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ClearWay: A Resilient IoT–GPS–IMU Smart Ambulance Alert System with Offline Fallback and Cybersecurity for Real-Time Emergency Traffic Management and Field Deployment

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ABSTRACT: Ambulance delays at traffic junctions represent a critical and preventable threat to emergency response efficiency, with each minute of delay reducing cardiac arrest survival probability by approximately 10%. Existing traffic management systems lack automated priority mechanisms for emergency vehicles, and prior IoT-based approaches suffer from single-point-of-failure risks: GPS blackouts in urban canyons, network outages, and absence of government-accepted manual override. This paper presents ClearWay v2, a resilient, multi-layer smart ambulance alert system that addresses all three gaps through: (i) GPS–IMU sensor fusion using a NEO-6M GPS module and MPU-6050 inertial measurement unit for continuous positioning accuracy even during GPS blackouts of up to 45 seconds; (ii) a five-tier offline fallback architecture (Online → Hybrid → Local-LoRa → Dead-Reckoning → SMS) ensuring uninterrupted operation without cloud or cellular connectivity; (iii) HMAC-SHA256 message authentication with TLS 1.3 encryption to prevent rogue preemption attacks; (iv) a hardware-level manual override at every junction controller for unconditional police control; and (v) a structured 90-day field deployment protocol at Namakkal Government Hospital, Tamil Nadu, covering 3 ambulances and 6 signalised junctions on NH-544. SUMO simulation across 300 runs (low/medium/high traffic density) demonstrates an 85.8% reduction in per-junction delay at high traffic density, a 63.1% reduction in end-to-end ambulance travel time, and V2I alert broadcast latency under 2.0 seconds. The enhanced architecture scores 9.1/10 on a seven-dimension real-world viability rubric, an improvement from 7.7 for the baseline design, and is aligned with UN SDG 3, SDG 11, and SDG 13.

KEYWORDS: *Smart ambulance alert; IoT traffic management; GPS-IMU sensor fusion; offline fallback; emergency vehicle preemption; ClearWay; LoRa; HMAC security; V2I communication; SUMO simulation; smart city; Namakkal pilot.*

I. INTRODUCTION

Emergency medical response time is among the most consequential factors in determining patient survival across a wide spectrum of critical conditions including cardiac arrest, trauma, stroke, and obstetric emergencies. The established clinical benchmark for pre-hospital emergency response is eight minutes or less from call receipt to scene arrival [1]. Yet in rapidly urbanising cities across India and the developing world, chronic traffic congestion at signalised intersections routinely causes ambulance delays far exceeding this threshold, with studies reporting average junction delays of 38–90 seconds per intersection under varying traffic densities.

The problem is systemic and structural. Existing traffic signal systems operate on fixed-time cycles or rudimentary vehicle-sensor triggers that cannot detect, identify, or prioritise emergency vehicles. Manual coordination between traffic police and ambulance drivers is unreliable, cognitively demanding under emergency conditions, and fundamentally unscalable in dense urban networks. The result is a preventable gap between the speed at which modern medicine can save lives and the speed at which ambulances can reach patients.

Two generations of emergency vehicle preemption (EVP) research have produced hardware solutions — infrared emitters, RFID tags, acoustic sensors — that address this gap, but each introduces new constraints: line-of-sight requirements, expensive per-junction infrastructure, or an inability to plan a multi-junction green corridor in advance. IoT-based GPS approaches [5, 6] have demonstrated multi-junction corridor capability but have not adequately addressed GPS blackouts in the urban built environment, absence of offline resilience, cybersecurity vulnerabilities, or the institutional acceptance requirements for real municipal deployment.

This paper presents ClearWay v2, a comprehensive response to these gaps. Beyond the foundational GPS-cloud-MQTT architecture of the first design iteration, ClearWay v2 introduces five critical engineering enhancements: GPS-IMU sensor fusion for robust positioning, a five-tier offline fallback stack, HMAC-SHA256 + TLS 1.3 security, hardware-level police override at every junction, and a fully specified 90-day field deployment protocol targeting Namakkal, Tamil Nadu as the pilot city. The combined effect is a system that can be deployed, approved by municipal authorities, and operated reliably in the complex real-world environment of Indian urban traffic.

The remainder of this paper is structured as follows: Section II reviews related literature; Section III presents the enhanced system architecture; Section IV details the GPS-IMU sensor fusion subsystem; Section V describes the five-tier offline fallback framework; Section VI covers the cybersecurity design; Section VII presents the RPSCA-v2 algorithm; Section VIII describes simulation results; Section IX presents the Namakkal pilot deployment framework; Section X discusses broader impact and limitations; Section XI concludes.

II. LITERATURE REVIEW

Emergency vehicle preemption research spans more than three decades, evolving from simple hardware triggers to cloud-integrated intelligent systems. Chou and Lu [2] provide a comprehensive review of optical EVP systems using infrared emitters and photodetectors at intersections. While widely deployed in North America, these systems are limited to single-junction preemption, require clear line-of-sight, and degrade in rain, fog, and high-ambient-light conditions — critical failure modes for year-round emergency operation.

GPS-based ambulance tracking for EVP was first rigorously evaluated by Kwon et al. [3], who demonstrated that continuous position telemetry enables predictive signal switching at multiple upcoming junctions. This multi-junction green corridor concept is the architectural foundation of ClearWay. However, Kwon's system assumed continuous GPS availability, an assumption that fails in urban environments with tall buildings, bridges, and tunnels. The fusion of GPS with inertial measurement has been explored extensively in autonomous vehicle research [16], but its application to low-cost IoT-based ambulance preemption systems has not been previously published.

IoT architectures for traffic management have proliferated following the commoditisation of ESP32 and similar microcontrollers. Bhuvaneswari et al. [4] demonstrated RFID-based single-junction preemption; Malik et al. [6] validated MQTT communication latency below 200 ms over 4G LTE using ESP32 nodes — a key performance requirement for real-time signal control. The selection of MQTT over HTTP or WebSocket for IoT traffic applications is well-supported by benchmarks showing 40–60% lower latency and 70% reduced bandwidth consumption [17].

Offline resilience is a largely unaddressed gap in existing EVP literature. Tettamanti et al. [11] validated EVP algorithms using SUMO simulation but did not model communication failures. Anbazhagan and Palanisamy [9] describe a smartphone-based V2I alert system but assume permanent connectivity. The closest prior work is the hybrid edge-cloud architecture for gaming latency reduction by Choy et al. [14], whose edge-first philosophy directly informs ClearWay v2's offline fallback tier design — though applied here to a fundamentally different domain.

Cybersecurity of IoT-based traffic infrastructure is an emerging research priority. Tubaishat et al. [15] identify unauthenticated command injection as the primary attack vector for sensor-based traffic systems. Ahmed and Bhargava [5] proposed TLS encryption for cloud-relay MQTT but did not address message authentication at the device level. ClearWay v2 extends this with HMAC-SHA256 per-unit authentication keys, closing the spoofing attack surface that prior GPS-EVP systems leave open. Earlier work by Srinivasan et al. [21, 24, 25] on replica reduction in user profile search systems and cloud auditing architectures [22] informs the data integrity and authentication principles applied here. Techniques from distributed query optimisation [23] also underpin the RPSCA-v2 path-prediction algorithm design.

In summary, while the component technologies of ClearWay v2 are individually well-studied, their integration into a single resilient, government-deployable ambulance preemption system with sensor fusion, offline fallback, cybersecurity, and a documented municipal approval pathway represents a contribution not previously achieved in the literature.

III. ENHANCED SYSTEM ARCHITECTURE

ClearWay v2 is structured across five interconnected layers: (1) the Enhanced On-board Ambulance Unit with sensor fusion; (2) the Five-Tier Offline Fallback Stack; (3) the Cloud Processing Layer with RPSCA-v2; (4) the Hardened Junction Controller Network; and (5) the Alert, Monitoring, and Override Layer. Table I presents the complete hardware and software specification.

TABLE I. ClearWay v2 — Complete Hardware and Software Specification

Component	Model / Spec	Role in ClearWay	Fallback Role
ESP32 Microcontroller	Dual-core 240 MHz, Wi-Fi/BT	Main IoT controller, MQTT pub	Runs RPSCA-Lite offline
GPS Module	NEO-6M, 1–5 m accuracy, 1 Hz NMEA	Real-time positioning	Dead-reckoning seed point
IMU (Accelerometer)	MPU-6050, 6-DOF, I2C	Sensor fusion with GPS	Full DR for 30 s GPS loss

GSM/LTE Module	SIM800L, quad-band 850–1900 MHz	Cloud MQTT over 4G	SMS fallback alert
LoRa Module	SX1276, 868 MHz, 5 km range	V2I junction BLE/LoRa direct link	Primary offline comms channel
Traffic Sig. Controller	ESP32 node + relay + PWM LED	Junction signal switching	BLE/LoRa direct from ambulance
Cloud Platform	Firebase RTDB / AWS IoT Core	RPSCA algorithm, dashboard	On-device RPSCA-Lite (flash)
HMAC Auth Layer	SHA-256, 256-bit secret per unit	Message authentication	Prevents rogue preemption
Manual Override	Physical button + LED status strip	Police/traffic override	Always active, hardware-level
Mobile Alert App	Flutter, Android/iOS	V2I driver notifications	SMS gateway fallback

A. Enhanced On-board Ambulance Unit

The ambulance unit integrates an ESP32 microcontroller with four peripheral modules: a NEO-6M GPS receiver (UART, 9600 baud), an MPU-6050 six-degree-of-freedom IMU (I2C, 400 kHz), a SIM800L GSM/LTE modem (UART), and an SX1276 LoRa transceiver (SPI). The ESP32 runs FreeRTOS with dedicated tasks for GPS parsing, IMU sampling, sensor fusion computation, MQTT publishing, and LoRa mesh management. A 2000 mAh LiPo battery with the vehicle's 12 V supply provides dual-redundant power.

GPS NMEA sentences are parsed at 1 Hz using the TinyGPS++ library. IMU data is sampled at 100 Hz. The sensor fusion task executes at 50 Hz, consuming fused position estimates from both inputs. MQTT payloads are published every 500 ms containing vehicle ID, timestamp, fused latitude/longitude, speed, heading, confidence level, and active tier identifier.

B. Hardened Junction Controller

Each junction controller is an ESP32 node with a 4-channel relay module interfacing with the physical signal hardware, an SX1276 LoRa transceiver for peer-to-peer ambulance communication, a Bluetooth Low Energy (BLE) stack for sub-10m proximity detection, and a tamper-evident physical enclosure with a hardware manual override button and tri-colour status LED strip. The override button is a latching switch that immediately transfers signal authority to a designated traffic officer and sends an MQTT alert to the monitoring dashboard. The button cannot be disabled by software under any condition.

IV. GPS–IMU SENSOR FUSION SUBSYSTEM

GPS signal degradation in urban environments is a well-documented and serious operational risk for any GPS-dependent system. Tall buildings, bridges, flyovers, and underpasses create multipath interference and signal shadowing that cause position jumps of 20–150 metres or complete signal loss. In the context of ambulance preemption, a position jump can cause the RPSCA-v2 algorithm to incorrectly identify the ambulance's road segment, triggering preemption at the wrong junction and failing to clear the correct one. ClearWay v2 addresses this through a Kalman-filter-based GPS–IMU fusion architecture.

A. Kalman Filter Design

The fusion algorithm uses a 4-state Kalman filter with state vector $x = [lat, lon, v\_lat, v\_lon]^{T}$, representing position and velocity in geographic coordinates. The GPS measurement model provides absolute position observations at 1 Hz with noise covariance R derived from the NEO-6M's reported HDOP value. The IMU provides linear acceleration measurements (corrected for gravity using the MPU-6050's built-in DMP quaternion output) that drive the prediction step at 50 Hz. When GPS HDOP exceeds a configurable threshold (default: 2.5) or no NMEA fix is received for 2.0 seconds, the filter enters Dead Reckoning (DR) mode: the prediction step continues using IMU data alone, with the process noise covariance Q inflated by a factor proportional to elapsed DR time to reflect growing position uncertainty.

B. Fusion Accuracy Validation

The sensor fusion subsystem was validated in bench and field tests across five GPS availability scenarios. Table II summarises positioning accuracy results. In open-road conditions, fusion reduces mean position error from 1.8 m (GPS-only) to 1.6 m by rejecting GPS outliers. In urban canyon conditions with partial obstruction, fusion reduces error from 6.4 m to 3.1 m. During complete GPS loss (underpass scenario), IMU-based dead reckoning maintains position error below 15 m for up to 30 seconds, sufficient for the RPSCA-v2 to maintain correct junction association in all test cases. GPS re-acquisition after blackout achieves re-lock within 4 seconds.

TABLE II. GPS–IMU Sensor Fusion Positioning Accuracy Under Varied Conditions

Condition	GPS Only (m)	IMU Only (m)	Fused (m)	Duration
Open road, clear sky	1.8	N/A	1.6	Continuous
Partial urban obstruction	6.4	N/A	3.1	Continuous
GPS loss — underpass	Lost	12.4	8.7	≤ 30 s
GPS loss — tunnel	Lost	18.2	13.9	≤ 45 s
GPS regained after loss	2.1	drift	1.9	Re-lock < 4 s

The practical implication is that ClearWay v2 maintains correct junction preemption even during the GPS blackouts most likely to occur at exactly the infrastructure points (underpasses, flyovers) where traffic junctions are frequently located. This closes the single most significant technical gap in the baseline design.

V. FIVE-TIER OFFLINE FALLBACK ARCHITECTURE

Dependence on a single communication channel — 4G cellular to cloud — is the most significant deployment risk in prior GPS-EVP systems. Network outages, SIM card failures, cloud downtime, and geographic coverage gaps are routine operational realities in Indian urban and semi-urban environments. A system that fails silently when connectivity is lost is unacceptable for life-safety infrastructure. ClearWay v2 implements a five-tier fallback stack that guarantees some level of ambulance preemption under any single-point or double-point failure of GPS and cellular connectivity. Table III details each tier.

TABLE III. ClearWay v2 Five-Tier Offline Fallback Architecture

Mode	Trigger Condition	Mechanism	Coverage
Online (primary)	4G + GPS active	Cloud RPSCA via MQTT	Full multi-junction corridor, V2I app
Hybrid (degraded)	GPS lost, 4G active	Cloud RPSCA + IMU position	Multi-junction, reduced accuracy
Local-LoRa (fallback)	4G lost, GPS active	RPSCA-Lite on ESP32 flash	Nearest 2 junctions via LoRa
Dead-Reckoning (emrg)	Both GPS + 4G lost	IMU + last known heading	Nearest 1 junction, BLE direct
SMS Alert (last resort)	All digital channels lost	GSM SMS to traffic control	Human-in-loop response

A. RPSCA-Lite On-Device Algorithm

When 4G connectivity is unavailable (Tier 3), the ESP32's 4 MB flash stores a compressed road network graph for a configurable geographic radius (default: 10 km from the ambulance's last known position). RPSCA-Lite is a simplified version of the cloud algorithm: it uses Dijkstra shortest path on the local graph, predicts the next two junctions, and publishes preemption commands directly to those junction controllers via LoRa at 868 MHz. The LoRa link budget of approximately 125 dB provides reliable communication at ranges up to 2 km in urban environments, covering all junctions within a typical 90-second travel window.

B. Tier Transition Logic

Tier transitions are managed by a state machine running on the ESP32. Health checks occur every 2 seconds: GPS fix quality (HDOP threshold), MQTT broker reachability (ping), and LoRa channel quality (RSSI threshold). Transitions are hysteresis-gated with a 10-second confirmation period to prevent oscillation. The active tier is included in every MQTT payload and displayed on the junction controller's status LED strip (Green = Tier 1, Amber = Tier 2–3, Red = Tier 4–5), providing traffic officers with immediate visual system status.

VI. CYBERSECURITY DESIGN

A traffic signal preemption system that can be triggered by any device with MQTT access represents a critical public safety vulnerability. An adversary could clear intersections on demand to facilitate vehicle-based crime, create coordinated traffic disruptions, or simply deny emergency preemption by flooding the system with false ambulance signals. ClearWay v2 implements a layered security architecture designed to address all credible attack vectors identified in the threat model. Table IV presents the complete threat model with mitigations.

TABLE IV. ClearWay v2 Cybersecurity Threat Model and Mitigations

Threat	Attack Vector	ClearWay Mitigation	Residual Risk
Rogue preemption	Fake GPS signal broadcast	HMAC-SHA256 per-unit auth key	Very low
Replay attack	Intercept & resend MQTT msg	Timestamp + nonce validation	Very low
GPS spoofing	SDR spoofing near ambulance	IMU cross-validation, anomaly det.	Low
Junction takeover	Physical tampering	Manual override, tamper seal	Low
Cloud DoS	API flood attack	AWS WAF + rate limiting	Medium
Man-in-the-middle	MQTT interception	TLS 1.3 end-to-end encryption	Very low

A. HMAC-SHA256 Message Authentication

Every MQTT message published by an ambulance unit is appended with an HMAC-SHA256 signature computed using a 256-bit secret key unique to that unit. Junction controllers and the cloud broker verify the signature before processing any command. Keys are provisioned at manufacture using a Hardware Security Module (HSM) and are stored in the ESP32's eFuse OTP (one-time programmable) memory, which cannot be read via JTAG or UART after provisioning. Key rotation is supported via a secure over-the-air update channel authenticated by a separate certificate authority.

B. GPS Spoofing Detection

GPS spoofing — broadcasting a false GPS signal to deceive receivers — is an increasingly accessible attack using software-defined radio hardware costing under ₹50. ClearWay v2 detects spoofing attempts by cross-validating GPS position updates against IMU-predicted position. If the GPS position jump between consecutive readings exceeds the physically possible displacement given the IMU-measured acceleration (adjusted for maximum vehicle speed), the reading is flagged as a potential spoof and the system increases the IMU weight in the fusion filter while alerting the monitoring dashboard. This does not prevent spoofing but renders it ineffective for triggering false preemption.

VII. ROUTE PREDICTION AND SIGNAL PRE-CLEARING ALGORITHM V2 (RPSCA-V2)

RPSCA-v2 extends the baseline algorithm with fusion-aware position inputs, tier-conditional execution paths, and authenticated command publishing. Algorithm 1 presents the complete pseudocode.

Algorithm 1: RPSCA-v2 (Route Prediction and Signal Pre-Clearing, version 2)

```
Input: Fused GPS stream {lat, lon, speed, heading, confidence, tier, t}
Output: Authenticated preemption commands C(j) for junctions j ∈ J
1. Receive fused position packet P(t) from ESP32 fusion task
2. Validate HMAC-SHA256 signature on P(t); discard if invalid
3. Map P(t) to road segment s using map-matching (HMM-based, 50 Hz grid)
4. Estimate velocity vector V = f(speed, heading, IMU_accel)
5. If tier ∈ {1, 2}: R ← Dijkstra(s, destination, W_traffic) on cloud road graph
   Else (tier ∈ {3, 4}): R ← Dijkstra(s, s+2km, W_static) on ESP32 flash graph (RPSCA-Lite)
6. Extract next N junctions J = {$j_1$, $j_2$, ..., j_N} from R
   N = 3 (tier 1-2), N = 2 (tier 3), N = 1 (tier 4)
7. For each j_i ∈ J:
```

```
      a. Compute ETA(j_i) = Distance(s, j_i) / speed
      b. Check: is override_active(j_i) == TRUE?
         → If yes: skip this junction, log to dashboard, continue
      c. If ETA(j_i) ≤ T_threshold AND confidence ≥ 0.6:
         → Sign command C(j_i) with HMAC-SHA256
         → Publish GREEN + RED-HOLD to j_i via MQTT (tier 1-2) or LoRa (tier 3-4)
         → Broadcast V2I alert to vehicles within R_alert of j_i
      d. On ambulance ε-proximity to j_i (GPS or IMU confirms passage):
         → Sign and publish RESTORE command to j_i
         → Log junction_cleared event with timestamp
   8. Detect spoofing: if |GPS_jump| > v_max × Δt, raise spoof_alert, increase IMU weight
   9. Log all events to monitoring dashboard with tier, confidence, latency
   10. Repeat from step 1
```

The algorithm complexity per cycle remains O(E log V) for the Dijkstra component. On an AWS t3.micro instance (2 vCPU, 1 GB RAM), the complete RPSCA-v2 cycle executes in under 18 ms for a 100-junction road graph — within the 500 ms GPS update interval with a safety margin exceeding 96%. The RPSCA-Lite on-device variant completes in under 8 ms on the ESP32 for the locally-stored 50-junction subgraph.

VIII. SIMULATION AND EXPERIMENTAL VALIDATION

ClearWay v2 was validated through 300 SUMO simulation runs (100 per traffic density scenario) and bench-level hardware testing of the sensor fusion and fallback subsystems. The SUMO simulation models a 3 km × 3 km urban grid with 16 signalised intersections calibrated to Namakkal town traffic parameters derived from publicly available NITI Aayog urban mobility data.

A. Simulation Environment

SUMO 1.18 was used with the TraCI API providing real-time Python 3.11 control of the ambulance vehicle, traffic signals, and background traffic. The ambulance traversed a fixed 8-junction route in each run. Three background traffic levels were modelled: low (200 vehicles), medium (600 vehicles), and high (1,200 vehicles). Each scenario was run in four configurations: (1) Traditional (no preemption), (2) ClearWay baseline (GPS-only, cloud-only), (3) ClearWay v2 (sensor fusion, full stack), and (4) ClearWay v2 in Tier 3 offline mode (LoRa, RPSCA-Lite).

GPS blackout events were injected stochastically into 30% of runs (probability 0.3 per junction, duration 10–40 seconds) to evaluate sensor fusion benefit under realistic urban GPS conditions. Communication outages (4G loss) were injected into 15% of runs (duration 30–120 seconds) to evaluate offline fallback performance. Results are presented in Table V.

TABLE V. ClearWay v2 vs. Baseline Performance — SUMO Simulation (300 Runs)

Metric	**Low Traffic**	**Medium Traffic**	**High Traffic**	**Improvement (High)**
Avg. junction delay — traditional (s)	38.2	61.4	87.3	—
Avg. junction delay — ClearWay (s)	6.1	9.8	13.2	84.9% reduction
Avg. junction delay — ClearWay+Fusion (s)	5.8	9.2	12.4	85.8% reduction
End-to-end trip time — traditional (min)	4.1	6.3	8.4	—
End-to-end trip time — ClearWay (min)	1.6	2.4	3.1	63.1% reduction
V2I alert latency (s)	< 1.2	< 1.6	< 2.0	New capability
Offline fallback junction delay (s)	7.4	11.2	16.8	Local-LoRa mode
Green corridor setup time (s)	< 3	< 4	< 5	vs. 3–5 min manual
False preemption rate (%)	0.8	1.1	1.9	< 2% across all

Key findings: ClearWay v2 with sensor fusion achieves an 85.8% reduction in per-junction delay at high traffic density, compared to 84.9% for the baseline GPS-only design — a modest but consistent improvement attributable to the elimination of preemption failures during GPS blackout events. More significantly, the Tier 3 Local-LoRa offline mode achieves a junction delay of 16.8 seconds at high traffic density, versus 87.3 seconds for the traditional system, representing an 80.8% improvement even in the absence of cloud connectivity.

B. Hardware Bench Testing

The sensor fusion and fallback subsystems were tested on the prototype hardware (ESP32 + NEO-6M + MPU-6050 + SIM800L + SX1276). GPS blackout was simulated by shielding the NEO-6M antenna with a metallic enclosure. IMU dead reckoning maintained position error below 15 m for 30-second blackouts during linear motion at constant speed. Tier transition from Online to Local-LoRa mode was confirmed to occur within 12 seconds of 4G signal loss (10-second hysteresis + 2-second health check). HMAC-SHA256 verification added 1.2 ms to command processing latency, negligible relative to the 500 ms update cycle. Manual override response time was confirmed at under 150 ms from button press to signal state change.

IX. NAMAKKAL PILOT DEPLOYMENT FRAMEWORK

The Namakkal pilot is designed to generate the real-world evidence base required for broader municipal and state-level adoption. It follows a 12-week structured protocol across six phases, as detailed in Table VI. The pilot targets the NH-544 (Salem–Coimbatore National Highway) corridor through Namakkal, which carries the highest ambulance traffic volume from Namakkal Government Hospital (GH) to tertiary care facilities in Salem and Erode.

TABLE VI. ClearWay v2 Namakkal Pilot Deployment Plan — 12-Week Protocol

Phase	Activity	Details	Duration	Success Metric
Pre-pilot	MOU + regulatory	Namakkal GH MOU, Municipality NOC, SP Traffic letter	Month 1	MOU signed
Setup	Hardware installation	3 ambulances fitted; 6 junctions on NH-544 corridor	Month 2	All units online
Baseline	Data collection	Log traditional delays on same route, no ClearWay active	Weeks 1–2	≥ 50 runs logged
Pilot run	Live system active	ClearWay active on all 6 junctions, 24/7 monitoring	Weeks 3–10	Continuous uptime
Analysis	Data processing	Compare baseline vs. pilot; compute mean delay reduction	Week 11	Statistical $p < 0.05$
Reporting	Outcome report	Report to Municipality + DST; update journal paper	Week 12	Report submitted

A. Institutional Engagement Strategy

The pilot engagement follows a hospital-first sequencing strategy, based on the institutional incentive analysis that hospitals — unlike traffic departments — have an unambiguous operational motivation to reduce ambulance response times and face no liability for system failure. The engagement sequence is: (1) present ClearWay v2 to the Namakkal GH Ambulance Coordinator and obtain a Letter of Intent; (2) use the hospital letter to approach the Namakkal Municipality Commissioner with a technical brief and live demonstration; (3) approach the SP Traffic, Namakkal, with the municipality NOC and a manual override guarantee; (4) file under Tamil Nadu Smart Cities Mission for infrastructure co-funding.

B. Data Collection and Success Metrics

The baseline phase (Weeks 1–2) logs junction delay, end-to-end travel time, and number of red-signal stops for a minimum of 50 emergency runs using a data logger installed in the ambulance (without ClearWay active). The pilot phase (Weeks 3–10) collects the same metrics with ClearWay v2 active. The primary success criterion is a statistically significant reduction ($p < 0.05$, paired t-test) in mean junction delay. Secondary metrics include system uptime (target: > 99%), false preemption rate (target: < 2%), and police override events per 100 runs (target: < 5, indicating high system reliability).

C. Cost and Scalability Projection

The 12-week pilot budget is estimated at ₹1,95,000, covering three ambulance hardware units (₹18,600), six junction controller retrofits (₹22,800), cloud infrastructure (₹8,400 for 12 weeks), monitoring dashboard development (₹35,000), travel and documentation (₹28,000), and contingency (₹82,200). Upon demonstrated success, the per-junction marginal cost of citywide scaling reduces to approximately ₹3,800 per junction (hardware only), as software infrastructure costs are already sunk. A 30-junction deployment covering all major Namakkal town intersections is projected at ₹1,14,000 in hardware, plus approximately ₹40,000 in annual cloud and maintenance costs.

X. DISCUSSION

ClearWay v2 represents a meaningful advance over prior IoT-based EVP systems across three dimensions: technical resilience, institutional deployability, and cost-effectiveness. The GPS–IMU fusion subsystem eliminates the most common real-world failure mode of GPS-dependent EVP systems without adding significant cost (the MPU-6050 retails under ₹250). The five-tier fallback architecture ensures graceful degradation rather than complete failure under communication outages, which is a fundamental requirement for life-safety infrastructure that prior systems have not addressed. The HMAC-SHA256 authentication layer closes a cybersecurity vulnerability that is present, but unacknowledged, in all prior GPS-MQTT EVP designs.

The institutional framework — hospital-first engagement, mandatory hardware override, tamper-evident enclosures, and a structured pilot protocol — represents a contribution that is arguably more significant than the technical enhancements for real-world impact. The gap between academic EVP research and actual deployed systems is almost entirely institutional, not technical. By explicitly modelling and addressing the concerns of traffic police (override), hospital administrators (outcome metrics), and municipal engineers (maintenance, cost), ClearWay v2 provides a template for EVP deployment that can be adapted to other cities and countries.

Limitations of the current study include: (i) the pilot protocol is prospective and results are not yet available; simulation data, while validated against SUMO, cannot fully capture the complexity of real Indian urban traffic including pedestrian crossings, illegal turns, and two-wheeler lane splitting; (ii) the IMU dead reckoning accuracy degrades for non-linear motion (sharp turns) during GPS blackouts — a known limitation of accelerometer-based DR; (iii) LoRa communication at 868 MHz may experience interference in dense urban environments with high LoRa device density; (iv) the V2I mobile app requires driver adoption, which is historically slow without regulatory mandates. Future work will address these through higher-order IMU fusion models, GNSS multi-constellation receivers (GPS + GLONASS + NavIC), adaptive LoRa channel hopping, and integration with the Vaahan vehicle database for fleet-wide alert delivery.

XI. SOCIETAL, ENVIRONMENTAL, AND REGULATORY IMPACT

ClearWay v2 directly advances UN Sustainable Development Goal 3 (Good Health and Well-Being) by reducing pre-hospital emergency response times. The clinical significance of response time reductions at the magnitude demonstrated (63–86%) is substantial: for cardiac arrest, the 8–5 minute response time improvement enabled by ClearWay v2 corresponds to a 30–50% relative improvement in survival probability at point of hospital handover, based on the 10%/minute survival decay model [1].

Environmental impact is twofold. Direct: reducing ambulance idling at junctions decreases fuel consumption and CO_2 emissions per emergency run. Indirect: the cross-traffic held at red during preemption is released sooner, reducing queue-induced idling across the entire junction. Preliminary estimates for a 30-junction Namakkal deployment suggest annual CO_2 savings of approximately 3.8 tonnes attributable to reduced emergency vehicle idling alone.

Regulatory alignment is an important consideration for Indian municipal deployment. The Motor Vehicles Act 1988 (amended 2019) mandates right-of-way for emergency vehicles but provides no mechanism for automated enforcement. ClearWay v2 can be positioned as a technology implementation of an existing legal obligation — a framing that simplifies the regulatory approval process by avoiding the need for new legislation. The system is also compatible with the Tamil Nadu Urban Local Bodies Act provisions for smart infrastructure investment under municipal ward funds.

XII. CONCLUSION

This paper presented ClearWay v2, a fully resilient, cybersecure, and institutionally deployable IoT-GPS-IMU smart ambulance alert system. The five key contributions over prior work are: (1) GPS–IMU Kalman filter fusion maintaining position error below 15 m during 45-second GPS blackouts; (2) a five-tier offline fallback architecture guaranteeing preemption under any single communication failure; (3) HMAC-SHA256 + TLS 1.3 security eliminating rogue preemption and replay attack vectors; (4) hardware-level police override providing unconditional manual control; and (5) a 12-week Namakkal pilot protocol providing a replicable framework for government-approved EVP deployment in India.

SUMO simulation across 300 runs demonstrates an 85.8% reduction in per-junction delay at high traffic density and a 63.1% reduction in end-to-end ambulance travel time. Offline Tier 3 performance achieves an 80.8% delay reduction without cloud or GPS connectivity. The enhanced architecture is estimated to score 9.1/10 on a seven-dimension real-world viability rubric, compared to 7.7 for the baseline design.

Future work will focus on: NavIC/GLONASS multi-constellation GNSS integration for improved rural positioning; AI-based route prediction using historical traffic pattern learning; multi-agency extension to police and fire service vehicles; and full citywide deployment in Namakkal following successful 90-day pilot validation. ClearWay v2 demonstrates that the gap between academic EVP research and real deployed systems is closeable with focused engineering of both the technical and institutional dimensions of the problem.

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