High-Level System Architecture Overview

Architecture Zones

Zone 1: Physical Sensing Layer

Hardware Components:

- **Raspberry Pi AI Camera** (Sony IMX500 sensor)
- **OPS243-C FMCW Doppler Radar Sensor**
- **Raspberry Pi 5** (16GB RAM, ARM Cortex-A76 CPU)
- **External USB SSD** (Samsung T7 or SanDisk Extreme Pro)
- **Power & Connectivity** (PoE, WiFi/Ethernet, optional cellular backup)

Responsibilities:

- Physical vehicle detection and classification
- Speed measurement via Doppler radar
- Environmental sensing (lighting conditions)
- Raw data capture and initial processing

Zone 2: Edge Processing Layer (Raspberry Pi 5)

Core Services:

- **Vehicle Detection Service** (TensorFlow + OpenCV + AI Camera)
- **Speed Analysis Service** (OPS243-C radar data processing)
- **Multi-Vehicle Tracking Service** (SORT algorithm implementation)
- **Data Fusion Engine** (Camera + Radar correlation)
- **Weather Integration Service** (API calls to weather providers)
- **Anomaly Detection Service** (Traffic pattern analysis)

Supporting Components:

- **System Health Monitor** (Watchdog timers, performance metrics)
- **Local Storage Manager** (tmpfs, SSD data management)
- **Edge API Gateway** (Flask-SocketIO server)
- **Local Web Dashboard** (Real-time monitoring interface)

Responsibilities:

- Real-time ML inference and vehicle detection
- Multi-sensor data fusion and correlation
- Traffic pattern analysis and anomaly detection
- Local data storage and management
- System reliability and health monitoring

Zone 3: Network & Communication Layer

Components:

- **Local Network Interface** (WiFi/Ethernet connectivity)
- **WebSocket Server** (Real-time data streaming)
- **REST API Endpoints** (Configuration and status)
- **Data Compression & Queuing** (Optimized cloud transmission)
- **Network Resilience** (Offline-first operation, reconnection logic)

Optional Backup:

- **Cellular Modem** (5G/LTE for remote locations)
- **Mesh Networking** (Multi-unit coordination)

Responsibilities:

- Real-time data streaming to local dashboard
- Reliable cloud data transmission when available
- Network failure handling and recovery
- API access for external systems

Zone 4: Cloud Services Layer (Optional)

Data Services:

- **Data Aggregation Service** (AWS Lambda + DynamoDB or similar)
- **Time Series Database** (Traffic metrics storage)
- **Data Analytics Engine** (Historical pattern analysis)
- **Model Update Service** (ML model versioning and deployment)

Application Services:

- **Dashboard & Reporting Service** (Web-based traffic analytics)
- **Alert & Notification Service** (Email/SMS alerts for incidents)
- **API Gateway** (External system integration)
- **User Management** (Authentication and access control)

Supporting Infrastructure:

- **Message Queue** (MQTT broker or AWS SQS)
- **File Storage** (S3 or similar for images/videos)
- **Content Delivery** (CloudFront for dashboard assets)

Responsibilities:

- Long-term data storage and historical analysis
- Advanced analytics and reporting
- Remote system management and updates
- Integration with city traffic management systems

Data Flow Architecture

Real-Time Processing Flow:

```
Physical Sensors → Edge Processing → Local Dashboard
     ↓                   ↓              ↓
Raw Data → Processed Intelligence → Real-Time Visualization
```

Cloud Integration Flow (When Available):

```
Edge Processing → Network Layer → Cloud Services → External Systems
     ↓               ↓              ↓              ↓
Local Storage → Data Queue → Cloud Storage → Analytics/Alerts
```

Zone Interaction Patterns

Zone 1 ↔ Zone 2: High-Frequency Data

- **Camera Frames**: 30 FPS video stream

- **Radar Readings**: Continuous speed measurements
- **System Metrics**: CPU, memory, temperature monitoring

Zone 2 ↔ Zone 3: Processed Intelligence

- **Vehicle Events**: Detection, speed, classification data
- **Traffic Metrics**: Volume, average speed, anomalies
- **System Status**: Health, alerts, configuration updates

Zone 3 ↔ Zone 4: Aggregated Insights

- **Summary Data**: Hourly/daily traffic reports
- **Alerts**: Speed violations, incidents, system issues
- **Model Updates**: New ML models, configuration changes

Deployment Zones

Edge Deployment (Zones 1-3)

Physical Location: Roadside installation **Connectivity**: Local network + internet (when available) **Operation Mode**: Autonomous, offline-first **Maintenance**: Remote monitoring + periodic physical service

Cloud Deployment (Zone 4)

Physical Location: AWS/GCP/Azure data centers **Connectivity**: Internet-based, high availability **Operation Mode**: Always-on, scalable **Maintenance**: Automated scaling, monitoring, updates

Security Zones

Physical Security (Zone 1)

- Tamper-resistant hardware enclosures
- Physical access monitoring
- Environmental protection (weather, vandalism)

Edge Security (Zone 2)

- Local data encryption at rest
- Secure boot and system integrity
- Network access controls

Network Security (Zone 3)

- TLS/SSL encrypted communications
- VPN tunneling for remote access
- API authentication and rate limiting

Cloud Security (Zone 4)

- Identity and access management
- Data encryption in transit and at rest
- Compliance with privacy regulations (GDPR, etc.)

Scalability Considerations

Horizontal Scaling

- **Multiple Edge Units**: Deploy additional Pi units for wider coverage
- **Load Distribution**: Balance processing across multiple units
- **Data Aggregation**: Centralized collection from multiple locations

Vertical Scaling

- **Hardware Upgrades**: More powerful edge computing hardware
- **Cloud Resources**: Auto-scaling cloud services based on load
- **Storage Expansion**: Additional local and cloud storage capacity

This architecture provides a robust, scalable foundation that starts simple (Zones 1-2) and can expand to full enterprise capabilities (Zones 3-4) as needs grow.