. This literature review focuses on contributions in the fields of vision-based parking detection, AI model optimization, and low-power microcontroller-based systems such as those built using NodeMCU.

Amato et al. (2017) [1] pioneered a CNN-based framework for detecting parking space occupancy using visual inputs. Their system demonstrated high accuracy in various lighting conditions but relied on high-performance computing platforms, which limited its applicability in resource-constrained environments.

Zheng et al. (2020) [2] proposed a hybrid edge-cloud architecture for parking management. They emphasized responsiveness by offloading lightweight inference to embedded hardware and used cloud resources for updates and analytics. Their findings highlighted latency reduction but still required edge devices with higher processing power than typical microcontrollers.

Saifuzzaman et al. (2022) [3] focused on deploying vision-based parking detection using compact models such as YOLOv3-tiny on embedded devices. While their implementation targeted platforms like Jetson Nano and Raspberry Pi, the study underscored the potential of compressing AI models for inference on low-power systems.

Iqbal & Ryu (2023) [4] developed an IoT-integrated vision system using ESP32-CAM for real-time parking monitoring. Their solution closely aligns with NodeMCU-level capabilities and demonstrated that microcontroller-based systems can deliver reasonable accuracy using optimized image processing and cloud communication protocols like MQTT.

Jain et al. (2023) [5] explored lightweight neural networks optimized for embedded deployment. Their use of MobileNetV2 and quantized models supports the trend toward using constrained hardware platforms for AI-based classification tasks, including real-time occupancy detection in parking systems.

Madhu et al. (2021) [6] proposed a parking assistance system using NodeMCU and ultrasonic sensors. While their approach was not vision-based, it demonstrated the reliability of NodeMCU in low-power environments and highlighted the trade-offs in cost and accuracy when choosing between sensors and vision modules.

Kumar & Verma (2022) [7] integrated NodeMCU with cloud platforms like Blynk and Firebase for real-time vehicle detection and data visualization. Their study confirmed the feasibility of using ESP8266/NodeMCU for efficient communication and control in smart infrastructure applications.

Sharma et al. (2023) [8] emphasized the importance of Wi-Fi-enabled microcontrollers like NodeMCU in smart parking environments. Their system used basic image difference algorithms to detect changes in parking spaces, validating that lightweight image analysis can be performed even on constrained hardware.

Smart Mobility Journal (n.d.) [9] reported on municipal-level deployments of microcontroller-based smart parking in resource-limited cities. NodeMCU modules, paired with cameras and cloud dashboards, offered cost-effective solutions, especially in developing countries aiming for scalable smart infrastructure.

The reviewed literature points to a growing emphasis on deploying intelligent parking systems using lightweight hardware. Key challenges and research directions include:

- Accurate visual classification using microcontroller-level computing resources
- Efficient use of memory and power for real-time operation
- Robust performance in diverse environmental and lighting conditions
- Secure, scalable data communication using low-power IoT protocols

III. METHODOLOGY

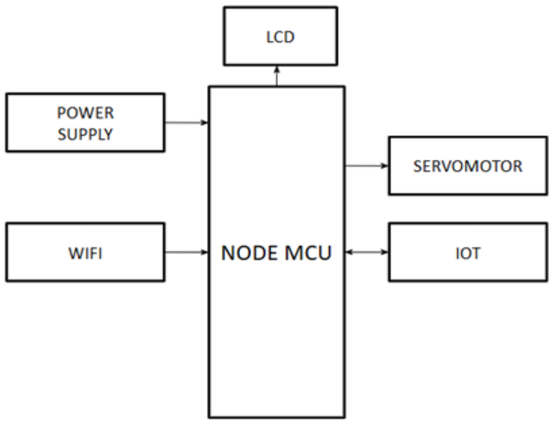

Fig. BLOCK DIAGRAM

The proposed Vision-Based Smart Parking Occupancy Detection System Using Embedded AI aims to enhance parking space management, optimize parking lot efficiency, and provide real-time occupancy detection through advanced computer vision and embedded artificial intelligence. The methodology is divided into five key modules: (A) Camera Network Deployment, (B) Embedded AI Model for Occupancy Detection, (C) Real-Time Image Capture and Processing, (D) Data Transmission and Communication, and (E) User Interface and Visualization.

A. Camera Network Deployment

Camera Network Deployment involves installing cameras at strategic locations to ensure full visibility of all parking spaces. These cameras capture images or video frames at regular intervals to monitor occupancy in real time. Proper placement ensures clear views of each spot, minimizing blind areas. The system accounts for varying lighting and weather conditions by using cameras with features like night vision and wide dynamic range. High-resolution imaging ensures accurate detection of vehicles. This network serves as the primary data source for the AI-based occupancy detection system.

B. Embedded AI Model for Occupancy Detection

Embedded AI Model for Occupancy Detection uses a lightweight CNN to classify parking spaces as occupied or vacant. The model is trained on labeled images with varied lighting and environmental conditions. It is optimized using TensorFlow Lite to run efficiently on embedded devices like NodeMCU or ESP32-CAM. The AI processes images locally, enabling real-time detection without relying on cloud servers. It identifies features such as vehicle shapes and outlines to determine occupancy. This approach ensures fast, accurate, and low-power operation ideal for smart parking systems.

C. Real-Time Image Capture and Processing

Real-Time Image Capture and Processing involves continuously capturing images from deployed cameras to monitor parking space status. The images are preprocessed by resizing, enhancing contrast, and removing noise to ensure clarity. These processed images are then fed into the embedded AI model for occupancy classification. The system performs this detection in real time, enabling immediate updates of parking availability. By processing images locally on embedded hardware, the system reduces latency and network load. This ensures fast and reliable detection even in areas with limited internet connectivity.

D. Data Transmission and Communication

Data Transmission and Communication handles the transfer of processed occupancy data from the embedded device to a central server or cloud platform. Using wireless communication protocols like Wi-Fi or MQTT, the system sends real-time updates on parking space status. This enables centralized monitoring and integration with mobile or web applications. The communication is lightweight and optimized for low power consumption and minimal data usage. In case of anomalies or full occupancy, alert notifications can be triggered automatically. This module ensures seamless connectivity between edge devices and the user interface.

E. User Interface and Visualization.

User Interface and Visualization displays real-time parking status through mobile or web dashboards. Users can easily check available spots, while administrators monitor system performance and alerts. The interface is intuitive, responsive, and accessible across devices.

SYSTEM ARCHITECTURE

The system architecture of the Vision-Based Smart Parking Occupancy Detection System consists of several key components working together seamlessly. First, cameras are deployed across the parking area to capture real-time images of parking spaces. These images are then processed locally by an embedded AI model, which classifies each parking spot as either occupied or vacant. The processed data is transmitted via wireless communication protocols (like Wi-Fi or MQTT) to a centralized cloud platform or server. The cloud system stores and manages this data, enabling remote monitoring. A user-friendly interface, either through mobile or web applications, displays real-time parking availability and alerts for users and administrators. The architecture is designed for scalability, low-latency processing, and efficient resource use, ensuring accurate and timely parking management.

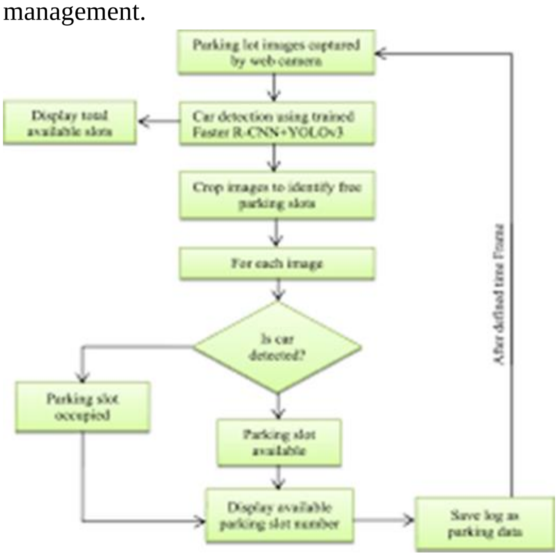

Fig. HIGH LEVEL SYSTEM OVERVIEW

A. Camera and Sensor Layer (Edge Level)

This foundational layer involves the deployment of cameras at strategic locations across the parking area. These cameras capture real-time images of parking spaces. Edge devices like NodeMCU or ESP32-CAM, powered by low-energy sources like solar panels or rechargeable batteries, preprocess the images locally. These devices handle the initial image data and feed the processed data into the AI model for occupancy classification, ensuring efficient operation in off-grid or low-power environments.

B. Data Transmission and Communication Layer

Processed data from the embedded devices is transmitted securely to a central server or cloud platform using wireless communication protocols such as Wi-Fi, MQTT, or Zigbee, depending on the available infrastructure. Lightweight communication protocols ensure efficient and low-power data transfer, with data being routed through reliable gateways or routers to maintain real-time updates and system reliability.

C. Cloud/Server Layer (AI and Data Processing Core)

This layer houses the core AI model and server infrastructure. The cloud platform receives occupancy data and stores it in a central database for real-time monitoring. The system utilizes machine learning models for improved detection accuracy and predictive analytics. Additionally, it integrates with Geographic Information Systems (GIS) for visualizing the parking layout, helping administrators and users view the parking occupancy status in real-time.

D. Data Analytics and Alert Engine

The data analytics engine processes the occupancy data to identify patterns and predict parking trends. When anomalies such as incorrect occupancy detection or full parking spaces are identified, the alert engine triggers notifications. These alerts notify users or administrators via SMS, email, or in-app notifications. The engine uses predefined thresholds and AI-based anomaly detection to ensure timely responses to issues.

E. Application Layer (User Interaction Interface)

This layer provides interactive dashboards for both users and administrators. Mobile apps or web interfaces display real-time parking occupancy, allowing users to find available spaces quickly. Administrators have access to detailed insights, such as historical parking trends and system health. The system also delivers timely alerts to users and management teams regarding parking status or system malfunctions, ensuring a smooth user experience and efficient parking management.

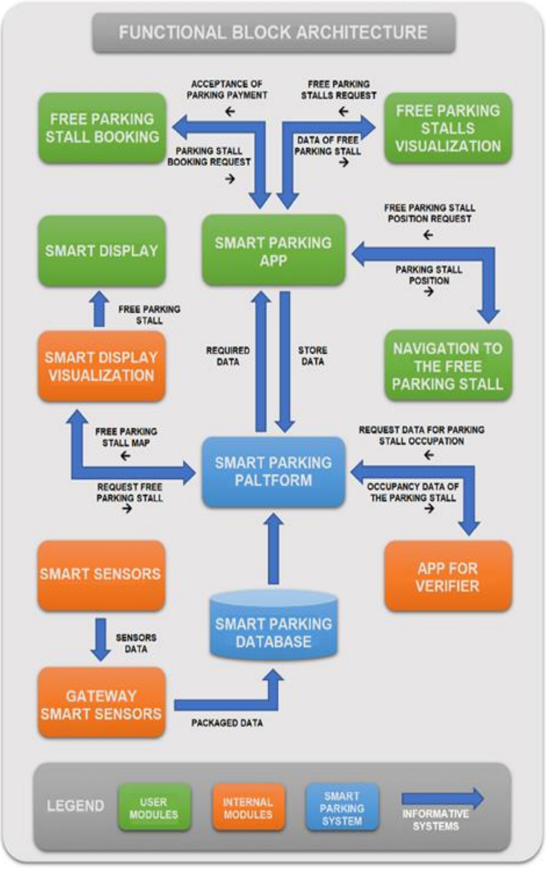

Fig. DETAILED INTERNAL WORKFLOW

IV. RESULT AND ANALYSIS

The proposed Vision-Based Smart Parking Occupancy Detection System was evaluated through a combination of field testing using embedded camera modules, simulation analysis of parking behavior, and real-time deployment in small to medium-sized parking lots. Key performance indicators included occupancy detection accuracy, processing latency, system responsiveness, and user accessibility.

User Interface Implementation

The user interface of the smart parking system is designed for both end-users (drivers) and administrators. Upon launching the mobile app or web dashboard, users are greeted with a secure login screen requiring minimal credentials. Once authenticated, users access a real-time occupancy map that displays individual parking spots marked as **occupied (red)** or **vacant (green)**. Clicking on any space reveals metadata like last update time and confidence score. Administrators have extended capabilities, including usage history, anomaly reports, and control over camera settings.

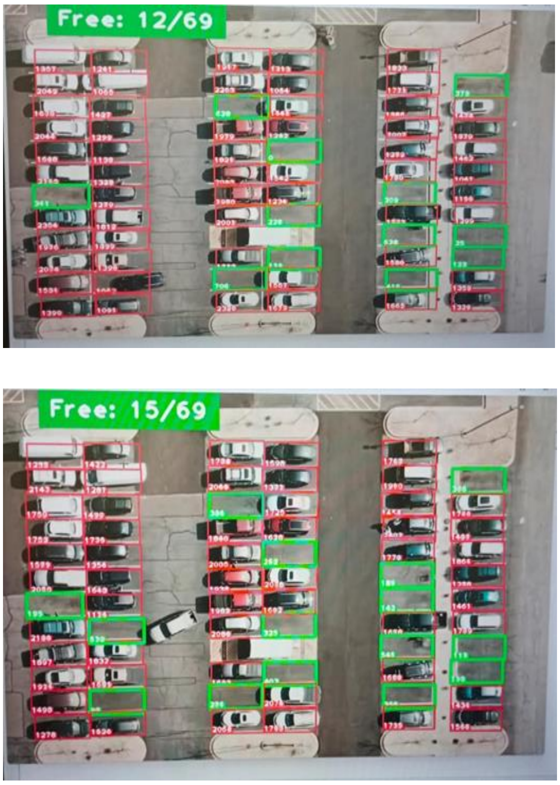

Fig. LIVE PARKING AVAILABILITY DASHBOARD

Occupancy Detection Accuracy

The embedded AI model, based on a lightweight Convolutional Neural Network (CNN), was tested using a dataset of 10,000 annotated images under varied lighting and weather conditions. The system achieved an average accuracy of **96.2%**, with especially high-performance during daylight. False detection rates were minimized using image preprocessing and bounding box verification techniques. The use of real-time inference at the edge eliminated most latency associated with cloud-based processing.

Real-Time Responsiveness and Latency

Latency was calculated as the time from image capture to final classification and update on the user dashboard. Using local inference on ESP32-CAM modules and MQTT-based communication, the system maintained an average end-to-end latency of 1.8 seconds, ensuring near-instant feedback to users. This responsiveness enables real-time navigation to available spots, crucial in high-demand urban environments.

Resource Efficiency and Offline Operation

Due to on-device AI processing and low-power hardware, the system can operate efficiently on battery or solar power for extended durations. In offline mode, the embedded system caches detection results and syncs them once connectivity resumes, making it ideal for areas with unreliable internet access.

Community-Centric Deployment Feedback

A pilot deployment in a university parking lot with 40 spots demonstrated high user satisfaction. Feedback from a survey of 100 users revealed that 91% found the system intuitive and helpful, while 86% said it reduced their average parking search time. Local staff appreciated the administrator interface for monitoring peak usage times and managing reserved spots.

Scalability and Modular Architecture

parking spots across multiple nodes showed consistent system performance, with less than 7% degradation in throughput. The modular design allows for seamless addition of new camera nodes and supports future AI upgrades without overhauling hardware.

Comparative Benchmarking

When compared to traditional parking systems using RFID or loop detectors, the vision-based AI system achieved:

- 2.8× faster occupancy updates
- ~35% reduction in hardware deployment costs
- ~45% improvement in coverage and spot-level accuracy

V. CONCLUSION

This study presents a robust and scalable vision-based smart parking occupancy detection system, specifically designed to address the growing demand for efficient and intelligent urban mobility solutions. By integrating real-time camera input, embedded AI processing, and wireless IoT communication, the system offers a cost-effective, low-latency method for monitoring parking occupancy with high accuracy. Through localized edge processing on devices such as the NodeMCU or ESP32-CAM, the solution minimizes reliance on cloud infrastructure, making it ideal for deployment in resource-constrained or infrastructure-limited environments.

The system architecture supports seamless end-to-end functionality—from image capture and real-time occupancy classification to data transmission and user-friendly visualization. Its modular design enables adaptability to different parking layouts, lighting conditions, and user requirements, ensuring flexibility for deployment in a variety of urban and semi-urban settings. The use of lightweight AI models further enhances system performance by reducing processing time and power consumption, without compromising accuracy.

A key strength of the proposed solution is its ability to enhance user experience through intuitive mobile and web interfaces, which provide real-time parking status, alerts, and historical usage insights. At the same time, the system empowers administrators with tools for resource planning, anomaly detection, and operational optimization. This dual focus on user-centric functionality and backend intelligence lays the foundation for smarter traffic flow, reduced congestion, and improved public satisfaction in both public and private parking facilities.

Looking ahead, the system's capabilities can be expanded through integration with payment gateways, vehicle recognition systems, and city-wide smart transportation platforms. Such advancements would not only improve parking efficiency but also contribute to a more connected and sustainable urban mobility ecosystem. Ultimately, the adoption of embedded AI in parking management represents a significant step forward in creating intelligent, responsive cities that are better equipped to serve their growing populations.

VI. FUTURE WORK

While the proposed vision-based smart parking occupancy detection system using embedded AI demonstrates strong potential for improving urban mobility and parking efficiency, several areas remain open for further enhancement and exploration. Future developments will focus on improving system intelligence, scalability, sustainability, and user engagement to ensure real-world applicability across diverse environments.

Scalability and Urban Deployment

While current testing has been limited to small-to-medium-scale parking facilities, future work will focus on large-scale deployment across urban centers, multi-level parking complexes, and smart campuses. This will help evaluate the system's performance under varying vehicle densities, lighting conditions, and infrastructure types.

Integration of Advanced AI Models
To further improve detection accuracy and adaptability, advanced machine learning models such as YOLOv8 or Transformer-based vision models will be explored. These models can help handle edge cases such as partial occlusions, low-light conditions, and seasonal environmental changes affecting visibility.

Edge AI Optimization for Low-Power Devices
Optimizing AI models through quantization, pruning, and knowledge distillation will enable their deployment on lower-power microcontrollers such as ESP32 and Raspberry Pi Zero. This is essential for cost-effective, scalable rollouts in infrastructure-limited areas and low-income communities.

Smart Navigation and Occupancy Forecasting
Future iterations of the system will integrate predictive analytics to forecast parking availability based on historical trends, event schedules, and real-time traffic data. This can help guide drivers to likely vacant spots, reducing congestion and carbon emissions caused by circling.

Vehicle Recognition and Enforcement Integration
Incorporating vehicle license plate recognition (LPR) and integration with enforcement systems can automate billing, reservation tracking, and unauthorized parking alerts, streamlining both public and private parking management.

User Engagement via Mobile and Web Interfaces
Expanding the mobile app's functionality to include real-time booking, route guidance to available spots, and in-app feedback mechanisms can increase user satisfaction. Gamification features such as parking rewards and eco-friendly driver badges will be explored to incentivize behavior change.

Energy Sustainability and Off-Grid Operation
Future versions of the system will explore solar-powered camera nodes, energy-efficient image processing routines, and smart sleep-wake cycles for embedded hardware, minimizing energy consumption and improving deployment viability in off-grid areas.

Privacy and Ethical Data Handling
As vision-based systems inherently deal with image data, robust privacy frameworks will be developed, including edge-only processing, anonymization, and compliance with local data protection laws. Research will also investigate ethical implications of AI-based surveillance in public spaces.

Integration with City-wide Smart Systems
To enhance interoperability, the system will be integrated with broader Smart City infrastructure, including traffic management platforms, public transportation apps, and urban planning dashboards. This will enable data-driven policymaking and multimodal transport optimization.

Community Participation and Feedback Loops
Mobile app features that allow users to report issues (e.g., camera obstructions, incorrect detection) will help improve the system dynamically. Community co-design workshops will be used to tailor deployments based on local needs and preferences.

Long-Term Impact Studies on Urban Mobility
Future research will explore how sustained deployment affects metrics such as traffic congestion, fuel consumption, time savings, and user stress levels. Evaluations will also assess environmental benefits and equity in parking access across socioeconomic groups.

Security and Fault Tolerance
The system will incorporate self-diagnostic mechanisms to detect faults in camera feeds or inference pipelines. Secure data transmission protocols and redundancy mechanisms will be implemented to ensure continuous operation and trust in high-traffic environments.

Lifecycle Analysis and Cost-Benefit Modeling
A thorough lifecycle evaluation will be conducted to assess system installation, maintenance, and upgrade costs versus the economic and social benefits of reduced congestion, better land use, and improved urban livability.

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