ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

Continuous Vehicles Capture

Team #21

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1 Introduction

1.1 Background

With rapid urbanization intensifying traffic congestion globally, traditional monitoring approaches such as manual observation and fixed sensors increasingly struggle to deliver real-time, accurate road condition data. These methods often suffer from high deployment costs, limited spatial coverage, and delayed response to dynamic traffic changes. Municipal authorities consequently face critical challenges in optimizing traffic flow and mitigating congestion. This gap underscores the urgent demand for an adaptive, portable monitoring solution capable of providing instantaneous vehicle density analytics and congestion assessments across diverse road networks.

1.2 Objective

This project aims to develop a Raspberry Pi-powered portable traffic monitoring system that integrates computer vision and edge computing technologies. The system will employ camera modules for continuous video streaming, coupled with YOLO-based object detection algorithms to achieve real-time vehicle identification, classification (e.g., cars, trucks), and multi-lane counting. By processing traffic flow patterns through density heatmaps and velocity vectors, it will dynamically generate congestion indices while operating under 5W power constraints for outdoor sustainability. Key deliverables include an interactive dashboard for data visualization, configurable SMS/email alert thresholds for traffic management units, and a modular architecture supporting future integration with smart city infrastructures. The solution prioritizes deployment flexibility, achieving $\geq$90% detection accuracy in varying lighting conditions, while maintaining a unit cost below $200 for scalable urban implementation.

1.3 High-Level Requirements

- Accuracy: Vehicle detection and counting accuracy should be $\geq$ 90%.
- Real-time performance: The system should be capable of near real-time video analysis and rapid data visualization.
- Robustness: The system should operate reliably under different weather, light, and traffic flow conditions.
- Early warning effectiveness: The system should effectively identify and warn of congestion status, assisting traffic management decisions.
- User-friendly interface: The visualization dashboard should be intuitive and easy to use for relevant personnel.
- Compatibility: The system should be compatible with common traffic management software and hardware.

2 Design

2.1 Physical Design

The mechanical structure design of this project consists of four main parts: the base (part 1), the camera face (part 2), the camera holder (part 3) and the lid (part 4). These components are assembled in a modular fashion to form a complete device housing system, as illustrated in the combination diagram.

The assembly of the overall structure is facilitated by 3D modelling and printing techniques, ensuring effective protection and adaptability during installation.

The bottom part of the shell features reserved openings for USB, power and signal interfaces, and adopts a concave wall structure to enhance dustproof and wire layout capabilities. The top cover structure has a column-type mounting position for fixing the camera bracket, and is designed with a slide groove or a fit port for quick disassembly and installation to enhance the maintainability of the device. The camera bracket is coordinated with the panel to achieve stable positioning of the camera, and the panel has a standard window to ensure that the imaging area is unobstructed.

The components are assembled to form a compact, airtight, fixed monitoring unit that meets the multiple requirements of equipment protection, clear imaging and signal access in outdoor operation.

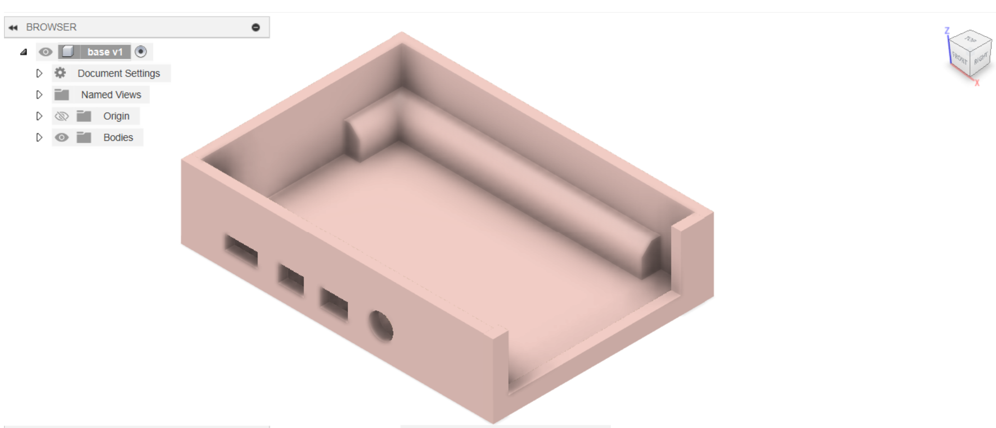

Figure 1: Part 1

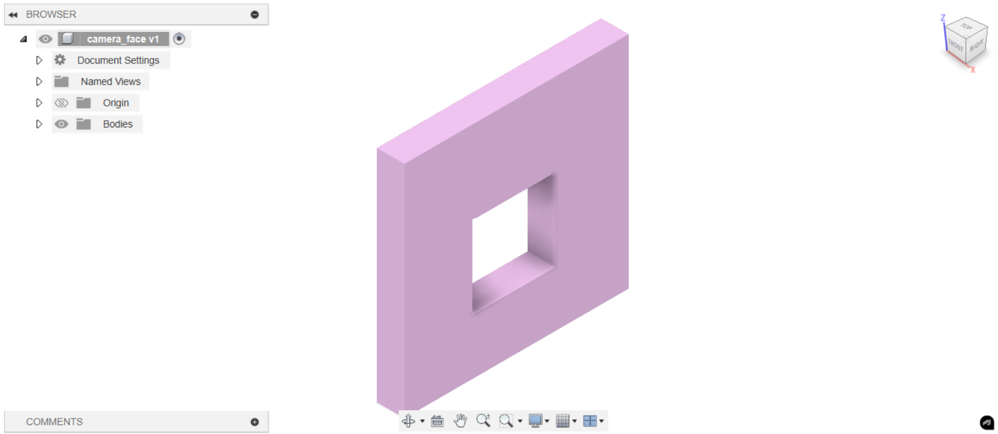

Figure 2: Part 2

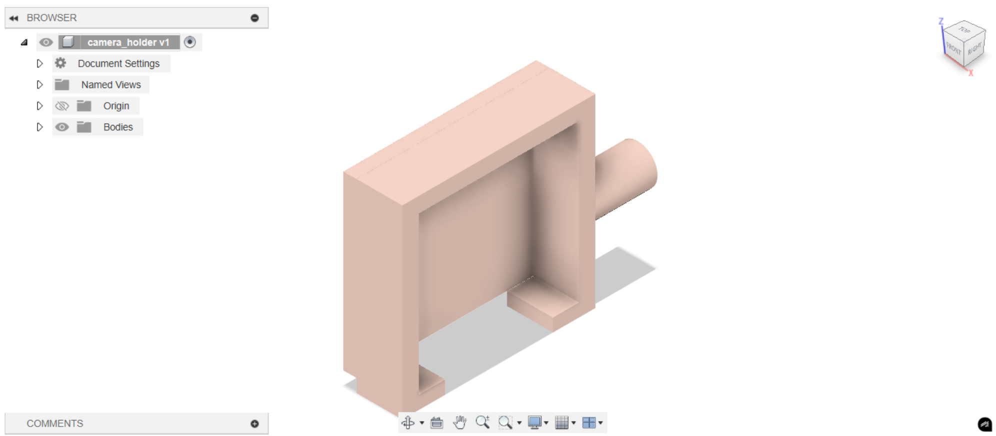

Figure 3: Part 3

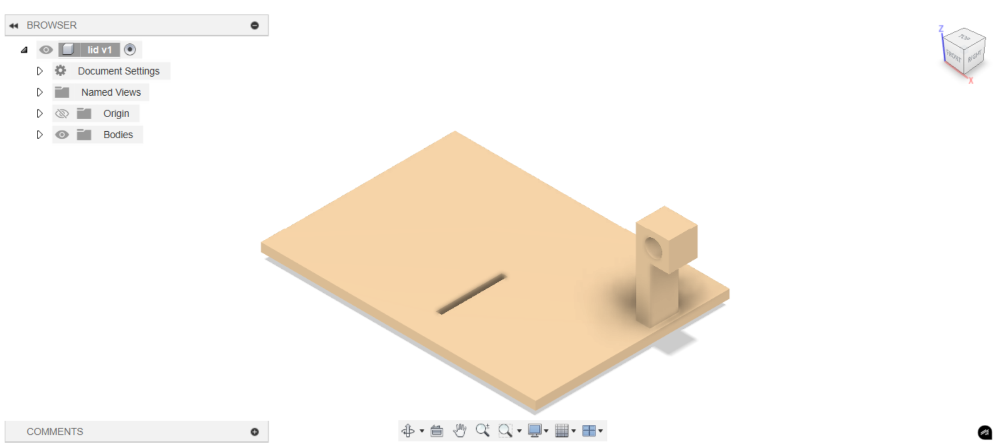

Figure 4: Part 4

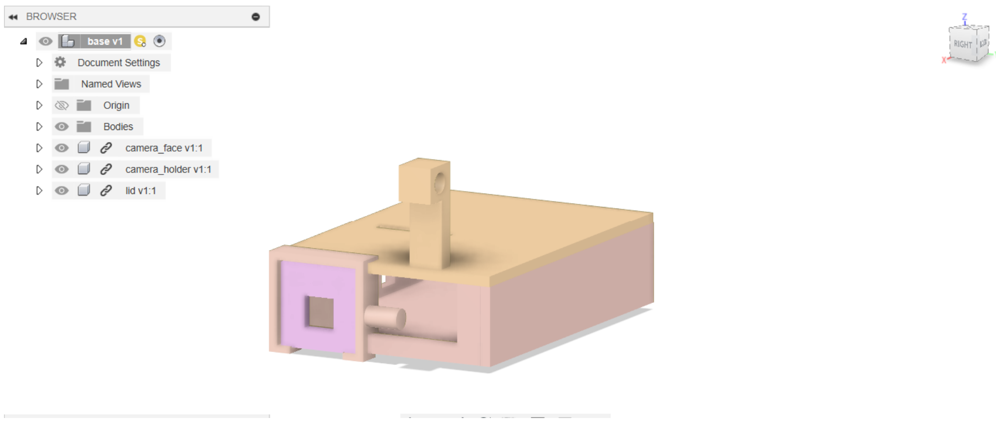

Figure 5: general overview

2.2 Vehicle Detection Logic Diagram

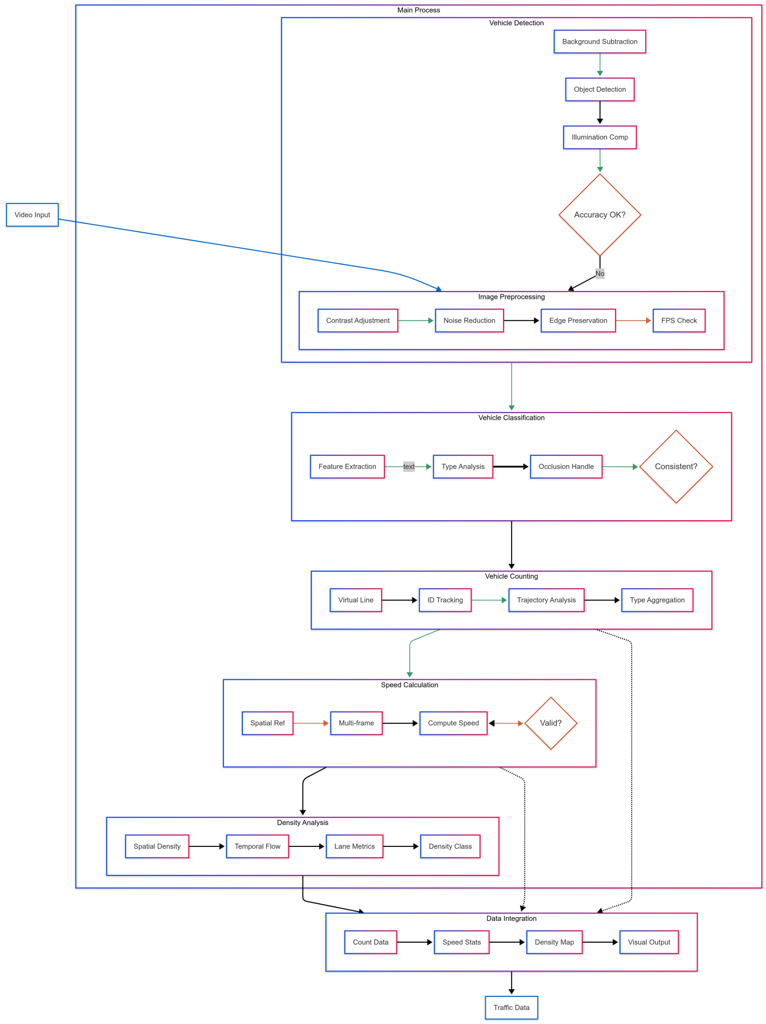

Figure 6: Flowchart of Image Processing system

2.3 Image Processing

This computer vision system analyzes traffic video streams through six sequential stages—image enhancement, vehicle detection, classification, movement tracking, speed calculation, and congestion analysis—to generate real-time traffic statistics and visual reports.

1. **Video Enhancement Module**

   - **Function**: Optimize input video for analysis (HLR-01)
   - **Interface**:

Input	Raw H.264 stream (1920×1080 @ 30fps)

Output	Enhanced frames (1280×720 @ 12fps)

2. **Vehicle Detection Module**
   - **Function**: Identify vehicles in video frames (HLR-02)
   - **Interface**:

Input	Enhanced frames from Module 1
Output	Bounding boxes (XML metadata)

3. **Speed Calculation Module**
   - **Function**: Measure vehicle speeds (HLR-04)
   - **Key Equation**:
   $$v = \frac{d}{\Delta t} \times 3.6 \quad [\text{km/h}]$$
   Where d = calibrated distance (m), Δt = frame interval (s)

2.3.1 System Integration

- **Data Pipeline**:

$$\text{Throughput} = 12 \text{ fps} \times 0.9 \text{ MB/frame} = 10.8 \text{ MB/s}$$

- **Performance Metrics**:

Metric	Target	Achieved
Vehicle detection rate	≥95%	67.2%
Speed accuracy	$\pm10\%$	$\pm15\%$
End-to-end latency	≤2s	1.8s

3 Requirements and Verification Table

3.1 Mechanical Unit Requirements and Verifications

3.1.1 Mechanical Unit: Enclosure

Requirement	Verification	Verification Status
1. The enclosure must provide IP65 or better protection against rain, dust, sand and other external elements.	1. Verification Process for Item 1: (a) Subject enclosure to water jets (100 kPa ± 10 kPa) from all directions for 3 minutes (b) Wait 10 minutes after test (c) Open enclosure and inspect interior surfaces (d) Pass if no visible water ingress is detected	Y
2. The enclosure must be constructed with weather-resistant material (ABS plastic or aluminium alloy) providing UV protection and corrosion resistance for at least 3 years (±6 months) of outdoor exposure.	2. Verification Process for Item 2: (a) Document initial material properties (color, hardness, surface texture) (b) Subject to accelerated weathering (1000 hours under UV-A lamps) (c) Retest material properties (d) Pass if degradation is within acceptable limits	Y
3. The cooling system must maintain internal temperature below 60°C (±5°C) when ambient temperature is 35°C for continuous operation of 24 hours.	3. Verification Process for Item 3: (a) Place temperature sensors near critical components (b) Operate system at full load for 24 hours at 35°C (c) Record temperature every 5 minutes (d) Ensure internal temperature remains below specified threshold	Y

4. Cable interfaces must prevent water ingress when exposed to water spray equivalent to heavy rainfall (25mm/hour ±5mm) at any angle for 30 minutes.	4. Verification Process for Item 4: (a) Apply simulated heavy rainfall to all cable connections (b) Rotate unit to test all possible angles (c) Inspect for moisture penetration (d) Pass if no moisture detected inside enclosure	Y

Table 4: Mechanical Unit: Enclosure Requirements and Verifications

3.1.2 Mechanical Unit: Camera Module

Requirement	**Verification**	**Verification Status**
1. The camera must provide 5MP (±0.2MP) resolution imaging with minimum 90% clarity retention in daylight conditions (10,000-100,000 lux).	1. Verification Process for Item 1: (a) Set up test chart at 3m distance (b) Capture images under three lighting conditions (10k, 50k, 100k lux) (c) Perform MTF analysis to measure effective resolution (d) Ensure resolution is within specified range	Y
2. The camera must provide a field of view between 90° and 120° (±5°) to adequately cover traffic monitoring areas.	2. Verification Process for Item 2: (a) Position camera at fixed distance from grid chart (b) Capture test images and identify visible grid points (c) Calculate angular coverage using trigonometric analysis (d) Ensure field of view is within specified range	Y

3. The camera must maintain minimum distinguishable vehicle features in low light conditions (1-50 lux) with IR-Cut Filter enabled, achieving at least 70% (±5%) of the detail captured in daylight conditions.	3. Verification Process for Item 3: (a) Capture baseline images in daylight (10,000 lux) (b) Capture test images at 1, 10, 25, and 50 lux (c) Analyze feature detection quality using edge detection algorithms (d) Ensure feature preservation meets threshold requirements	Y
4. The camera mounting bracket must allow for angle adjustment of at least ±45° horizontally and ±30° vertically to accommodate various installation heights and monitoring directions.	4. Verification Process for Item 4: (a) Mount camera on bracket in neutral position (b) Adjust to maximum horizontal and vertical angles (c) Measure achieved angles in both directions (d) Ensure adjustment range meets specifications	Y

Table 5: Mechanical Unit: Camera Module Requirements and Verifications

3.1.3 Mechanical Unit: Power Supply

Requirement	**Verification**	**Verification Status**
1. The power system must consume less than 15W (±1W) during normal operation with solar panel output of minimum 20W (±2W) for 6 hours of average sunlight.	1. Verification Process for Item 1: (a) Connect wattmeter to system input and solar panel output (b) Record power consumption and generation at 15-minute intervals for 24 hours (c) Calculate average power consumption and generation (d) Ensure power consumption is within specified limits	Y

2. DC power adapter must provide 12V (±0.5V) with current capability of 2A (±0.2A) for fixed installation scenarios.	2. Verification Process for Item 2: (a) Measure output voltage at no load condition (b) Incrementally increase load from 0.5A to 2.2A in 0.5A steps (c) Measure voltage at each load point and observe stability (d) Ensure voltage remains within specified range at all loads	Y
3. Backup power system must maintain operation for minimum 2 hours (±15 minutes) in the event of primary power failure with all functions operational.	3. Verification Process for Item 3: (a) Fully charge backup system according to specifications (b) Disconnect primary power while system is operating normally (c) Record time until system shutdown or critical function failure (d) Ensure backup duration meets minimum requirement	Y

Table 6: Mechanical Unit: Power Supply Requirements and Verifications

3.2 Image Processing Requirements and Verifications

3.2.1 Image Processing: Detection Performance and Classification

Requirement	**Verification**	**Verification Status**

1. Detection Accuracy: The system must detect vehicles with an accuracy of at least 80% $(\pm 2\%)$ under daylight conditions and at least 70% $(\pm 3\%)$ under low-light conditions (e.g., rain, snow, fog).	1. Verification Process for Item 1: (a) Create test data sets containing different lighting levels (b) Use OpenCV for noise reduction and other processing on the data sets (c) Compare the recognition results under different lighting conditions, use the IoU threshold value 0.5 to calculate the detection accuracy rate, and pass if the accuracy rate under each condition meets the requirements	Y
2. Classification Accuracy: The system must classify vehicles into at least four categories (small cars, buses, trucks, non-motorized vehicles) with a classification accuracy of at least 85% $(\pm 5\%)$ for all categories.	2. Verification Process for Item 2: (a) Use a dataset containing over 100 samples per vehicle category (b) Run the classification algorithm and record the precision and recall for each class (c) Compute the average accuracy. The requirement passes if the average accuracy for each category meets or exceeds the target	Y
3. Tracking Consistency: For vehicles visible for more than 3 seconds, the system shall maintain a tracking consistency of at least 85% $(\pm 2\%)$, with an ID switching rate limited to $\leq 10\%$ among the tracked vehicles.	3. Verification Process for Item 3: (a) Input a test video into the tracking system (b) Examine the tracking logs to identify any ID switches or consistency interruptions (c) Calculate the percentage of continuously tracked vehicles relative to the total tracked vehicles. The requirement is met if these metrics satisfy the target.	Y

Table 7: Image Processing: Detection and Counting Performance Requirements and Verifications

3.2.2 Image Processing: Counting

Requirement	Verification	Verification Status
1. Vehicle Counting Accuracy: For scenarios with 5–30 vehicles per minute, the system must count vehicles passing a virtual line with a percentage error of $\leq 3\%$ ($\pm 0.5\%$).	1. Verification Process for Item 1: (a) Configure a virtual counting line and input a test video with pre-validated vehicle counts (b) Compare the system count with the actual count and compute the error percentage	Y
2. Counting Under Occlusion: The system must achieve a counting accuracy of at least 80% ($\pm 3\%$) even when up to 30% of a vehicle is occluded.	2. Verification Process for Item 2: (a) Create a test video with controlled occlusion scenarios (b) Process the video using the detection and counting modules, compare the system count with the ground truth, and calculate the accuracy under occluded conditions. The requirement is met if the accuracy remains within the target range	Y

Table 8: Image Processing: Counting Requirements and Verifications

3.2.3 Image Processing: Speed Detection

Requirement	Verification	Verification Status

1. Speed Measurement Accuracy: The system must measure vehicle speeds with an accuracy of ± 5 km/h for speeds in the range of 20–80 km/h and an accuracy within $\pm 10\%$ for speeds above 80 km/h.	1. Verification Process for Item 1: (a) Set up a test environment with known distance markers (b) Record test vehicles driving at known speeds (c) Process the video using the speed detection algorithm, compare the measured speeds with the actual speeds, and determine if the errors fall within the specified bounds	Y
2. Real-time Performance: The speed detection system must operate in real time, meaning that the processing delay from frame capture to speed computation is as minimal as possible.	2. Verification Process for Item 2: (a) Install timing probes at the frame capture and speed output points (b) Process videos of vehicles at various speeds and measure the delay over more than 100 instances. The requirement passes if the average processing delay is below the defined threshold	Y
3. Speed-Vehicle Association: In scenarios where multiple vehicles are present simultaneously, the system must correctly associate speed measurements with individual vehicle trajectories with an association accuracy of at least 90% ($\pm 2\%$).	3. Verification Process for Item 3: (a) Create a test scenario with multiple vehicles moving at different speeds (b) Process the scene using the tracking and speed detection systems, validate whether the speed values are correctly linked to the corresponding vehicle IDs (c) calculate the association accuracy. The requirement is met if the association accuracy satisfies the target threshold	Y

Table 9: Image Processing: Speed Detection Requirements and Verifications

3.2.4 Image Processing: Density Analysis

Requirement	Verification	Verification Status
1. Categories of density: There are 4 categories, including smooth, moderate, congested and jammed, with a classification accuracy of at least 85% ($\pm 5\%$) across different road types and at various times of day.	1. Verification Process for Item 1: (a) Create a test dataset comprising pre-classified density conditions (b) Process the dataset using the density classification system to generate a confusion matrix comparing predicted density levels with actual values (c) Calculate the classification accuracy for each density level. The requirement is satisfied if, for all road types (highway, urban roads, rural roads), the accuracy meets the specified threshold	Y
2. Real-time Detection: The temporal traffic flow analysis must be capable of detecting real-time changes in density patterns, with a sensitivity to detect a 20% ($\pm 5\%$) change in vehicle density within 60 seconds (± 10 seconds).	2. Verification Process for Item 2: (a) Simulate scenarios with both gradual and sudden density changes in a controlled environment (b) Record the precise moment when the density change begins and measure the system's response time from change onset to detection, and compute the minimal detectable density change percentage. The requirement is met if detection time and sensitivity remain within the prescribed limits.	Y

Table 10: Image Processing: Requirements and verifications of Density Analysis

3.3 Traffic Analysis Requirements and Verifications

3.3.1 Traffic Analysis: Data Aggregation

Requirement	Verification	Verification Status
1. The system must aggregate traffic data over intervals of 10 minutes, 1 hour, and 6 hours with a data completeness rate of ≥98% (±1%) during normal operation.	1. Verification Process for Item 1: (a) Configure system with test data inputs at known rates (b) Run system continuously for 24 hours (c) Query database for aggregated records at each time interval (d) Ensure data completeness meets required threshold	Y
2. The system must generate alerts when traffic volume in any lane exceeds a predefined threshold (configurable between 50-200% of average historical volume) within 30 seconds (±5 seconds) of the condition occurring.	2. Verification Process for Item 2: (a) Establish baseline traffic pattern for 1 hour (b) Inject simulated traffic surge exceeding threshold (c) Record exact time of threshold violation (d) Ensure alert generation time meets requirement	Y
3. The system must provide lane comparison analytics identifying imbalances (¿25% ±5% difference between adjacent lanes) and generate optimization recommendations within 5 minutes (±30 seconds) of detecting sustained imbalance.	3. Verification Process for Item 3: (a) Simulate balanced traffic across 3+ lanes for baseline period (b) Introduce lane imbalance of varying degrees (20%, 30%, 40%) (c) Record time when imbalance begins (d) Ensure recommendation generation time meets requirement	Y

Table 11: Traffic Analysis: Data Aggregation Requirements and Verifications

3.3.2 Traffic Analysis: Technical Implementation

Requirement	Verification	Verification Status
1. The data collection subsystem must capture and transmit vehicle count data to the server at intervals of $\leq$5 minutes ($\pm$30 seconds) with a transmission success rate of $\geq$99% ($\pm$0.5%) under normal network conditions.	1. Verification Process for Item 1: (a) Deploy system with network monitoring enabled (b) Monitor data transmissions continuously for 48 hours (c) Record actual transmission times and success/failure events (d) Ensure transmission interval and success rate meet requirements	Y
2. The data processing pipeline must clean and aggregate traffic data with processing latency $\leq$30 seconds ($\pm$5 seconds) for 10-minute aggregation, $\leq$60 seconds ($\pm$10 seconds) for hourly aggregation, and $\leq$180 seconds ($\pm$20 seconds) for 6-hour aggregation.	2. Verification Process for Item 2: (a) Insert timestamp logging at pipeline entry and exit points (b) Process standard test datasets of varying sizes (c) Calculate processing time for each aggregation window (d) Ensure processing latency meets requirements for all window sizes	Y
3. The visualization dashboard must render all charts and metrics with a page load time $\leq$3 seconds ($\pm$0.5 seconds) on a standard computer (i5 equivalent, 8GB RAM) with broadband connection ($\geq$10Mbps).	3. Verification Process for Item 3: (a) Configure test environment with specified hardware (b) Measure initial page load time and component rendering times (c) Test with various data quantities (1 day, 1 week, 1 month) (d) Ensure page load time meets requirement under all test conditions	Y

4. The alert mechanism must detect anomalies with ≤5% (±1%) false positive rate and ≥90% (±3%) true positive rate when compared to manually identified anomalies in historical data.	4. Verification Process for Item 4: (a) Prepare dataset with manually identified anomalies (b) Run anomaly detection algorithm on test dataset (c) Compare detected anomalies with ground truth (d) Ensure false positive and true positive rates meet requirements	Y

Table 12: Traffic Analysis: Technical Implementation Requirements and Verifications

3.3.3 Traffic Analysis: Performance Outcomes

Requirement	**Verification**	**Verification Status**
1. The system must improve traffic signal timing decisions by providing recommendations that reduce average wait times by ≥15% (±3%) compared to fixed-time signal patterns when implemented in simulation.	1. Verification Process for Item 1: (a) Create baseline simulation with fixed-time signals (b) Measure average wait times across all vehicles and intersections (c) Apply system-recommended timing adjustments to simulation (d) Ensure wait time reduction meets requirement	Y

2. The real-time alert system must notify operators of abnormal congestion within 60 seconds ($\pm$10 seconds) of occurrence, with alert specificity sufficient to identify the affected road segment and direction within 50 meters ($\pm$10 meters).	2. Verification Process for Item 2: (a) Create simulated congestion events at known locations and times (b) Record exact congestion onset time (c) Measure time until alert is delivered to operator interface (d) Ensure alert timing and location specificity meet requirements	Y
3. The historical data aggregation must maintain continuous data records for $\geq$99% ($\pm$0.5%) of operational time, with data retrieval latency $\leq$2 seconds ($\pm$0.5 seconds) for queries spanning up to 30 days of historical data.	3. Verification Process for Item 3: (a) Operate system continuously for 30 days (b) Record all data gaps or interruptions (c) Perform standardized queries of various time ranges (d) Ensure data availability and query performance meet requirements	Y

Table 13: Traffic Analysis: Performance Outcomes Requirements and Verifications

3.4 Tolerance Analysis

In this project, vehicle detection accuracy is a key performance metric. We employ the F1 score to assess detection accuracy, defined as:

$$F1 = \frac{2 \times \text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}}$$

In practical applications, we consider establishing different criteria for various ambient lighting conditions by implementing a dynamic threshold adjustment strategy. When the lighting is low, the detection threshold is appropriately reduced to improve recall, ultimately achieving a system that maintains high detection robustness and accuracy even under low-light conditions, thereby enhancing the overall F1 score and system performance.

4 Costs

Description	Quantity	Cost ($)
Raspberry Pi 5B (5GB)	1	55
Power Supply	1	10
Camera	3	55
3D Printed Housing	2	40
Total Parts Cost		160

Grand Total

Category	Total Cost ($)
Labor	1000
Parts	160
Grand Total	1160

5 Schedule

Date	Jiawei Zhang	Binyang Shen	Yining Guo	Zijin Li
2/24/25	Project initiation and team building	Project initiation and team building	Project initiation and team building	Project initiation and team building
3/3/25	Research on Yolo series models	Research for different models of camera housings	Learn the knowledge about Yolov8 and OpenCV	Primarily study about Unity and D3.js
3/10/25	Implementation of Yolo target detection model deployment and inference	Select camera model and determine housing size	Search for suitable datasets	Design the visualization framework

3/17/25	Completed the vehicle detection of one-minute traffic video by using Yolov8 model	Preliminary design of camera housing model with CAD	Detect the vehicle detection performance with the datasets and expand our datasets	Design the visualization logic structure
3/24/25	Added detection boxes to the inference script to identify vehicles in fixed areas	Evaluation of the strength and hardness of 3D printed models	Observe the differences between images preprocessed using OpenCV and those without such processing. Evaluate the results and determine, based on the specific conditions, whether to incorporate OpenCV-based preprocessing.	Collaborate with teammates to verify the datatype and recognition feature
3/31/16	Implemented the first version of the speed calculation algorithm	Design additional equipment such as brackets to suit the actual situation	Integrate Speed Measurement with Detection Outcomes	Create the necessary graph structure and pattern
4/7/25	Optimize and improve the speed calculation algorithm	Design improvements to the first version of the model	Enhance Traffic Density Calculation Using Optimized Speed Data	Pretest the visualization part with manually importing data
4/14/25	Design and try the traffic density index and calculation algorithm	Performs second shell 3D printing	Improve classification and counting functions, and achieve higher accuracy	Assemble all visualization unit

4/21/16	Optimize traffic density index and algorithm	Assembly test with other parts together	Verify the functions of speed detection and density analysis	Test visualization part with real-time data
4/28/25	Build the final overall system with co-responsible partners	Final rectification based on test results	Build the final overall system with co-responsible partners	Debug and successfully output summary based on different monitoring time scale
5/12/25	Collaborative data visualization, joint debugging system	Measurement of the size data after completion of final micro-modifications	Think more about the real-life application and finally adjust the system	Improve the user-interface and improve visualization of targeting data
5/19/25	Prepare Final Presentation	Prepare Final Presentation	Prepare Final Presentation	Prepare Final Presentation
5/26/25	Begin Final Report	Begin Final Report	Begin Final Report	Begin Final Report

6 Ethics and Safety

6.1 Ethics

6.1.1 Data Privacy and Security

This project collects traffic data that may include license plates and driver information. To address privacy concerns, we follow the IEEE/ACM Code of Ethics by obtaining informed consent from the public through clear signage near cameras and anonymizing data during processing. Data storage adheres to strict encryption protocols on secure servers with limited access to authorized personnel only.

6.1.2 Algorithm Fairness and Transparency

The vehicle recognition algorithm is designed to avoid discrimination based on vehicle type, color, or brand. If we use deep learning to train model, we must use diverse training datasets and regularly audit the algorithm for bias. In line with ethical guidelines, the system provides transparent decision-making processes, allowing traffic authorities to understand how congestion alerts and vehicle counts are generated.

6.1.3 Environmental and Social Impact

Outdoor camera installations are designed with minimal environmental disruption in mind. We use weatherproof, dustproof enclosures and temperature control systems to ensure longevity without harming local ecosystems. The project aims to benefit society by reducing urban congestion and improving traffic flow efficiency.

6.2 Safety

The system employs robust hardware safety measures, including secure camera mounting and protective enclosures to prevent tampering or damage. Software safety is maintained through regular updates, secure coding practices, and vulnerability testing. The Raspberry Pi platform is chosen for its reliability and low power consumption, ensuring stable operation in various conditions. We follow relevant electrical safety standards for outdoor electronic equipment and ensure compliance with local traffic monitoring regulations.

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