AI–based Pavement Condition Monitoring & Management System for Sustainable Urban Infrastructure

Submitted in partial fulfillment of the requirements of the degree

BACHELOR OF ENGINEERING IN **COMPUTER ENGINEERING**

By

Kushl Alve D12B/04

Neelkanth Khithani D12B/23

Jatin Navani D12B/34

Vedang Gambhire D12B/16

Name of the Mentor

Prof. Dr. (Mrs.) Sharmila Sengupta

Vivekanand Education Society's Institute of Technology,

An Autonomous Institute affiliated to University of Mumbai

HAMC, Collector's Colony, Chembur,

Mumbai-400074

University of Mumbai (AY 2024-25)

CERTIFICATE

This is to certify that the Mini Project entitled **“AI–based Pavement Condition Monitoring & Management System for Sustainable Urban Infrastructure”** is a bonafide work of **Kushl Alve (04), Neelkanth Khithani (23), Jatin Navani (34), Vedang Gambhire (16)** submitted to the University of Mumbai in partial fulfillment of the requirement for the award of the degree of **“Bachelor of Engineering”** in **“Computer Engineering” .**

(Prof. Dr. (Mrs.) Sharmila Sengupta)
Mentor

(Prof. Dr. (Mrs.) Nupur Giri)
Head of Department

(Prof. Dr. (Mrs.) J. M. Nair)
Principal

Mini Project Approval

This Mini Project entitled "**AI–based Pavement Condition Monitoring & Management System for Sustainable Urban Infrastructure"** by **Kushl Alve (04), Neelkanth Khithani (23), Jatin Navani (34), Vedang Gambhire (16)** is approved for the degree of **Bachelor of Engineering** in **Computer Engineering.**

Examiners

1………………………………………
(Internal Examiner Name & Sign)

2………………………………………
(External Examiner name & Sign)

Date:

Place:

Contents

Abstract

The project titled "AI-based Pavement Condition Monitoring and Management System for Sustainable Urban Infrastructure" aims to improve the infrastructure of Mumbai by addressing critical pavement issues using advanced artificial intelligence (AI) technology. The system integrates with existing municipal infrastructure to monitor pavement conditions in real-time, utilizing cameras mounted on authorized garbage trucks. This generates geo-tagged video data that is processed to detect anomalies like potholes, illegal parking, and other obstructions. The insights are displayed on a dashboard accessible to municipal authorities, enabling efficient decision-making for maintenance and urban planning. By automating the monitoring and maintenance of pavements, the system reduces the need for manual inspections, leading to quicker responses and more sustainable urban infrastructure management. It aligns with national initiatives like the AMRUT and Smart City Mission, aiming to enhance pedestrian safety and urban walkability, while fostering collaboration among government bodies, NGOs, and private entities. The project spans 12 months and involves developing a prototype of an electronic control unit (ECU), data collection and anomaly detection using AI, cloud deployment for scalability, and a user-friendly dashboard for visualizing pavement conditions. The system's impact will be measured by improvements in maintenance response times, infrastructure conditions, and overall city planning efficiency.

Acknowledgements

We would like to express our sincere gratitude to Vivekanand Education Society’s Institute of Technology for their support throughout our project. Their assistance in gathering project-related information was invaluable. We are delighted to extend our heartfelt appreciation to Prof. Dr. Sharmila Sengupta, our TE Mini-Project Mentor, for her generous assistance and valuable advice in developing the project synopsis. Her guidance and suggestions were instrumental in our project's development.

Our profound thanks go to Dr. (Mrs.) Nupur Giri, the Head of the Computer Department, and Dr. (Mrs.) J.M. Nair, our Principal, for granting us the opportunity to undertake this project. Their support was essential in successfully completing both the project synopsis and project review.

We would like to express our deep gratitude to all the teaching and non-teaching staff for their unwavering encouragement, support, and selfless assistance throughout the project. Their contributions were indispensable to our project's success.

List of Abbreviations

AMRUT: Atal Mission for Rejuvenation and Urban Transformation

PUSHP: Progressive, Unstoppable, Spiritual, Humanity First, and Prosperous Bharat

BMC: Brihanmumbai Municipal Corporation

ECU: Electronic Control Unit

SLA: Service Level Agreement

PMGSY: Pradhan Mantri Gram Sadak Yojana

SQC: State Quality Coordinators

UAV: Unmanned Aerial Vehicle

GPS: Global Positioning System

SME: Small & Medium Enterprises

NGO: Non-Governmental Organization

List of Figures

1 Introduction

1.1 Introduction

The Atal Mission for Rejuvenation and Urban Transformation - AMRUT programme *Ministry of Housing and Urban Affairs* [1] focuses on reducing pollution by switching to public transport or constructing facilities for non-motorized transport and infrastructure creation. The Smart Cities Mission *Government of India* [2] with the objective of inclusive urban development by providing core infrastructure, and implementing 'Smart' solutions through retrofitting, redevelopment, and Greenfield development. The PUSHP Mantra highlights five key values—Progressive, Unstoppable, Spiritual, Humanity First, and Prosperous Bharat—PM Modi's vision by utilizing technology to enhance urban infrastructure. [3] City of Mumbai, a densely populated metropolitan city, faces the above urban and city planning challenges, particularly in managing, accounting and auditing effective management of its pavements / footpaths ‘Walkable cities do not happen by accident. Cities only become walkable if they are planned and designed with walkability in mind.’ [4] In the National Survey of Walkability Index [5], Mumbai scored 0.85.

Mumbai got its ‘Pedestrian First’ footpath policy in 2014 aiming– ‘reduce pedestrian conflicts with vehicular traffic to minimum’, ‘right to pedestrian’, ‘connected and continuous’, ‘footpaths to be constructed on both sides of the road of minimum width 9 meters–2023-24 policy’, but is not seen in action by Brihanmumbai Municipal Corporation (B.M.C.) directed by the Bombay High Court last February 2023 stated by the Question of Cities [6]. The Mumbai pedestrian urban infrastructure facilities reveal several challenges like–illegally parked vehicles often blocking entire pedestrian pathways, encroachments [7] by shanties, hawkers, and vendors obstructing the smooth flow of movement, seasonal problems such as falling tree branches, waste dumping, and inherent pavement issues—like broken, waterlogged, or uneven surfaces—further restrict safe pedestrian passage etc. all accounting for nearly 50% of the road fatalities. [6]

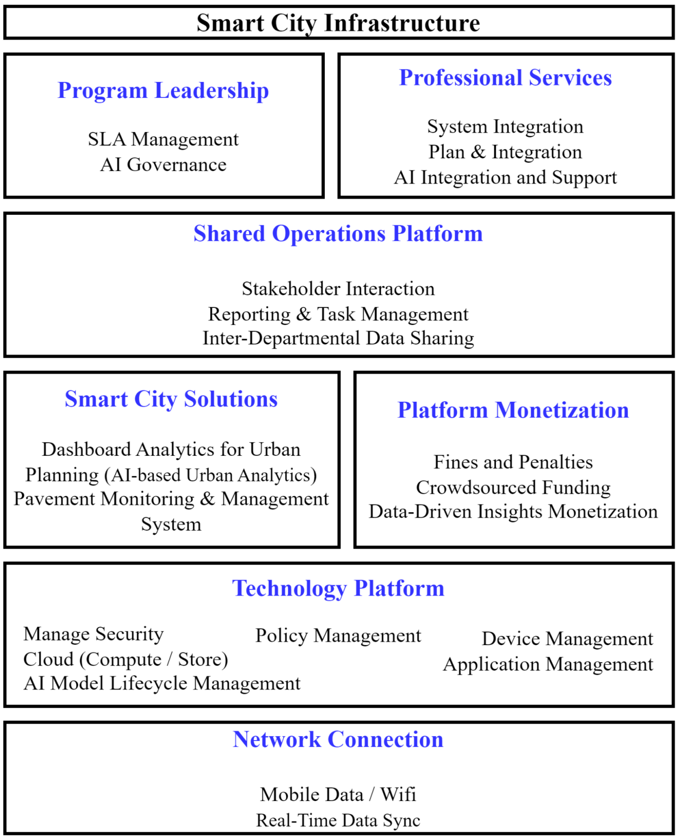

Figure 1. Proposed System in the Smart City Infrastructure

Our proposal which aligns with AMRUT programme, Smart City Mission and PUSHP Mantra proposes a 3–dimensional solution for the problem (1) ***Data and Monitoring:*** Effective evaluation requires accurate data and reliable monitoring systems, which our system aims to provide by camera video data acquisition across 24 administrative wards. The automated monitoring reduces the need for extensive manpower. (2) ***Urban Planning and Integration:*** System aligns and complements the pre–existing intra–governmental system and entities with a broader view of urban development and smart city development plans. (3) ***Maintenance and Sustainability:*** Our system's ability to monitor the deterioration of pavements over time ensures that long-term planning is supported, allowing authorities to perform preemptive repairs and prioritize maintenance based on predicted risks. Aiming to solve these critical pavement issues by using advanced AI technology coupled with the existing Mumbai city infrastructure. We are targeting smart city planning by mounting an Electronic Control Unit (ECU) on municipal corporation authorized garbage trucks for collecting geo–tagged videos of the lateral and surface views of the roads. Garbage trucks in Mumbai usually have fixed garbage collection routes [8] across all 24 administrative wards which can be effective against manual inspection of pavements and would generate periodic location–based data by the mounting of our cameras.

The significant images segregated from the video processing hardware unit would give insight regarding the condition of the pavements on that road. Now the usage of different image processing techniques will be used for extracting pool of features / defects including surface level and vertical objects with factors such as ***environmental*** (fallen trees / branches / uplifting of pavement due to tree roots etc.), ***maintenance defects*** (cracks or uneven surfaces / potholes / waterlogging etc.), ***encroachments*** (illegal parked vehicles / barricades / hoardings (boards), shanties, unauthorized hawkers / vendors), others (broken lamp post / open manholes, broken benches and railing etc.) with images of features along with their geo–tagged location.

These extracted insights / anomalies are then used for a ready visualization displayed using a dashboard made available to the municipal corporation (typically B.M.C). administrative authorities. This would further facilitate improved decision making for city planning, synchronous crisis addressal within the departments of municipal corporations. along with periodic surveys and timely maintenance. The anomaly detection using image processing, feature extraction, object detection and AI would not only provide better actionable insights by the municipal corporation admin but also predict future pavement deterioration trends, season–wise pavement condition data thus aiding long-term urban planning and precise budget allocation for maintenance.

When our system detects any pavement issue, monitored by the local constituency Corporator [9], the dashboard will provide critical information such as an image, the severity of the issue, its type, and its geo-tagged location. This enables the Corporator to make informed decisions through the system dashboard, where they can audit the issue and generate a pavement issue complaint based on the referred details from our system. The complaint is then forwarded by the Corporator to the respective Ward Authority–Assistant Commissioner for further action, who contacts the department head to resolve the issue. We have identified three key departments within the municipal corporation / Brihanmumbai Municipal Corporation (B.M.C.) framework that align with our project scope: (1) ***Maintenance Department***, (2) ***Environment Department***, (3) ***Encroachment Department***. [11] The HOD then assigns the task to a team of officials responsible for addressing the pavement conditions, while also preparing an expense report, which is submitted to the Additional Commissioner for approval. This ensures not only the resolution of the issue but also the accountability of the tasks completed, thereby creating a seamless loop within the Urban Planning process. This overall structure is aiming for improval of the factors in the core of Smart Urban Planning like reducing the *latency* in the pre-existing methods, improval of sustainability indexes: ***walkability index*** *(WI)*, ***traffic congestion index*** *(TCI)*, ***safety index*** *(SI)* under Mumbai, improving the ***Infrastructure Maintenance Efficiency*** *(IME)*, ***Public Transport Accessibility*** *(PTA)*. Sustainable Development Goals: No. 09 ***Innovation and Infrastructure***, No. 11 ***Sustainable Cities and Infrastructure***. Providing data for Perspective Planning and SLA (Service Level Agreement) guarantee from the Detection and Monitoring System. Some existing minor solutions to these problems; Meri Sadak**:** Meri Sadak service enables citizens to register their feedback regarding roads across India. The application is meant for grievance redressal relating to roads built under Pradhan Mantri Gram Sadak Yojana (PMGSY) and Other Roads (Non-PMGSY). The application allows the citizens to register a complaint regarding the pace of work, quality of work, land disputes etc. for a PMGSY and Non PMGSY road along with photographs of the site. The complaints are handled by the respective State Quality Coordinators (SQCs) of the Nodal Department in the State Governments. [12]

1.2 Motivation

The rapid urbanization of cities like Mumbai has led to significant challenges in infrastructure management, particularly concerning the maintenance of pavements. Poorly maintained pavements pose serious risks to public safety, contribute to traffic disruptions, and increase repair costs for municipalities. Traditional inspection methods are often inefficient, relying on manual surveys that are time-consuming and prone to human error. Moreover, the lack of continuous monitoring limits the ability to identify and address emerging issues, leading to further deterioration of urban infrastructure. The urgent need for effective solutions to enhance pavement condition assessment and management has become increasingly critical in ensuring the safety and accessibility of urban spaces. By addressing these challenges, there is an opportunity to not only improve public safety but also to promote sustainable urban development and enhance the overall quality of life for city residents.

1.3 Problem Statement & Objectives

The urban landscape of Mumbai faces significant challenges that hinder pedestrian movement and safety. Obstructed footpaths due to illegal parking, hawkers, and encroachments restrict the mobility of pedestrians, making navigation difficult and unsafe. Additionally, deteriorating pavement conditions, characterized by cracks, potholes, and uneven surfaces, pose serious safety risks for those traversing the city. Seasonal hazards, such as waterlogging and fallen branches during monsoon seasons, further exacerbate these issues, creating perilous conditions for pedestrians. The reliance on labor-intensive manual inspection processes is inefficient, failing to allow for proactive maintenance of the infrastructure. Alarmingly, over 50% of road fatalities in Mumbai are linked to poor pavement conditions and inadequate pedestrian infrastructure, highlighting the urgent need for improvement. Moreover, with a low walkability index of approximately 0.85, Mumbai ranks 30th among other cities, underscoring the critical need for enhancements in pedestrian safety and accessibility

- ***Hardware Electronic Control Unit* (ECU) Prototyping**
    - This unit will be mounted on either side of the authorized autonomous vehicle to capture real time video of the roadside. Significant frames extracted from the videos will be uploaded onto the cloud.
- **Curation of a dataset**
    - The images will further be the source for object detection and anomaly analysis and will provide significant status about the surface and lateral views of the pavement.
- **Visualization of curated dataset**
    - Summarizing the curated dataset along with providing critical information such as pavement conditions, obstructions and maintenance needs, including analytics to facilitate effective decision-making and operational efficiency.
- **Object and anomaly detection**
    - Training Machine Learning algorithm for detecting anomalies.
    - Optimization of the trained model for more accuracy.
- **Scaling and deployment of detection system**
    - Deployment of the system on cloud infrastructure to achieve scalability. This involves hosting both software and hardware components on the cloud to facilitate remote management, crowdsourcing and revenue generation by the civic bodies (typically B.M.C.)
    - System to handle large volumes of data and perform analysis and periodical report generation, scale seamlessly with increasing data loads, adapt to changing requirements.
- **Align with the Civic Bodies/ Organization Infrastructure**
    - Aligning the detection system with the civic body (typically B.M.C.) existing infrastructure to enhance coordination, improve data sharing, and streamline maintenance decision-making processes.
- **Impact Measurement of the System in Urban City (B.M.C, Mumbai)**
    - Assessing the system's effectiveness in the civic body workflow by evaluating improvements in maintenance response times, infrastructure conditions, and pedestrian safety, operational efficiency.

2 Literature Survey

2.1 Survey of Existing Systems

1. Smart monitoring of road pavement deformations from UAV images by using machine learning. [12]

- **UAV (unmanned aerial vehicles):** Smart Monitoring of road pavement deformations using high-resolution **aerial images of road surfaces** combined with machine learning techniques is used to detect surface defects, such as potholes and cracks. The paper focuses on pre-processing the data and using **decision tree classification** for effective **crack detection.**
- **High-Resolution Data and Advanced Detection**: UAVs capture multispectral images for detecting surface defects like cracks and potholes. Machine learning algorithms, including classification trees and Canny edge detection, enhance accuracy (up to 96% in some cases). UAVs offer high-resolution imagery (up to 2 cm/pixel), allowing even small cracks to be detected, contributing to the system's high precision.

2. Smartphone applications for pavement condition monitoring: A review. [13]

- **Smartphone Sensors**: Smartphones equipped with accelerometers, gyroscopes, and GPS capture data on road conditions. Machine learning algorithms process this data to detect surface defects like **roughness, potholes, and cracks** with reasonable accuracy, sometimes achieving results comparable to more costly methods.

3. Improved YOLOv5-Based Real-Time Road Pavement Damage Detection in Road Infrastructure Management. [14]

- **Efficient Channel Attention module (ECA-Net) :** Focuses on enhancing the YOLOv5 model for more efficient and accurate real-time detection of road pavement damages, such as **vertical and horizontal cracks, alligator cracks, and potholes.** Trained on the RDD 2022 dataset, which features images from six countries, the enhanced model demonstrates improved accuracy, robustness, and speed, making it a valuable tool for real-time road infrastructure management.
- **Generalization to new or unseen damage types :** As the model is primarily trained on the RDD 2022 dataset, which might not cover all possible road conditions globally.

4. Pavement Patch Detection and Measurement from Video Data Using a Parking Camera. [15]

- **Patch Detection for Pavement Assessment :** The system automates the detection of pavement defects, particularly **road patches**, by using video data collected from **car-mounted cameras**. The method relies on **visual characteristics such as closed contours and similar textures** between the patch and the surrounding intact pavement. This data is processed through image processing algorithms to detect and track defects like patches.
- **Cost Efficiency :** By using existing vehicle-mounted cameras, the system eliminates the need for expensive, dedicated road inspection vehicles, which can cost as much as £500,000 to purchase and £20 to £40 per kilometer to operate.

5. The State-of-the-Art Review on Applications of Intrusive Sensing, Image Processing Techniques, and Machine Learning Methods in Pavement Monitoring and Analysis. [16]

- **Intrusive Sensing and Real-time Monitoring :** It can detect and predict pavement conditions, such as **cracks, potholes, and structural weaknesses**. The system uses embedded sensors (e.g., stress-strain, fiber optic) to continuously monitor pavement conditions under traffic loads, offering real-time updates on structural health.
- **Advanced Image Processing :** Techniques such as noise reduction, edge detection, and morphological operations improve accuracy in detecting surface defects like cracks and potholes.
- **Machine Learning for Automation :** Algorithms such as SVM, ANN, and CNN automate the detection and prediction of pavement defects, providing high accuracy and reducing the need for manual inspections.

6. Road Pavement Monitoring Using Smartphone Sensing with a Two-Stage Machine Learning Model. [17]

- **Utilizes smartphone sensors** integrated into a two-stage machine learning model. **First stage:** Random Forest Classifier detects potential road anomalies. **Second stage:** Gaussian Process Classifier classifies anomalies into categories like normal road, large cracks, road bumps, and potholes.
- Transforms time-series data into **geospatial data**, making the system speed-independent and adaptable to urban settings.

7. Road Condition Monitoring Using Smart Sensing and Artificial Intelligence. [18]

- **Advanced Technologies in RCM**: Road Condition Monitoring uses smart sensors **(RGB cameras, thermal sensors, LiDAR)** and AI technologies (ML and DL models) to detect and classify pavement distresses like cracks and potholes efficiently.
- **Platforms and Approaches**: Ground vehicles, UAVs, and smartphones are key platforms for sensor deployment, each offering unique advantages. DL models, especially CNNs, are prominent for high-accuracy detection and segmentation of road issues

2.2 Limitation Existing system or Research gap

1. Smart monitoring of road pavement deformations from UAV images by using machine learning. [12]

- **Limitations on Ground-Level Hazards**: UAVs may miss key pedestrian hazards like obstructions, illegal parking, or street-level dangers, limiting their effectiveness for urban pedestrian safety projects.
- **Weather and Operational Dependencies**: UAV operations are impacted by adverse weather conditions (e.g., monsoons) and require regulatory approvals, making them less reliable for continuous monitoring in congested areas.

2. Smartphone applications for pavement condition monitoring: A review.[13]

- **Accuracy Concerns**: The accuracy of smartphone-based monitoring can vary due to factors such as driver behavior, vehicle dynamics, and the specific smartphone model, which can affect the consistency of data collection.
- **Environmental Sensitivity**: The paper notes that environmental factors, such as weather conditions and vehicle speed, can affect the accuracy of smartphone data for PCM. These variables may lead to inconsistent detection rates.
- **Data Variability**: The smartphone sensors collect **indirect data,** which requires significant preprocessing, including signal filtering and machine learning, to transform the raw data into actionable insights. This can increase the complexity and computational requirements.

3. Improved YOLOv5-Based Real-Time Road Pavement Damage Detection in Road Infrastructure Management. [14]

- **Computational Complexity :** This is mainly due to the enhancements made to the YOLOv5 architecture, such as incorporating ECA-Net and Focal Loss, which potentially would **hinder the deployment** on low-power or resource-constrained devices.
- **Overfitting, Latency, Bias :** Although label smoothing was used to prevent overfitting, the model may still struggle with **diverse environments and road conditions not reflected in the training data**. Furthermore, despite improvements in real-time processing, larger datasets or high-resolution images could **reduce detection speeds**, especially in edge devices. Lastly, the model's reliance on the RDD 2022 dataset could introduce biases if the **data does not fully represent global road damage types**, potentially skewing its performance in varied real-world scenarios.

4. Pavement Patch Detection and Measurement from Video Data Using a Parking Camera. [15]

- **Initial Setup Costs :** Although using existing vehicle-mounted cameras is cost-effective compared to dedicated inspection vehicles, the initial setup costs for integrating these cameras into municipal vehicles and ensuring proper calibration can still be substantial.
- **Impact of Weather Conditions :** The effectiveness of video data can be compromised by weather conditions, including rain, snow, or fog, which may obscure visibility and affect the clarity of captured images. This can lead to missed detections or false positives.

5. The State-of-the-Art Review on Applications of Intrusive Sensing, Image Processing Techniques, and Machine Learning Methods in Pavement Monitoring and Analysis. [16]

- **Challenges with Cost and Complexity :** The installation of intrusive sensors is costly, complex, and requires skilled personnel for data interpretation. Additionally, the system generates large volumes of data, which can be difficult to process in real-time.

6. Road Pavement Monitoring Using Smartphone Sensing with a Two-Stage Machine Learning Model. [17]

- **Training Data Requirements :** The effectiveness of machine learning models is contingent upon the availability of a large and diverse dataset for training. Collecting sufficient labeled data for various road conditions can be challenging and resource-intensive.
- **Categorization Challenges :** The model categorizes anomalies into broad categories (normal road, large cracks, bumps, potholes). This simplification may overlook nuanced defects or variations in pavement conditions that require more detailed analysis.

7. Road Condition Monitoring Using Smart Sensing and Artificial Intelligence. [18]

- **Challenges:** Key challenges include the need for real-time processing, data standardization, and improved characterization of pavement damage to enhance maintenance prioritization.

2.3 Mini project Contribution

Group Member Name	**Contribution in Mini Project**
Kushl Alve	Data Acquisition, Data Pre–processing, Model Training, Model Optimization, Documentation.
Neelkanth Khithani	Conceptualization, Research, Data Acquisition, Data Pre-processing, Project Management, Documentation.
Jatin Navani	Research, Data Pre–processing, Model Training, Testing and Validation, Documentation.
Vedang Gambhire	Data Acquisition, Model Optimization, Testing and Validation.

3 Proposed System

3.1 Introduction

Mumbai being a metropolitan city with dense urbanization has been facing pavement management issues [6] in terms of settlements around them, illegal parking, hawkers on the pavements, huge hoardings, fallen trees etc. Sometimes the surface condition of the pavements also deteriorates and potholes, open manholes, uneven roads, cracks and even waterlogging become a huge crisis for pedestrians as well as travelers.

Civic body. authorized garbage trucks usually move along these pavements [8] and can be used to gather our research related data. The idea is to mount an ***Electronic Control Unit*** on these trucks for collecting videos of the lateral and surface views of the roads. The significant images segregated after video processing would give insight regarding the condition of the pavements on that road as well as its geo-tagged location, thus providing a curated dataset for further analysis.. This would provide ***cost effectiveness*** against manual inspection of pavements and would generate ***periodic location–based data***. Further the video data generated would be substantial for ***planning and maintenance by civic/municipal divisional authorities.*** Usage of different image processing techniques and AI for extracting pool of features / defects including surface level and vertical objects with factors such as environmental (fallen trees / branches / uplifting of pavement due to tree roots etc.), defects (cracks or uneven surfaces / potholes / waterlogging etc.), human interference (illegal parked vehicles / barricades / hoardings (boards), shanties, unauthorized hawkers / vendors), others (broken lamp post / open manholes, broken benches and railing etc.). This would provide a trained AI model for validation and testing of unseen cases.

The Municipal Authorities would highly benefit from the ***ready dashboard visualization*** provided regarding the anomalies (hoarding, potholes etc.) detected from the images along with its geo–location so as to integrate prompt action for management of pavements. Usage of ***cloud infrastructure and storage*** for raw video data would ensure a secure and reliable backup for the future. An ***user-friendly, multi–lingual, (one of a kind) web application*** for the ***municipality***. would be developed for pavement condition monitoring and management. This would further facilitate improved decision making, ***synchronous crisis addressal*** within the departments of Municipal Authorities along with ***periodic surveys and timely maintenance***. The anomaly detection using image processing, feature extraction, object detection and AI would not only provide better ***actionable insights*** by the Municipality Officials but also help in predicting ***future pavement deterioration trends, season–wise pavement condition data*** thus aiding ***long-term urban planning and precise budget allocation*** for maintenance by the Municipal authorities.

The project supports key government initiatives like the ***AMRUT*** [1]***, Smart City Mission*** [2]***, PUSHP*** [3], aligning with national goals of enhancing urban infrastructure, reducing urban congestion, and improving pedestrian safety through smarter city planning. This would create research potential to **foster collaborations** between Municipal bodies, NGOs, SMEs, private technology providers, architects and contractors contributing to ***smart city initiatives*** and possibly ***stimulating local start-ups***. This would create labor opportunities for ***daily–wage workers*** and ***business ideas*** for all other stakeholders.

3.2 Architectural Framework

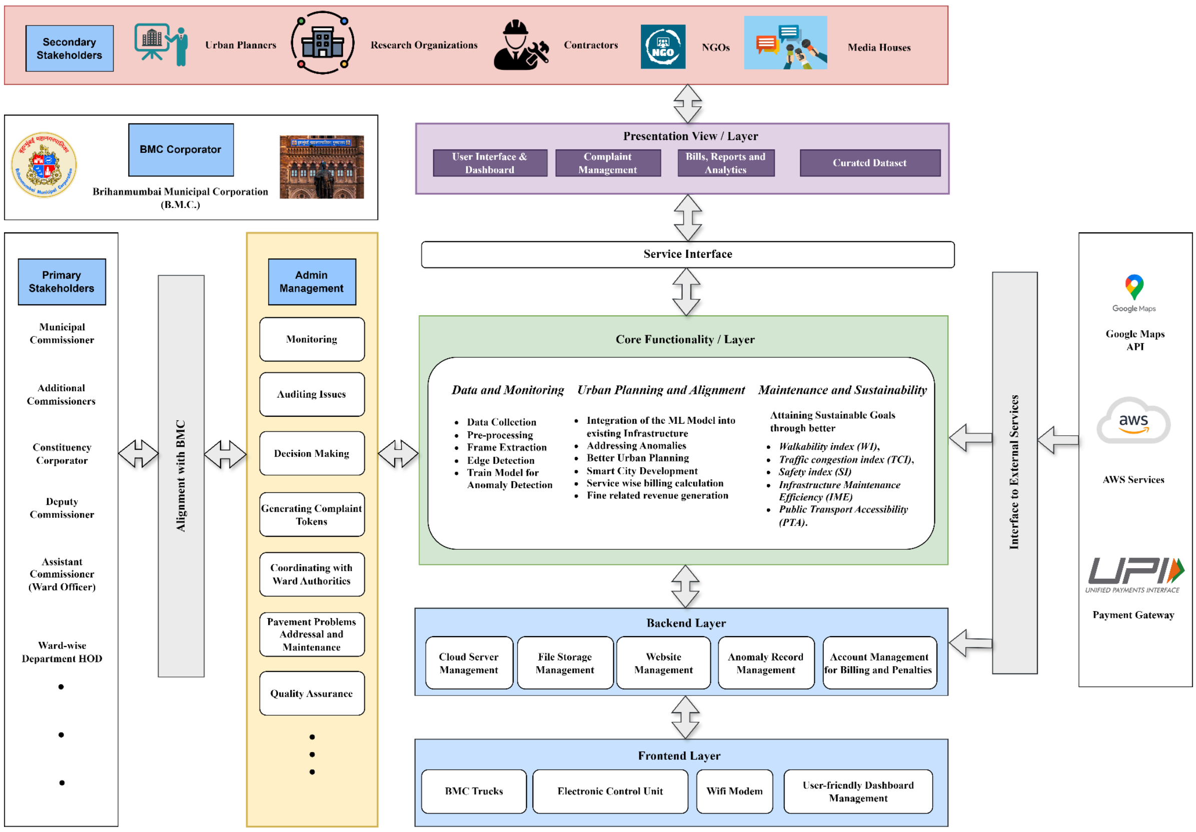

Figure 2. Proposed Service Level Architecture Diagram

The demands of the city infrastructure of Mumbai require a multi-layered system to ensure efficient urban planning and management. BMC **lies in the Network Connection layer**, which integrates mobile data and Wi-Fi for real-time data synchronization. A **Technology Platform** is provided for managing security, policies, devices, and AI models, supporting operational efficiency and revenue generation opportunities. Our solution will also function as a **Shared Operations Platform**, enabling inter-departmental data sharing and task management, benefiting secondary stakeholders. **Smart City Solutions**, such as AI-based analytics for urban planning and pavement monitoring, will enhance decision-making. Additionally, **Platform Monetization** introduces revenue streams through fines, penalties, and data monetization. The system provides **Program Leadership** to oversee AI governance and SLA management, ensuring sustainability.

The **Network layer consists of** both hardware and software components. The Electronic Control Unit (ECU), mounted on municipal corporation trucks, captures geo-tagged videos and generates datasets through frame extraction, which are uploaded to cloud storage. The AI module then processes this dataset using machine learning algorithms for feature extraction, anomaly detection, and severity analysis, providing actionable insights for pavement management.

The solution aligns seamlessly with the existing municipal corporation/Brihanmumbai Municipal Corporation (B.M.C.) infrastructure, requiring no overhauling of the existing framework. Complaints raised by Constituency Corporators will be processed through the established channels, where Ward Officers oversee technical aspects, and the appropriate departments—Maintenance, Environment, or Encroachment—are tasked with addressing issues. This alignment ensures that our AI-based system complements BMC's workflows, enhancing task allocation and reporting without disrupting the current processes. Upon alignment of this system with the municipal corporation infrastructure, system Dashboard can be utilized by the Ward Corporator to monitor and audit irregularities in the pavements of its constituency and to help them generate a Maintenance Complaint Report for his area to submit it to the relevant municipal corporation divisional authorities. Internal coordination within the municipal corporation / Brihanmumbai Municipal Corporation (B.M.C.) will be improved via the following factors:

(1) Elimination of manual time consuming and high cost pavement inspections,
(2) Enhancing quick responsive decision-making for maintenance and improvements activities,
(3) Legal eviction procedure and revenue loss due to encroachments,
(4) Administering the policy of fine/challan/penalty and thus initiate Revenue generation,
(5) Improving task prioritization and resource allocation to the Departmental workforce team,
(6) Bill generation for manpower/material usage and efficient distribution of funds for maintenance,
(7) Reduction of public complaints regarding delays in construction and extended response times for grievances,
(8) Facilitating the identification of high walkability areas, ensuring satisfaction of common man,
(9) Planning and developing sustainable cities through optimized urban infrastructure management.

The Research Outcomes of the Pavement Management System can be utilized by ***primary (within BMC) and secondary (non-BMC)*** stakeholders who can implement actionable insights and adopt technological advancements, leading to sustainable city planning and optimized urban infrastructure management. Additionally, it can contribute and align with India's National–level Programmes and Missions under Smart City and Urban Infrastructure like–AMRUT, Smart City Mission, PUSHP. It also increases the engagement of diverse stakeholders—including central and state government bodies (for e.g. MMRDA), other state urban planners, technology providers, and community members creating a robust ecosystem for implementing smart solutions. In the field of Communication / Dissemination / Advocacy, it highlights the role of media coverage, decision-making through endorsement, and even promotes the involvement of special interest groups like disaster management bodies, etc. An evidence base is established through crowdsourcing contributions and stimulating new research, ensuring a continuous feedback loop for improving sustainability measures. It emphasizes the need for policy changes and reorganization of departments and services within the municipal corporation/ Brihanmumbai Municipal Corporation (B.M.C.).

3.3 Algorithm and Process Design

1. **System Overview**:
    - The Electronic Control Unit (ECU), mounted on municipal corporation trucks, captures geo-tagged videos of pavement conditions in the city.
2. **Data Generation**:
    - As the trucks drive around, they record videos that are processed to generate datasets through frame extraction. These datasets are then uploaded to cloud storage for further analysis.
3. **AI Module Processing**:
    - The AI module processes these datasets using machine learning algorithms for:
        - **Feature Extraction**: Identifying specific characteristics of pavement conditions.
        - **Anomaly Detection**: Recognizing defects or unusual conditions.
        - **Severity Analysis**: Assessing the seriousness of identified issues.
4. **Image Processing Techniques**:
    - Various image processing techniques are employed to extract features and defects, including:
        - **Environmental Factors**: Identifying issues such as fallen trees or branches and uplifted pavement due to tree roots.

- **Maintenance Defects**: Spotting cracks, uneven surfaces, potholes, and areas prone to waterlogging.
- **Encroachments**: Detecting illegal parking, barricades, hoardings, shanties, and unauthorized vendors obstructing the pathways.
- **Other Issues**: Highlighting problems such as broken lamp posts, open manholes, and damaged benches or railings.

5. **Visualization and Decision Making**:
   - The extracted insights and anomalies are visualized on a user-friendly dashboard made available to municipal corporation authorities, such as the B.M.C. This visualization aids improved decision-making for city planning and enables synchronized crisis response across municipal departments.
6. **Long-Term Planning and Maintenance**:
   - The system facilitates periodic surveys and timely maintenance of pavements. Anomaly detection and feature extraction provide better actionable insights for municipal administration, enabling predictions of future pavement deterioration trends and seasonal pavement condition data, thereby supporting long-term urban planning and precise budget allocation for maintenance.

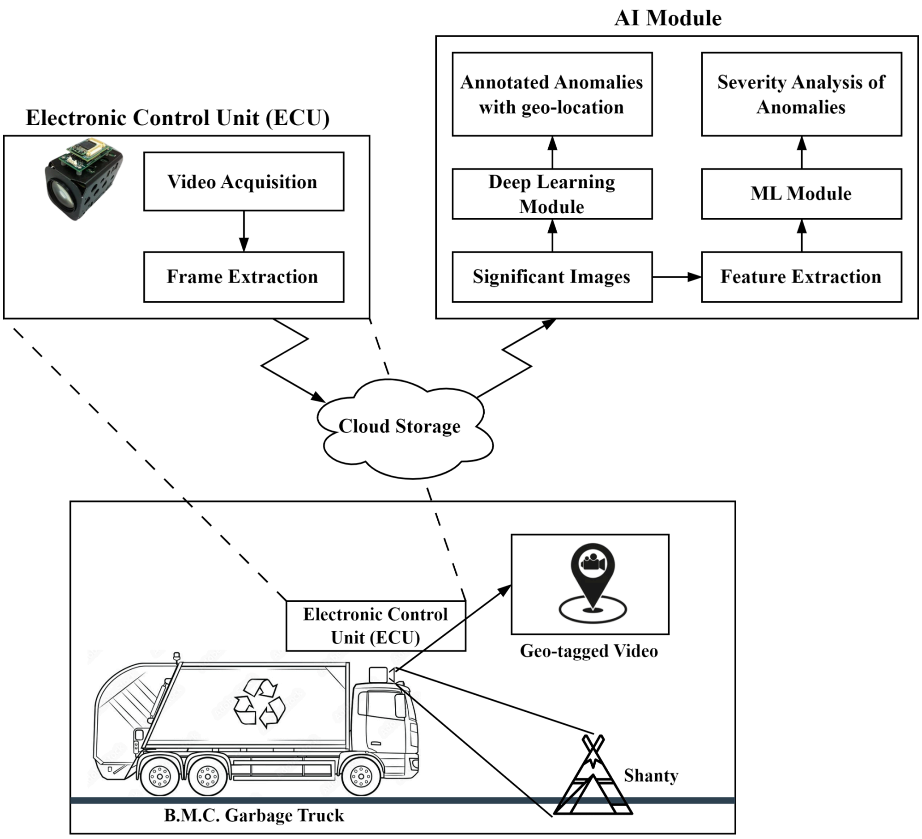

Figure 3. Block Diagram for the Proposed System for Data and Monitoring

3.4 Methodology Applied

A. Electronic Control Unit (ECU) for Municipal Corporations Trucks

The Electronic Control Unit (ECU) will use a Video Processing Unit (VPU) connected to the camera along with a GPS module for location data. The Raspberry Pi processes the video and generates differential images and uploads it to the cloud via a Wi-Fi Modem. The system operates with a stable power supply, monitored by a Battery Capacity Indicator to ensure continuous functionality during monitoring routes.

B. Data Collection

Equip municipal corporation. authorized garbage trucks with ECU for daily video data of pavement conditions. The captured images from the video uploaded on the cloud will facilitate anomaly detection using image processing and AI. The images will be associated with a precise location, facilitating better tracking of pavement conditions.

C. Data Pre–processing and Feature Extraction

Frame extraction to isolate relevant images of pavement and footpath surfaces. Further image processing will be performed for noise reduction, segmentation, edge detection and feature extraction for identifying environmental anomalies (fallen trees / branches / uplifting of pavement due to tree roots etc.), pavement defects (cracks or uneven surfaces / potholes / waterlogging etc.), human interference (illegal parked vehicles / barricades / hoardings (boards), shanties, unauthorized hawkers / vendors) and others (broken lamp post / open manholes, broken benches and railings etc.).

D. Anomaly Detection

Use the extracted image features to create a curated dataset for training the AI model. The dataset will contain various classes of anomalies with labeled data for each anomaly type using deep learning algorithms. Further optimization will be included to improve accuracy and reduce latency, ensuring that the model works efficiently even in real-time and large-scale urban scenarios.

E. Scalability

Host the trained model, raw video data, and processed images on a cloud infrastructure. This will allow for scalable and remote access to the system for municipal corporation officials. Video data and extracted insights will be securely stored for future reference and analysis. The system will handle large volumes of incoming data, performing anomaly detection and generating reports on pavement conditions, complete with geo-tagged imagery.

F. Visualization

An user-friendly dashboard will be developed to provide municipal corporation administrators with updates on pavement conditions. The dashboard will feature: (1) Map-based visualization for geo-tagged anomalies. (2) Detailed information on each anomaly type with images and severity analysis. (3) Actionable insights, such as which department to contact for repair.

G. Testing and Deployment

The system will be tested through pilot deployment in selected wards of Mumbai. Validation will include accuracy assessments of anomaly detection, efficiency in data processing, and user satisfaction with the dashboard's functionality. Mumbai–pavements performance data will be used to refine and improve the model and system components.

H. Alignment with Existing Infrastructure

The production–ready website will be delivered to the municipal corporation. Then the Corporators will be able to log in and access dashboards specific to their respective constituencies for monitoring conditions, auditing issues, and initiating complaints tokens for solving the maintenance issues. The complaints will be forwarded by them to the relevant Authorities for further Smart City Urban Planning.

I. Impact Measurement for Maintenance and Sustainability

The system's impact in the municipal corporation workflow will be evaluated through key performance parameters such as reduced maintenance response times (latency reduction), improved pavement and infrastructure conditions, and pedestrian safety and accessibility.

3.5 Hardware & Software Specifications

1. **Hardware Components:**
   Cameras: High-resolution cameras are placed for comprehensive coverage of the pavements.
   Processing Units: GPUs like NVIDIA GeForce RTX handle real-time video processing and deep learning inference.
   Storage: High-capacity storage units store both raw footage and processed data.
2. **Software Components:** (1) Deep Learning Frameworks: TensorFlow or PyTorch are used for training and deploying object detection and tracking models. (2) Computer Vision Libraries: OpenCV is used for preprocessing and background

subtraction. (3) Database Management: SQL or NoSQL databases store passenger count data and statistics for later analysis.

3. **System Scalability:**

   The system is designed to scale across multiple train compartments and routes. Cloud infrastructure (AWS, Azure) allows for processing and data storage to be scaled as more trains and cameras are added to the system.

3.6 Experiment and Results for Validation and Verification

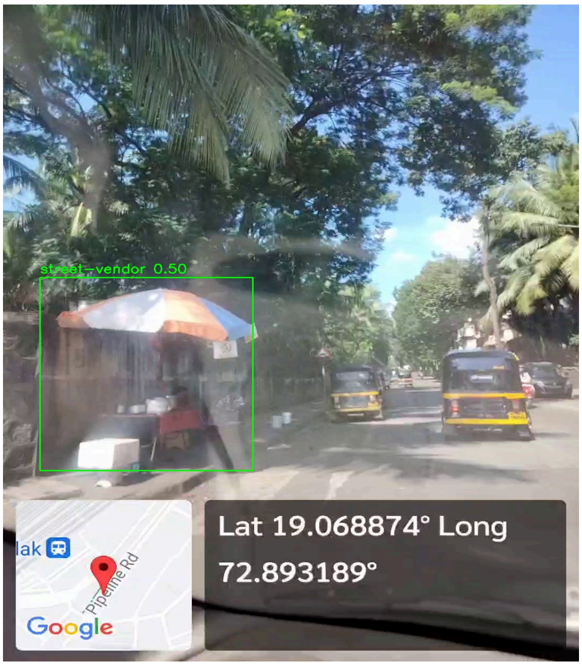

Figure 4. Identified Street Vendor using trained YoloV9 Model

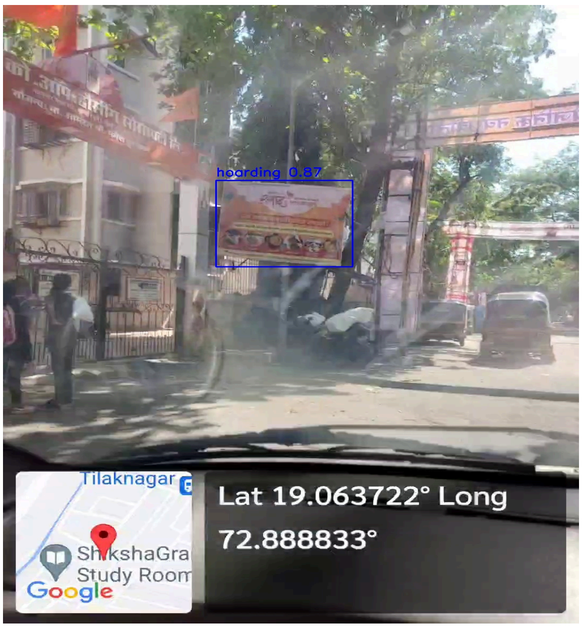

Figure 5. Identified Illegal Hoarding using trained YoloV9 Model

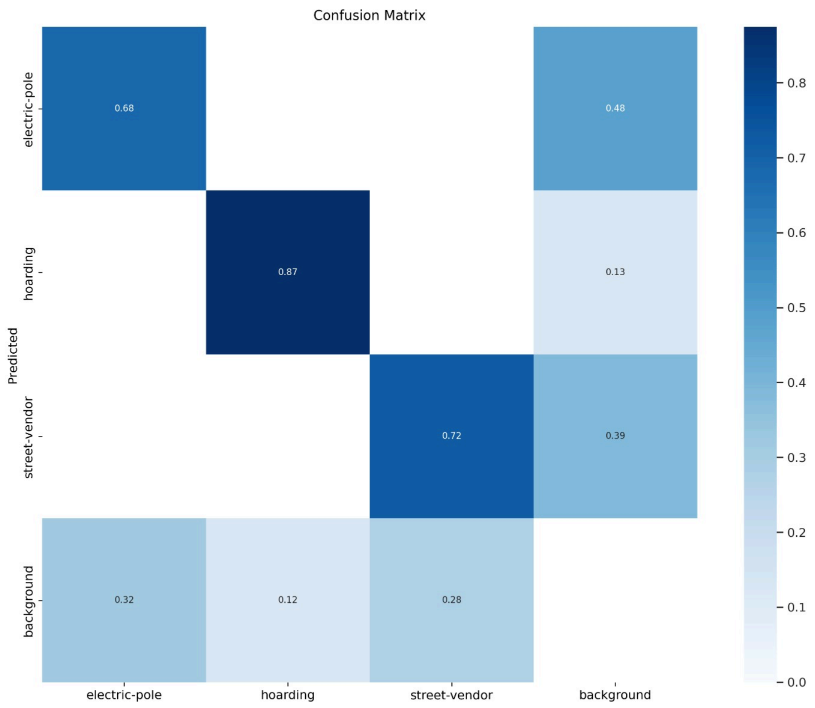

Figure 6. Confusion Matrix for trained YoloV9 Model

3.7 Result Analysis and Discussion

1. **Confusion Matrix Overview (Refer Figure 6)**:
    - The confusion matrix presents the performance of the YOLO v9 model in classifying objects such as *electric poles*, *hoardings*, *street vendors*, and *background*.
    - Diagonal elements represent correct classifications, while off-diagonal elements represent misclassifications.
    - **Key observations:**
        - **Electric pole**: The model correctly classifies electric poles with an accuracy of 68% (0.68), but 32% of them were mistaken for background.
        - **Hoarding**: It shows the best performance here with 87% accuracy. Only 13% were misclassified.
        - **Street vendor**: The model identified street vendors correctly 72% of the time, with a significant misclassification rate of 39% into background.
        - **Background**: 32% of the background was misclassified as electric poles, and 28% as street vendors.

2. **Analysis**:
    - The model demonstrates a strong ability to detect hoardings and street vendors, while it struggles a bit more with differentiating between electric poles and background.
    - A key challenge might be the model's sensitivity to background clutter, leading to higher confusion with objects like electric poles and street vendors, which often appear in noisy environments.
3. **YOLO Detection Example (Refer Figure 4 and Figure 5)**:
    - The image shows a detection of a *street vendor* with a confidence score of **0.50**.
    - The detection is presented alongside geographic data (Lat: 19.068874°, Long: 72.893189°), highlighting the street vendor's location.
4. **Analysis**:
    - While the object detection confidence is moderate (0.50), the model was able to correctly classify the street vendor in a cluttered urban environment. The integration of GPS coordinates provides precise localization, which is useful for urban planning or enforcement scenarios where the location of street vendors needs to be tracked.
    - There might be room for improvement in the confidence score, suggesting that refining the model with better training data or optimizing detection parameters could improve reliability.

3.8 Conclusion and Future work

The proposed system aims to transform the maintenance of urban infrastructure, in Mumbai where pedestrian safety is significantly affected by deteriorating pavement conditions. Through the integration of advanced technologies such as video processing, machine learning, and cloud deployment, this system provides an automated and scalable solution to identify pavement anomalies like cracks, potholes, obstructions, and encroachments. With an ECUmounted on Municipal Corporation trucks, real-time data collection becomes seamless, while the cloud infrastructure facilitates remote monitoring and analysis. The system's user-friendly dashboard equips authorities with critical insights for prioritizing maintenance tasks based on the severity of detected issues, thus reducing the dependency on labor-intensive manual inspections and significantly enhancing pedestrian safety. Additionally, this system contributes to the long-term goals of developing smarter cities with more walkable and safer environments.

In the future, several enhancements can further optimize and expand the system's capabilities. Continuous improvements in AI models will increase accuracy in detecting more complex anomalies. Real-time data processing can be enhanced through the use of edge computing to reduce latency. The system can be scaled for implementation in other cities, accommodating different infrastructure challenges by customizing datasets and models to suit varied geographical conditions. Collaborating with public and private stakeholders, including government agencies, civil engineers, and private companies, will help refine the system and ensure its effectiveness in guiding urban planning and policy decisions.

References

[1] "AMRUT (Atal Mission for Rejuvenation and Urban Transformation)," *Ministry of Housing and Urban Affairs*, [Online]. Available: https://mohua.gov.in/cms/amrut.php.

[2] Ministry of Housing and Urban Affairs, Government of India**,** “Smart cities mission,” *MoHUA*, [Online]. Available: https://mohua.gov.in/cms/smart-cities.php.

[3] Times of India, "5 petals of PUSHP will make Viksit Bharat: PM Modi tells Indian diaspora in New York," *The Times of India*, Sep. 27, 2024. [Online]. Available: https://timesofindia.indiatimes.com/world/us/5-petals-of-pushp-will-make-viksit-bharat-pm-modi-tells-indian-diaspora-in-new-york/articleshow/113576007.cms.

[4] "About," *Pedestrians First*, [Online]. Available: https://pedestriansfirst.itdp.org/about.

[5] V. Nikumbh, "Mumbai Reader No. 9," *Urban Design Research Institute*, [Online]. Available: https://www.udri.org/wp-content/uploads/Mumbai%20Reader/MR%209/MR%209%20vineet%20Nikumbh%20Low.pdf.

[6] "Footpaths in India: The Dangerous Gap Between Policy and Reality," *Question of Cities*, [Online]. Available: https://questionofcities.org/footpaths-in-india-the-dangerous-gap-between-policy-and-reality/.

[7] "Land Encroachment in Maharashtra," Law Crust, [Online]. Available: https://lawcrust.com/land-encroachment-in-maharashtra/.

[8] "Trash collection schedule, routes on BMC's website," *Times of India*, [Online]. Available: https://timesofindia.indiatimes.com/city/mumbai/trash-collection-schedule-routes-on-bmcs-website/articleshow/48322230.cms.

[9] R. Puranik, "Understanding Mumbai’s Municipal Corporation," *Citizen Matters*, Mar. 28, 2022. [Online]. Available: https://citizenmatters.in/understanding-mumbais-municipal-corporation/.

[10] Municipal Corporation of Greater Mumbai, "Departmental Manuals," *MCGM Portal*. [Online]. Available: https://portal.mcgm.gov.in/irj/portal/anonymous/qldeptmanuals.

[11] "Meri Sadak PMGSY," Ministry of Rural Development, Government of India. [Online]. Available: https://rural.gov.in/en/services/meri-sadak-pmgsy.

[12] H. B. Ibrahim, M. Salah, F. Zarzoura, et al., "Smart monitoring of road pavement deformations from UAV images by using machine learning," *Innov. Infrastruct. Solut.*, vol. 9, no. 16, 2024. [Online]. Available: https://doi.org/10.1007/s41062-023-01315-2.

[13] A. M. Al-Sabaeei, M. I. Souliman, and A. Jagadeesh, "Smartphone applications for pavement condition monitoring: A review," *Constr. Build. Mater.*, vol. 404, p. 134207, 2023. [Online]. Available: https://doi.org/10.1016/j.conbuildmat.2023.134207.

[14] A. Sami, A. S. Saadman, K. Deb, and I. H. Sarker, "Improved YOLOv5-Based Real-Time Road Pavement Damage Detection in Road Infrastructure Management," *Algorithms*, vol. 16, no. 9, p. 452, 2023. [Online]. Available: https://doi.org/10.3390/a16090452.

[15] S. C. Radopoulou and I. Brilakis, "Patch detection for pavement assessment," *Autom. Constr.*, vol. 53, pp. 95-104, 2015. [Online]. Available: https://doi.org/10.1016/j.autcon.2015.03.010.

[16] Y. Hou, Q. Li, C. Zhang, G. Lu, Z. Ye, Y. Chen, L. Wang, and D. Cao, "The State-of-the-Art Review on Applications of Intrusive Sensing, Image Processing Techniques, and Machine Learning Methods in Pavement Monitoring and Analysis," *Eng.*, vol. 7, pp. 845-856, 2021. [Online]. Available: https://doi.org/10.1016/j.eng.2020.07.030.

[17] K. Zhao, S. Xu, J. Loney, A. Visentin, and Z. Li, "Road pavement health monitoring system using smartphone sensing with a two-stage machine learning model," *Automation in Construction*, vol. 167, 2024, Art. no. 105664. Available: https://doi.org/10.1016/j.autcon.2024.105664.

[18] E. Ranyal, A. Sadhu, and K. Jain, "Road Condition Monitoring Using Smart Sensing and Artificial Intelligence: A Review," *Sensors*, vol. 22, no. 8, Art. no. 3044, Apr. 2022. Available: https://doi.org/10.3390/s22083044.

[19] https://www.ndtvprofit.com/business/how-indias-richest-civic-body-earns-and-spends