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SEMTOS: Smart Emergency Management and Traffic Orchestration System

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Abstract - *Rapid urbanization and severe vehicular congestion across metropolitan road networks critically delay emergency medical services, directly increasing mortality during the Golden Hour. Legacy traffic signal preemption mechanisms relying on optical line-of-sight sensors, radio-frequency identification tags, or standalone cloud-only global positioning systems frequently fail under non-line-of-sight queue spillbacks, indiscriminate driver alert fatigue, and cellular network blackouts. This paper presents SEMTOS (Smart Emergency Management and Traffic Orchestration System), a multi-tier Internet of Things and Edge-AI traffic orchestration framework that integrates four core capabilities: Haversine-based predictive spatial signal preemption, YOLOv8 computer vision queue-aware green-light hold scaling, directional dot-product vector-filtered civilian driver alerting, and an offline ESP32 Bluetooth Low Energy hardware failover mechanism, validated through an interactive React and Three.js 3D Digital Twin. When an approaching ambulance streams encrypted telemetry over Transport Layer Security 1.3 to an event-driven Node.js cloud dispatcher, SEMTOS computes real-time arrival windows and scales upstream green phases dynamically based on YOLOv8 lane queue counts so standing bottlenecks flush before emergency vehicle arrival. Simultaneously, directional vector mathematics dispatches sub-50ms audio-visual mobile alerts exclusively to civilian vehicles aligned with the active emergency lane vector. During cellular outages, onboard ESP32 microcontrollers broadcast proximity beacons directly to roadside signal controllers for autonomous offline preemption. Experimental validation demonstrates a 70.5 percent reduction in high-density junction transit delay and 100 percent failover continuity.*

Key Words: Smart Emergency Management, Traffic Signal Preemption, YOLOv8 Edge-AI, Vehicle-to-Everything (V2X), ESP32 Bluetooth Low Energy (BLE), 3D Digital Twin, Intelligent Transportation Systems.

1. INTRODUCTION

Urban road infrastructure across rapidly expanding metropolitan corridors faces acute saturation, resulting in prolonged intersection queues and unpredictable travel times. For Emergency Medical Services (EMS), fire tenders, and critical-care patient transport, every minute spent stationary behind gridlocked intersections directly erodes survival probabilities during the clinical Golden Hour. Conventional fixed-time traffic controllers operate on predetermined phase cycles that are entirely agnostic to approaching emergency vehicles, forcing ambulances to rely on acoustic sirens that frequently induce panic among surrounding motorists without clearing downstream queues.

1.1 Problem Statement and Motivation

Existing Emergency Vehicle Traffic Signal Preemption (EVTSP) deployments exhibit three critical vulnerabilities. First, optical infrared (IR) and passive Radio-Frequency Identification (RFID) readers require short-range or line-of-sight proximity, triggering green phases too late when 20 to 30 civilian vehicles are already queued ahead of the ambulance (Wang et al., 2024). Second, cloud-only Vehicle-to-Everything (V2X) GPS systems broadcast indiscriminate radius alerts that notify drivers on perpendicular or opposite lanes, causing alert fatigue and erratic lane changes. Third, purely cloud-dependent preemption architectures suffer single-point-of-failure collapse whenever 4G/5G cellular packets drop in dense urban canyons or underpasses.

1.2 Objectives of the Proposed System

To overcome these limitations, this paper proposes SEMTOS (Smart Emergency Management and Traffic Orchestration System). The primary engineering objectives are: (1) to formulate a Haversine spatial preemption engine coupled with YOLOv8 Edge-AI vision analytics that scales green-light hold durations proportionally to real-time intersection queue density (Bakirci, 2024); (2) to eliminate civilian driver alert fatigue via directional dot-product vector filtering with sub-50ms WebSocket dispatch latency; (3) to guarantee zero-downtime hardware fault tolerance using an ESP32 Bluetooth Low Energy (BLE) proximity fallback during cellular blackouts (Bage and Sharma, 2024); and (4) to

validate multi-junction emergency corridors safely using a React and Three.js 3D Digital Twin (Zhao et al., 2024).

2. LITERATURE SURVEY AND EXISTING SYSTEMS

Recent literature has explored cooperative vehicle-infrastructure signal preemption, deep-learning traffic density estimation, and digital twin simulation. Research on EVTSP strategies demonstrates that triggering signal priority without accounting for standing queue spillbacks often traps the emergency vehicle behind stationary traffic (Wang et al., 2024). Concurrently, advances in single-stage object detectors specifically YOLOv8 have enabled real-time vehicle detection and lane density estimation on edge computing nodes (Bakirci, 2024). In parallel, cyber-physical Digital Twin frameworks have emerged as a reliable paradigm for modeling adaptive signal control before physical deployment (Zhao et al., 2024).

2.1 Comparative Analysis of Existing Frameworks

Despite progress in individual domains, existing frameworks rarely unify predictive cloud spatial mathematics, computer-vision queue flushing, directional driver alerting, and embedded offline failover into a single cohesive platform. Table 1 summarizes the architectural comparison between legacy preemption systems and the proposed SEMTOS platform.

Table -1: Comparison of Preemption Systems and SEMTOS

Feature	RFID / IR	Cloud GPS	SEMTOS
Trigger Mode	<50 m LOS	Radius GPS	ETA + Vision
Queue Flush	No (Fixed)	No (Static)	YOLOv8 Scaled
Driver Alert	Siren Only	All Lanes	Vector-Filtered
Offline Mode	Local Only	None (Fails)	ESP32 BLE Auto
3D Twin Test	No	Limited	React + Three.js

3. PROPOSED SYSTEM ARCHITECTURE AND METHODOLOGY

The SEMTOS architecture follows a four-tier cyber-physical pipeline integrating mobile telemetry, event-driven cloud orchestration, Edge-AI computer vision, and embedded microcontroller failover.

3.1 Haversine Predictive Spatial Signal Preemption

As the emergency vehicle traverses an urban corridor, its onboard telemetry unit streams real-time latitude, longitude, speed, and compass heading vectors over a Transport Layer Security (TLS 1.3) WebSocket channel to the Node.js cloud dispatcher. The dispatcher continuously evaluates the great-circle Haversine distance between the ambulance and upcoming signalized intersections along its active route vector. Rather than waiting for fixed proximity thresholds, the orchestrator computes a dynamic Estimated Time of Arrival (ETA) window and initiates phase transitions early enough to clear standing queues before the ambulance reaches the stop line.

3.2 YOLOv8 Edge-AI Queue Analytics and Deadlock Rerouting

To prevent queue spillbacks from blocking the emergency lane, roadside Edge-AI vision nodes execute a YOLOv8 object detection pipeline on live intersection camera feeds (Bakirci, 2024). The model classifies and counts waiting vehicles within each approach lane polygon and computes a real-time queue dissipation time. The cloud orchestrator scales the green-light hold duration proportionally to the detected queue length. Furthermore, if YOLOv8 detects a stationary downstream gridlock where vehicle velocity remains zero across consecutive frames, SEMTOS automatically triggers deadlock rerouting and updates the ambulance navigation path.

3.3 Directional Vector-Filtered Civilian Driver Alerting

Conventional broadcast systems alert all motorists within a circular radius, causing confusion on cross streets and opposing lanes. SEMTOS resolves this by computing the directional dot product between the ambulance heading unit vector and the relative displacement and heading vectors of civilian vehicles ahead. Audio-visual mobile yield notifications are dispatched exclusively to civilian drivers whose angular alignment falls within the active approach corridor, achieving sub-50ms alert dispatch latency while eliminating alert fatigue on unrelated lanes.

3.4 Offline ESP32 BLE Hardware Failover Mechanism

To eliminate single points of failure during 5G or cellular network outages, SEMTOS incorporates a hardware fallback layer using ESP32 Wi-Fi/BLE microcontrollers (Bage and Sharma, 2024). Whenever the onboard ambulance controller detects packet loss or WebSocket heartbeat timeouts exceeding 500 milliseconds, it automatically elevates its BLE advertising power and broadcasts encrypted proximity beacon packets containing the emergency vehicle identifier and approach vector. Roadside ESP32 signal controllers continuously scan for authenticated BLE advertisements and

autonomously override local traffic signal relays to grant an offline green corridor.

3.5 React and Three.js 3D Digital Twin Validation

Because stress-testing emergency signal preemption across live multi-junction urban intersections poses safety risks, SEMTOS interfaces bi-directionally with an interactive 3D Digital Twin built using React.js and Three.js (Zhao et al., 2024). The Digital Twin renders multi-lane intersections, dynamic civilian traffic queues, signal phase states, and ambulance trajectories in real time, enabling repeatable benchmarking of queue flushing, deadlock rerouting, and cellular-to-BLE failover transitions.

4. IMPLEMENTATION AND EXPERIMENTAL EVALUATION

The SEMTOS prototype was implemented and evaluated across a hybrid hardware-software testbed combining the Node.js TLS 1.3 event-driven dispatcher, the YOLOv8 Edge-AI inference module, ESP32 Wi-Fi/BLE microcontrollers driving physical traffic signal LED arrays, and the React/Three.js 3D Digital Twin environment. Table 2 outlines the key subsystem specifications and measured operational benchmarks.

Table -2: SEMTOS Subsystem Specifications and Benchmarks

Subsystem	Technology Stack	Benchmark
Cloud Dispatcher	Node.js + TLS 1.3	38.4 ms Latency
Edge-AI Vision	YOLOv8 Queue Model	94.6% mAP @ 32 FPS
Vector Filter	Haversine + Dot Prod.	98.2% Precision
Offline Failover	ESP32 BLE 5.0 Beacon	140 ms Override
3D Digital Twin	React.js + Three.js	60 FPS Telemetry

4.1 Experimental Results and Discussion

To quantify the transit efficiency of SEMTOS, multi-junction emergency runs were evaluated across three traffic density regimes: low density (5 to 10 vehicles per lane, 14.2s SEMTOS vs 26.5s Cloud GPS vs 42.0s Legacy), moderate density (15 to 25 vehicles per lane, 24.8s SEMTOS vs 49.0s Cloud GPS vs 78.5s Legacy), and high/gridlock density (30+ vehicles per lane). Legacy fixed-time/RFID preemption incurred an average junction transit delay of 134.0 seconds under high density due to un-flushed standing queues, whereas cloud-only GPS preemption reduced delay to 88.5 seconds. By combining predictive Haversine arrival windows with YOLOv8 queue-scaled green holds and directional driver yield alerts, SEMTOS reduced mean high-density junction transit delay to 39.5 seconds representing a 70.5 percent improvement over legacy systems and a 55.4 percent improvement over cloud-only GPS preemption.

5. CONCLUSIONS AND FUTURE SCOPE

This paper presented the design, architecture, and prototype evaluation of SEMTOS, an event-driven IoT and Edge-AI traffic orchestration system engineered to accelerate emergency vehicle transit and improve intersection safety. By coupling Haversine spatial preemption with YOLOv8 queue-density scaling, SEMTOS proactively flushes intersection bottlenecks prior to ambulance arrival. Directional dot-product vector filtering delivers sub-50ms mobile alerts exclusively to obstructing vehicles in the active emergency lane, eliminating cross-lane alert fatigue, while the onboard ESP32 BLE beacon guarantees uninterrupted offline signal preemption during cellular blackouts. Validated through a React and Three.js 3D Digital Twin, SEMTOS provides a resilient, cyber-secure (TLS 1.3), and cost-effective smart-mobility architecture. Future work will extend SEMTOS to multi-agency green-wave corridor coordination across simultaneous emergency dispatches and integration with centralized municipal command centers.

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