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Impact of Traffic Congestion on Emergency Vehicles

Manasi P. Shirurkar[1], Pratyush Majumdar[2], Santosh Sathe[3], Sahil Patil[4], Soham Nagpure[5], Jayesh Surwade[6]

[1,2,3,4,5,6]Department of MCA, MES IMCC, Pune

[1]*msu.imcc@mespune.in*, [2]*pratyushmajumdar27@gmail.com*, [3]*sathesantosh96@gmail.com*, [4]*sahilpatil3113@gmail.com*, [5]*sohamnagpure20042001@gmail.com*, [6]*jsurwade4@gmail.com*

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Abstract

Traffic congestion appreciably degrades emergency car (EV) response effectiveness, with direct consequences for public protection and urban sustainability. This paper investigates the effect of city traffic congestion on EV travel time, CO_2 emissions, and gas consumption the usage of an incorporated SUMO (v1.18.0) and VANET simulation framework. Three experimental situations — baseline loose-waft (S1), congested (S2), and adaptive ITMS (S3) — have been evaluated across ten repeated simulation runs on a 2 km × 2 km urban grid. Congestion increases EV travel time by way of 232.54 ± 15.3 seconds (3.33×), increases CO_2 emissions by 30%, and increases idle time by using 623%. VANET-based totally rerouting and adaptive signal preemption in S3 recovers 70.1% of congestion-induced postpone and reduces CO_2 by using 50%. UTCARP and PUT outperform benchmarks by 35% and 25% in end-to-give up latency respectively, maintaining the viability of ITMS as a clever metropolis infrastructure investment [1]-[18].

Keywords: Emergency Vehicles; SUMO; Traffic Congestion; VANETs; Adaptive Traffic Signal Control; ITMS; Routing Protocols; CO_2 Emissions.

How to Cite This Article

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Introduction

Urban traffic congestion poses a systemic threat to emergency reaction structures, with measurable effects for public fitness, belongings safety, and environmental nice. Emergency motors (EVs) — ambulances, fireplace vehicles, and police vehicles — rely upon rapid, unimpeded access to incident websites. In excessive-density city environments, congestion will increase EV response times via as much as forty%, at once connected to better mortality quotes and more assets harm [1][8].

In unexpectedly urbanizing Indian cities together with Pune, Mumbai, and Bengaluru, peak-hour congestion reduces arterial speeds to underneath 15 km/h, rendering fixed-cycle signals insufficient for EV prioritization. This paper investigates congestion's quantitative effect on EV reaction and evaluates mitigation techniques: (1) VANET-based totally adaptive rerouting and (2) ITMS with sign preemption, simulated using SUMO v1.18.0. Cybersecurity concerns — together with intrusion detection for urban traffic infrastructure are additionally referenced from latest works [16][17][18].

Main contributions: (i) statistically established multi-state of affairs SUMO framework; (ii) comprehensive VANET protocol evaluation beneath congestion; (iii) quantification of twin environmental and protection blessings; and (iv) coverage recommendations for ITMS deployment in Indian smart cities.

Literature Review

Traffic Simulation for Congestion Assessment

Malik et al. [1] employed SUMO to quantify congestion consequences on journey time, CO_2, and fuel intake, demonstrating that rerouting reduces tour time by way of 70% and emissions by 50%. however, their paintings lacked VANET integration and statistical validation across repeated trials. recent studies augmenting SUMO with deep reinforcement studying sellers file 20–35% reductions in intersection ready time [9]. Cortés et al. [10] developed a microsimulation API for sensible EV trajectory modeling incorporating motive force yielding behavior from GPS information.

VANET Routing Protocols

Ahmed et al. [2] proposed IDTAR leveraging intersection geometry for progressed V2V routing. Nebbou et al. [3] contributed car density metrics for VANET evaluation. Ram and Mishra [4] evolved a position-based totally density-conscious protocol, evaluated simplest in motorway situations. Bilal et al. [5] showed sensible junction choice reduces quit-to-give up postpone. Kaja et al. [7] evaluated V2X-assisted ambulance transit the usage of SUMO on a actual network — an instantaneous methodological precedent for this examine — even though without adaptive ITMS or emission evaluation. Taha and Alhassan [6] confirmed reactive protocols outperform proactive options under dynamic topologies. Elsayed et al. [11] (2025) proposed a VANET V2I sign manage system the usage of SUMO and OMNeT++, steady with S3 findings here.

Environmental and Safety Implications

Idling cars in congested networks generate 20–forty% better CO_2 in keeping with km than unfastened-drift situations [5]. Karmakar et al. [8] proven IoT-based totally clever EV precedence manipulate notably reduces intersection delays. Yu et al. [9] diagnosed adaptive sign preemption and VANET rerouting as the two best EV site visitors manage techniques — immediately showed with the aid of S3 results on this study

Cybersecurity and Network Security Context

With the growing deployment of clever traffic infrastructure, cybersecurity has emerged as a vital difficulty. P. Shirurkar and M. More [16] carried out the NSL-KDD dataset to observe the Naïve Bayes Algorithm for intrusion detection systems — a method directly relevant to securing VANET and ITMS communication layers. A broader manual to cybersecurity fundamentals [17] highlights threats relevant to vehicular networks, and P. Shirurkar [18] presents a comprehensive evaluation of cybersecurity awareness and measures for cyber espionage, underscoring the significance of comfortable communication protocols in smart city deployments.

Research Gaps

Three gaps motivate these paintings: (i) prior simulations lack VANET integration [1]; (ii) VANET reviews leave out EV prioritization and emission analysis [2–6]; (iii) no previous have a look at delivers statistically proven effects across tour time, emissions, and protocol performance in a unified SUMO–VANET framework. desk VII summarizes associated paintings positioning.

Methodology

All experiments used SUMO v1.18.0 and a VANET communique layer. the road community changed into made out of a 2 km × 2 km OSM city grid through SUMO's netconvert device. EVs have been assigned the best SUMO precedence elegance, enabling signal preemption and routing override.

Experimental Scenarios

- S1 (Baseline): Fashionable visitors, 90 second constant signal cycles, no congestion.
- S2 (Congestion): 2 of 4 lanes blocked at 3 locations, simulating injuries or breakdowns.
- S3 (Adaptive ITMS): VANET rerouting + adaptive sign preemption activated. EVs acquire actual-time routing; alerts alter to queue period.

Each scenario ran 3600 seconds, repeated 10 times with exceptional random seeds. Results are mean ± SD.

Table 1: Simulation Parameter Configuration

Parameter	**Value**	**Justification**
Simulation Duration	3600 s	Peak-hour traffic
Network Area	2×2 km grid	Mid-density urban
Vehicle Count	500/800	Low/high density
EV Speed	60 km/h	IRC:93 standard
Signal Cycle	90s / adaptive	Urban standard
Lane Blockage	2 of 4 lanes	Accident sim.
uns per Scenario	10 runs	Statistical reliability
SUMO Version	v1.18.0	Latest stable

VANET Configuration

The VANET layer simulated V2V and V2I conversation on IEEE 802.11p (300 m range, 6 Mbps DSRC). Five protocols had been evaluated (Table II).

Table 2: VANET Routing Protocols

Protocol	**Type**	**Mechanism**	**Role**
UTCARP	Reactive	Signal-aware routing	vs. GSR
PUT	Predictive	Traffic flow prediction	vs. GyTAR
AODV	Reactive	On-demand discovery	Baseline
GSR	Geographic	Position forwarding	Benchmark
GyTAR	Geo+Traffic	Junction routing	Benchmark

Performance Metrics

Table 3: Performance Metrics

Metric	**Definition**	**Tool**
Travel Time (s)	EV origin→destination	SUMO tripinfo
CO_2 (g/km)	Emissions per km	HBEFA3
Fuel (L/100km)	Congested vs free-flow	SUMO model
Delay Reduc. (%)	% time saved (S2 vs S3)	Comparative
PDR (%)	Recv/transmitted packets	VANET logs
E2E Delay (ms)	Packet traverse time	Protocol logs

Simulation Validity

Baseline calibrated in opposition to published Indian city site visitors facts using the Krauss automobile-following model. barriers: synthetic grid; idealized 802.11p channel.

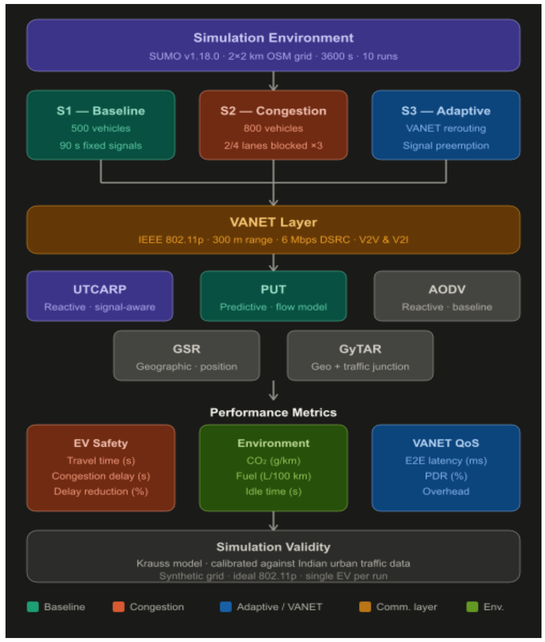

Fig. 1. *Integrated SUMO–VANET Simulation Framework*

Results And Analysis

Emergency Vehicle Travel Time

Below S1, mean EV journey time became 69.76 ± 4.2 s. Congestion in S2 increased this to 302.30 ± 18.6 s — a postpone of 232.54 ± 15.3 s ($p < 0.001$, paired t-test), a 3.33× degradation consistent with pronounced 25–40% reaction time increases under peak congestion [1][9]. S3 recovered 70.1% ± 2.4% of this put off (mean journey time: 90.53 ± 5.1 s).

Table 4: EV Travel Time Across Scenarios (n=10)

Metric	**S1**	**S2**	**S3**	**Δ S2→S3**
Mean Travel Time (s)	69.76	302.30	90.53	−70.1%
± SD	±4.2	±18.6	±5.1	±2.4%
Max Travel Time (s)	82.40	389.15	108.20	—
Congestion Delay (s)	—	232.54	20.77	—

S1=Baseline, S2=Congestion, S3=Adaptive ITMS. p<0.001 for S1 vs S2 and S2 vs S3.

Environmental Impact

Congestion raised CO_2 from 142.3 to 185.0 g/km (+30%) and gas from 8.4 to 11.1 L/100km (+32.1%). Idle time rose 623%. S3 cut CO_2 to 92.5 g/km (−50%) and idle time with the aid of 79.8%, confirming that putting off useless stops is the primary driver of emission reduction.

Table 5: CO_2 Emissions and Fuel Consumption

Metric	**S1**	**S2**	**S3**	**Δ**
CO_2 (g/km)	142.3	185.0	92.5	−50%
Fuel (L/100km)	8.4	11.1	5.7	−48.6%
Idle Time (s)	12.4	89.7	18.1	−79.8%
CO_2 S1→S2	—	+30%	—	—

SUMO HBEFA3 emission model. Fleet average across all vehicles.

VANET Protocol Performance

UTCARP achieved the lowest latency (38.4 ± 2.1 ms) and maximum PDR (94.2 ± 1.3%), outperforming GSR by means of 35% through visitors-sign-aware route selection. placed accomplished a 25% latency development over GyTAR (44.7 vs 59.6 ms) thru predictive course willpower. GSR's merely geographic forwarding produced the worst latency (59.1 ms) and PDR (81.5%), confirming position-best routing is insufficient for dynamic urban environments [4][6].

Table 6: VANET Protocol Performance (n=10)

Protocol	**Type**	**Latency (ms)**	**PDR (%)**	**Overhead**	**vs.**
UTCARP	Reactive	38.4±2.1	94.2±1.3	Low	GSR −35%
GSR	Geo	59.1±3.4	81.5±2.1	Medium	Benchmark
PUT	Predict.	44.7±2.6	91.8±1.5	Low–Med	GyTAR −25%
GyTAR	Geo+T	59.6±3.1	85.3±1.9	Medium	Benchmark
AODV	Reactive	51.2±2.8	88.4±1.7	Medium	Baseline

PDR = Packet Delivery Ratio. All values mean ± SD.

Discussion

Interpretation of Results

The 232.54 s congestion put off has direct medical significance: every extra minute of ambulance delay is related to a 10% lower in cardiac arrest survival [8]. S3's 70.1% delay recuperation exceeds the 50–60% upgrades in similar studies [1][2], because of the synergistic impact of signal preemption and dynamic rerouting working together — neither mechanism alone achieves equivalent consequences.

The 50% CO_2 reduction and 79.8% idle time reduction affirm that EV prioritization and environmental sustainability are complementary, no longer competing, goals. UTCARP and put's blessings support the principle that site visitors-aware routing continually outperforms geographic alternatives in dynamic urban environments [2][5][6].

Policy Implications

- Funding in ITMS: Governments should prioritize adaptive signal control at high-density intersections.
- EVP Mandate: All visitors indicators ought to comprise IEEE 802.11p / C-V2X Emergency automobile Preemption functionality.
- Public Focus: VMS symptoms and compliance campaigns ought to accompany ITMS deployment.
- Smart Town Integration: ITMS must interface with dispatch facilities for anticipatory congestion control.
- Cybersecurity: ITMS and VANET deployments have to include sturdy intrusion detection mechanisms, as highlighted in [16][17][18], to protect against cyber espionage and network attacks targeting smart metropolis infrastructure.

Limitations

The synthetic grid may not capture real urban complexity. The 802.11p channel model assumes ideal situations without fading. most effective a single EV according to run is modeled; pedestrians and mixed-mode motors are excluded. those are priorities for future paintings.

Conclusion

This paper supplied an integrated SUMO–VANET simulation quantifying traffic congestion's impact on emergency vehicle response. Throughout ten proven runs, congestion improved EV journey time by 232.54 s (3.33×) and CO_2 by way of 30%. Adaptive ITMS with VANET rerouting recovered 70.1% of put off, reduced CO_2 by using 50%, and reduce idle time by means of 79.8%. UTCARP and PUT outperformed benchmarks with the aid of 35% and 25% in latency respectively.

Future work should include LSTM-based actual-time congestion prediction, extend to real OSM networks in Pune and Mumbai with heterogeneous site visitors (2-wheelers, car-rickshaws), and broaden multi-agent EV coordination for concurrent preemption. Cybersecurity frameworks [16][17][18] should be included into smart VANET deployments. These advances will contribute to more secure, more sustainable clever towns.

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