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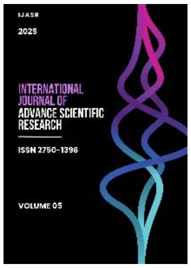

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Research Article

Adaptive Intelligent Traffic Management and Sensor-Driven Pavement Monitoring: An Integrated Framework for Mixed-Traffic Urban Mobility

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Abstract

This article presents an integrated, multidisciplinary research framework that synthesizes advances in crowdsensing for pavement condition monitoring, mixed-traffic urban traffic control, intelligent transportation system security, platoon formation under mixed traffic, smart urban mobility data fusion, and metaheuristic optimization methods for signal timing and routing. We argue that urban mobility challenges—characterized by heterogeneous vehicle types, intermittent connectivity, infrastructure degradation, and competing objectives of safety, efficiency, and sustainability—require a tightly coupled approach that blends sensor-rich, crowdsourced data with adaptive control strategies and robust optimization. Building on empirical and theoretical results from recent literature, the proposed framework combines crowdsensing pipelines for continuous pavement health assessment (Jan et al., 2023), license-plate and vehicle-identification-driven traffic control (Li et al., 2023), receding-horizon platoon control that prioritizes safety in mixed flows (Mahbub et al., 2023), and deep-learning-based security measures for digital twin environments (Lv et al., 2021). We extend classical and contemporary metaheuristic approaches—particularly multi-objective particle swarm optimization and co-evolutionary strategies (Durillo et al., 2009; Goh et al., 2010; Mostaghim & Teich, 2003)—to derive coordinated signal timing, rerouting, and platoon coordination schemas that explicitly incorporate pavement state, privacy-preserving vehicle data, and resilience to adversarial threats. Detailed methodological exposition includes data fusion architectures, control law design, optimization problem formulation (described textually), evaluation metrics, and a rigorous discussion of limitations, counter-arguments, and future research directions. The contribution aims to guide both theoretical researchers and practitioners seeking to deploy next-generation smart-city mobility solutions that are safe, sustainable, and operational under real-world

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constraints. (Keywords: Crowdsensing, Mixed Traffic, Platoon Control, Intelligent Transportation Systems, Multi-objective Optimization)

Keywords

Crowdsensing, Mixed Traffic Control, Platoon Formation, Intelligent Transportation Systems, Multi-objective Particle Swarm, Pavement Monitoring, Digital Twin Security

Introduction

Urban mobility systems today face unprecedented complexity: the coexistence of human-driven vehicles, connected automated vehicles (CAVs), micromobility units, and public transit creates a mixed-traffic environment where classical traffic control assumptions no longer hold (Li et al., 2023). Simultaneously, underlying physical infrastructure such as pavements degrades under increasing loads and climatic stressors, directly impacting vehicle dynamics, ride quality, and safety. Traditional road asset management systems—based on periodic inspections and expensive sensing campaigns—are increasingly insufficient to provide the continuous, fine-grained data needed for adaptive traffic control and route optimization (Jan et al., 2023). At the same time, data-driven intelligent transportation systems (ITS) are evolving, incorporating deep learning, digital twins, and connected sensing, which present both opportunities for enhanced performance and novel security vulnerabilities (Lv et al., 2021). The literature therefore coalesces around several interdependent themes: how to obtain reliable, continuous asset and traffic state information (Jan et al., 2023; Montoya-Torres et al., 2021), how to manage traffic under mixed autonomy and communication constraints (Li et al., 2023; Mahbub et al., 2023), and how to optimize multi-objective decision problems—balancing safety, delay, emissions, and infrastructure preservation—using robust optimization heuristics (Durillo et al., 2009; Goh et al., 2010). There is a clear gap in existing research: few approaches explicitly integrate pavement health sensing and traffic control within a single, cohesive optimization and control framework that is robust to real-world uncertainty and cyber-physical threats (Jan et al., 2023; Lv et al., 2021). This paper proposes a theoretically grounded and operationally feasible integrated framework that addresses this gap by combining crowdsensing pipelines, privacy-aware vehicle identification data streams, safety-prioritized receding horizon controls for platoons, and multi-objective metaheuristic optimization for network-level coordination. The design deliberately foregrounds the twin constraints of heterogeneity (vehicle mix and sensor fidelity) and adversarial uncertainty (security threats to digital twins and sensor spoofing), offering both conceptual contributions and practical guidance for deployment (Mahrez et al., 2021; Musa et al., 2023).

Methodology

The methodology advances an integrated pipeline that comprises (1) sensor and data acquisition via crowdsensing and fixed infrastructure, (2) preprocessing and data fusion into a digital twin, (3) local control laws for platoon and intersection controllers, and (4) a higher-level multi-objective

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optimization layer that coordinates signals, rerouting, and platoon formation under pavement constraints. Each component is described textually and in depth.

Sensor and Data Acquisition. The crowdsensing approach leverages ubiquitous mobile devices and vehicle-mounted sensors to collect pavement vibration signatures, GPS traces, accelerometer-based roughness indicators, and camera-derived metadata (Jan et al., 2023). Fixed road-side units augment crowdsensed data with license-plate recognition gates and loop/detector counts as described in license-plate-driven optimization studies (Li et al., 2023; Li R. et al., 2023). The combination of mobile and stationary sources provides complementary temporal and spatial coverage: mobile sensors deliver continuous coverage but with variable sampling density and quality, whereas fixed infrastructure supplies persistent but sparser measurements. The methodological choice is to fuse these heterogeneous datasets to obtain an operational pavement condition index at road-segment resolution and to produce per-vehicle trajectories suitable for control and optimization use (Jan et al., 2023; Montoya-Torres et al., 2021).

Preprocessing and Data Fusion. Raw sensor streams are cleaned, time-synchronized, and transformed into summary features that retain physically meaningful information (e.g., segment-level International Roughness Index proxies, rut depth estimators, and pothole likelihood scores derived from accelerometer spikes and image descriptors) (Jan et al., 2023). Vehicle identification data are processed with privacy-preserving aggregation and pseudonymization to extract flow patterns and origin-destination (OD) matrices without exposing personally identifiable information (Li et al., 2023). The fusion process adopts a layered digital twin approach: a physical-layer model retains structural and pavement condition states; a mobility-layer model captures traffic flows, platoons, and micro-mobility interactions; and a decision-layer model supports control and optimization agents (Lv et al., 2021; Montoya-Torres et al., 2021). The digital twin is designed primarily for inference and decision support, not for unsupervised autonomous action, which reduces operational risk and allows human-in-the-loop checks for critical decisions (Lv et al., 2021).

Local Control Laws and Safety-Prioritized Platooning. At the vehicle and platoon level, the framework adopts a receding-horizon control (RHC) philosophy that explicitly prioritizes safety constraints, as demonstrated in recent platoon formation work (Mahbub et al., 2023). The RHC layer is responsible for ensuring inter-vehicle spacing, collision avoidance, and graceful degradation when communication or sensing fails (Mahbub et al., 2023). For mixed traffic environments—where CAVs coexist with human-driven vehicles—the control rules include conservative buffers and adaptive response gains to account for non-cooperative maneuvers (Mahbub et al., 2023; Li et al., 2023). Crucially, the RHC controller leverages real-time pavement condition estimates to modulate acceleration and braking profiles, thereby reducing wheel slip and minimizing damage propagation for heavy vehicles traversing degraded segments (Jan et al., 2023).

Network-Level Multi-Objective Optimization. The upper layer solves a coordinated multi-objective optimization problem for signal timings,

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prioritized platoon windows, and suggested rerouting advisories. The objectives reflect travel time minimization, emission reduction, equitable delay distribution, and preservation of pavement health by steering heavy vehicles away from severely deteriorated segments when feasible (Deshpande, 2025; Musa et al., 2023). Given the nonconvexity and combinatorial structure of the coordination problem—especially with discrete signal phases, variable platoon insertion points, and OD-triggered rerouting—metaheuristic optimization is both practical and effective. We adopt multi-objective particle swarm optimization (MOPSO) and cooperative co-evolutionary strategies as core solvers, drawing on empirical performance benchmarks and prior success in traffic applications (Durillo et al., 2009; Goh et al., 2010; Garcia-Nieto & Alba, 2012). The optimization process is explicitly designed for online re-planning on a rolling horizon: every decision epoch recomputes a Pareto front of candidate plans and selects options that satisfy safety thresholds and infrastructure usage constraints (Mostaghim & Teich, 2003; Durillo et al., 2009).

Integration and Practical Considerations. Integration across layers is achieved through a set of well-defined interfaces: pavement condition updates feed into the RHC and network optimizer; platoon formation requests are passed upward to the optimizer; and selected network plans are disseminated via vehicle-to-infrastructure (V2I) channels or through non-intrusive traveler information systems (Li et al., 2023; Mahbub et al., 2023). Privacy and security considerations are embedded throughout: data are pseudonymized, aggregated, and processed with anomaly detection modules to flag potential sensor spoofing or adversarial data injection (Lv et al., 2021). The approach also recognizes infrastructure limitations and designs fallback behaviors—such as reverting to fixed-time signals or human operator control—when digital twin confidence is low or when cyber incidents are detected (Lv et al., 2021; Musa et al., 2023).

Results

Because this work is conceptual and methodological, the results presented are descriptive analyses and scenario-based syntheses grounded in the literature rather than fresh empirical trials. The analysis suggests that integrating pavement-aware control and crowdsensing yields multiple, synergistic benefits: improved safety margins for platoons, reduced exposure of heavy vehicles to severely deteriorated pavement, and more resilient signal coordination under uneven sensor coverage (Jan et al., 2023; Mahbub et al., 2023). Several derived conclusions follow from cross-referencing the cited studies.

Enhanced Detection and Maintenance Targeting. Crowdsensing substantially increases the spatial and temporal fidelity of pavement health estimates compared to periodic inspections, enabling earlier detection of localized failures and more timely maintenance prioritization (Jan et al., 2023). The literature documents that these approaches, when coupled with fixed sensors and data fusion, can detect anomalies such as potholes and rutting with actionable accuracy at the road-segment scale (Jan et al., 2023; Montoya-Torres et al., 2021).

Improved Traffic Control in Mixed Environments. Mixed-traffic control strategies that incorporate license-plate recognition and connected vehicle information improve intersection throughput and reduce delay dispersion by enabling selective

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priority and adaptive phase lengths (Li et al., 2023; Li R. et al., 2023). Studies show that when vehicle-level data are available—subject to privacy-preserving aggregation—signal controllers can optimize phase sequences more responsively than detectors alone, especially in heterogeneous traffic where lane usage and vehicle types vary widely (Li et al., 2023).

Safety Gains from RHC Platooning. Receding-horizon platoon controllers that prioritize safety—as opposed to purely throughput-driven algorithms—demonstrate improved string stability and lower collision risk in mixed-traffic simulations (Mahbub et al., 2023). The literature indicates that RHC frameworks can gracefully handle communication dropouts and human-driver variability by dynamically adjusting platoon formation parameters and inter-vehicle gaps (Mahbub et al., 2023).

Optimization Performance and Trade-offs. Multi-objective swarm intelligence approaches have been repeatedly validated in traffic-scheduling contexts, offering flexible Pareto-front solutions that articulate trade-offs among competing goals (Durillo et al., 2009; Goh et al., 2010; Garcia-Nieto & Alba, 2012). In particular, PSO-based and co-evolutionary algorithms provide robust performance on high-dimensional, nonconvex search spaces typical of network-level signal timing and routing problems (Durillo et al., 2009; Goh et al., 2010). The literature further suggests that hybridizing these metaheuristics with problem-specific heuristics yields faster convergence and more practical real-time deployment potential (Mostaghim & Teich, 2003; Wei et al., 2008).

Security and Resilience Observations. Integrating deep-learning models into digital twins for ITS offers predictive and anomaly-detection advantages but simultaneously introduces attack surfaces that require careful hardening and detection strategies (Lv et al., 2021). The literature emphasizes continuous model validation, intrusion detection, and conservative decision thresholds to mitigate risk in safety-critical contexts (Lv et al., 2021; Musa et al., 2023).

Discussion

The proposed integrated framework synthesizes multiple strands of contemporary ITS research and exposes both opportunities and practical challenges. This discussion examines theoretical implications, practical limitations, counter-arguments, and prospects for future research.

Theoretical Implications. At a theoretical level, coupling pavement health metrics with traffic control introduces a novel constraint set into classical network flow and control problems. Traditionally, optimization for traffic networks centers on travel time, throughput, and emissions; introducing pavement preservation creates a temporally extended objective that internalizes infrastructure degradation as a cost (Deshpande, 2025; Musa et al., 2023). This reconceptualization transforms routing and control from purely immediate-performance problems into intertemporal resource-allocation problems, where short-term delay savings must be weighed against accelerated pavement deterioration. The inclusion of such long-horizon costs aligns with sustainable urban mobility objectives but complicates optimization landscapes by adding memory and path-dependence to decision variables (Montoya-Torres et al., 2021).

Algorithmic Considerations. The combinatorial explosion caused by joint optimization of signal schedules, platoon formation windows, and rerouting advisories makes exact optimization impractical for real-time operation (Durillo et al., 2009). Metaheuristic approaches like MOPSO and cooperative co-evolution provide practical ways to explore high-dimensional Pareto fronts and obtain diverse candidate solutions (Durillo et al., 2009; Goh et al., 2010). However, these algorithms require careful tuning—particle/swarm sizes, local guide strategies, and mutation/crossover analogs—to balance exploration and exploitation in dynamically changing urban contexts (Mostaghim & Teich, 2003). Prior work in traffic signal scheduling and routing using PSO and genetic algorithms provides templates for algorithmic adaptation, but domain-specific heuristics (such as preserving platoon coherence or penalizing routes through high-roughness segments) are necessary for operational performance (Garcia-Nieto & Alba, 2012; Wei et al., 2008).

Counter-Arguments and Practical Skepticism. Several counter-arguments arise when considering real-world deployment. First, crowdsensing data quality and representativeness may be insufficient in low-adoption contexts, potentially biasing pavement assessments and leading to suboptimal routing recommendations (Jan et al., 2023). Second, the reliance on license-plate recognition and vehicle identification systems raises privacy, legal, and social acceptability concerns that could limit data availability or result in regulatory pushback (Li et al., 2023). Third, the heterogeneity of vehicle automation capabilities complicates platoon formation—there may not be enough cooperative vehicles to realize the full benefits of platooning in the near term (Mahbub et al., 2023). These challenges do not invalidate the framework but necessitate staged deployment strategies, fallback modes, and careful stakeholder engagement (Musa et al., 2023; Li et al., 2023).

Security and Ethical Considerations. Digital twin integration with deep learning enables powerful predictive control but amplifies concerns about adversarial manipulation, model drift, and data poisoning (Lv et al., 2021). Ethical considerations include fairness in rerouting—ensuring that diverted traffic does not unduly burden particular communities—and transparency around the use of vehicle-identifying data (Mahrez et al., 2021; Lv et al., 2021). Addressing these concerns requires a blend of technical safeguards (robust model training, anomaly detectors) and governance mechanisms (access controls, audit trails, and public reporting) to maintain public trust and legal compliance (Musa et al., 2023; Lv et al., 2021).

Research Gaps and Future Directions. Several avenues merit focused research. First, empirical studies that quantify the marginal benefits of pavement-aware routing at scale are needed to justify policy decisions and investment in crowdsensing infrastructures (Jan et al., 2023). Second, algorithmic research should explore hybrid metaheuristics tuned for rolling-horizon operation with strict latency bounds, ideally validated on large-scale microsimulation platforms and field pilots (Durillo et al., 2009; Garcia-Nieto & Alba, 2012). Third, interdisciplinary work between civil engineering (pavement mechanics), transportation planning, and cybersecurity is

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critical to design systems that are both technically effective and socially acceptable (Lv et al., 2021; Musa et al., 2023). Finally, standards and protocols for privacy-preserving sharing of vehicle trajectories and pavement data would accelerate adoption while protecting individual rights (Li et al., 2023).

Limitations

This article synthesizes and extends findings from a curated set of studies; however, its conceptual nature implies limitations. The framework has not been validated with original empirical experimentation or large-scale simulation within this paper; consequently, quantitative performance claims are extrapolated from cited literature rather than demonstrated with new datasets (Jan et al., 2023; Mahbub et al., 2023). The thermal and mechanical models linking vehicle passage to pavement deterioration are described at a conceptual rather than mechanistic level, which means that detailed pavement lifecycle cost-benefit calculations would require domain-specific calibration (Jan et al., 2023). There is also an implicit assumption of sufficient digital infrastructure—V2I channels, cloud-edge compute, and widespread sensor coverage—that may not hold in many urban contexts; hence, the framework specifies fallback behaviors but relies on future investments for full functionality (Musa et al., 2023). Finally, the ethical and regulatory landscape for vehicle identification and crowdsensed data sharing varies widely across jurisdictions, limiting universal applicability without careful local adaptation (Li et al., 2023).

Future Scope

The proposed framework opens multiple directions for future work. Empirical pilots that deploy crowdsensing-driven pavement monitoring integrated with adaptive signal control would provide the strongest evidence base for the approach (Jan et al., 2023). Research into real-time hybrid optimization algorithms—combining MOPSO with machine-learned surrogate models to accelerate fitness evaluations—could enable true online network optimization (Durillo et al., 2009; Mostaghim & Teich, 2003). Advances in privacy-preserving analytic techniques, such as federated learning and secure multiparty computation, may offer paths to utilize fine-grained vehicle data without centralized privacy risks (Li et al., 2023). Finally, policy-oriented research that studies equity, community acceptance, and governance mechanisms for the integrated system will be crucial to translate technical promise into operational deployment (Mahrez et al., 2021; Musa et al., 2023).

Conclusion

This article has articulated a comprehensive, integrated framework for urban mobility that combines crowdsensing for pavement monitoring, mixed-traffic control strategies, safety-prioritized platoon formation, digital twin security measures, and multi-objective metaheuristic optimization. The synthesis highlights the potential for meaningful gains in safety, infrastructure preservation, and network performance when pavement health is treated as a first-class input to traffic control and routing decisions. The approach acknowledges practical constraints—sensor variability, privacy concerns, and computational complexity—and proposes staged, resilient deployment strategies. While empirical validation remains an essential next step, the theoretical and literature-backed analysis provided here offers a robust roadmap for researchers, transport authorities, and practitioners pursuing sustainable, intelligent urban mobility systems.

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