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GAME-THEORETIC APPROACH TO DYNAMIC CONTROL SUBAREA ADJUSTMENT IN OVERSATURATED URBAN ROAD NETWORKS: EVIDENCE FROM GUANGZHOU

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Abstract: Driven by rapid urbanization and motorization, peak-hour oversaturation has become a chronic issue in Guangzhou's urban road network. Core districts such as Tianhe and Haizhu frequently experience congestion indices exceeding 7.8 during morning and evening peaks, with average vehicle speeds dropping below 19 km/h. Queue spillover triggers cascading "domino effects," severely degrading system-wide traffic efficiency. While control subareas serve as fundamental units for regional signal coordination, conventional static partitioning fails to adapt to dynamic traffic fluctuations, and existing dynamic methods often neglect strategic interactions and interest conflicts among subareas, leading to suboptimal coordination.

This study proposes a game-theoretic framework for dynamic subarea adjustment under oversaturated conditions, using Guangzhou as a case study. We develop two decision-making paradigms: a centralized cooperative game model that minimizes total network control cost, and decentralized non-cooperative models—including Stackelberg and Nash equilibria—that account for autonomous subarea behavior. Through theoretical derivation, numerical simulation, and validation via the VISSIM microsimulation platform, we analyze equilibrium properties and system performance across different game structures.

Results demonstrate that the centralized model achieves the lowest total control cost—31.5% lower than the Nash equilibrium—but suffers from poor real-time responsiveness due to computational complexity. The Stackelberg model, leveraging a "central guidance-subarea response" mechanism, strikes an optimal trade-off: it reduces total delay by 18.2% compared to Nash, increases adjustment frequency by 112.5% relative to centralized control, and maintains robust performance under uncertainty. Meanwhile, the Nash model exhibits superior robustness (delay fluctuation ≤4.8% under ±20% data noise) but incurs significant efficiency losses.

Parametric analysis reveals that when the collaboration weight $\lambda > 0.6$, subarea merging probability increases by 42% and queue lengths decrease by 27%. Furthermore, constraining subarea size to 2-5 intersections optimally balances management overhead and coordination benefits—a finding validated across Guangzhou's heterogeneous urban fabric. This research provides both theoretical grounding and a practical implementation pathway for intelligent, adaptive traffic control in oversaturated megacities, directly supporting Guangzhou's "14th Five-Year Plan" for Intelligent Transportation Systems (ITS).

Keywords: Oversaturated road network; Control subarea; Game equilibrium; Dynamic adjustment; Signal coordination

1 INTRODUCTION

1.1 Research Background

1.1.1 Severity of oversaturation in Guangzhou

Guangzhou's urbanization rate surged from 66.2% in 2010 to 86.1% in 2024, accompanied by a motor vehicle fleet exceeding 4 million. This dual pressure has pushed traffic demand consistently beyond capacity thresholds, rendering oversaturation a norm during peak hours. According to the 2024 Guangzhou Annual Report on Transportation Development [1], core zones—including Zhujiang New Town (Tianhe), Guangzhou Avenue South (Haizhu), and Huanshi East (Yuexiu)—recorded average congestion indices of 8.0, 7.9, and 7.7, respectively, all classified as "severe congestion." On arterial corridors like Tianhe Road and Middle Guangzhou Avenue, peak-hour speeds plummet to 16-18 km/h—over 52% slower than off-peak levels.

Under such conditions, queues propagate at 12-16 meters per minute, with approximately 35% of intersections experiencing spillover. This phenomenon reduces adjacent link capacities by 25-45%, initiating a feedback loop of "congestion diffusion → efficiency collapse." A notable example occurred in April 2024: queue overflow at the Tianhe Road-Sports West Road intersection triggered a chain reaction across six downstream junctions, inflating regional average delay from 13 to 38 minutes—a 192.3% increase.

The situation intensifies during mega-events. During the 135th Canton Fair, traffic volume around the Pazhou Convention and Exhibition Center spiked by 60%, pushing demand intensity $D(t)=q(t)/C^{cap}$ to 1.9. Spillover slashed traffic efficiency by 50% on East Xin'gang Road and Yuejiang Middle Road, exposing critical vulnerabilities in current control strategies.

Limitations of Traditional Subarea Partitioning

Control subarea delineation is foundational for coordinated signal optimization. Guangzhou currently employs two primary approaches:

Static zoning: Based on historical OD matrices (2018-2020), K-means clustering partitions the city into 32 fixed subareas[2]. For instance, Tianhe District is divided into five static zones. However, this method cannot respond to real-time surges—during a morning peak, the Zhujiang New Town subzone exhibited green time utilization below 48%, while the adjacent Wushan zone suffered spillover onto the South China Expressway entrance.

Early dynamic zoning: Pilot efforts in Panyu District used density-based clustering with real-time loop and camera data, reducing delays by 11%. Yet, the objective—minimizing intra-subarea delay—ignored inter-subarea externalities. Green extensions in one zone increased neighboring queue lengths by 32%, undermining system-wide performance[3].

1.1.2 Potential of game theory in traffic control

Game theory offers a principled approach to modeling multi-agent strategic interactions. In Guangzhou, early applications include:

Route choice games: Using User Equilibrium (UE), the Intelligent Traffic Command Center redistributed flows between South China and Guangyuan Expressways, boosting average speeds by 10% during peaks .

Signal timing games: Wang et al. applied a Stackelberg model to dual intersections on Middle Guangzhou Avenue, achieving a 19% delay reduction[4].

Regional coordination: A 2022 trial in Tianhe treated subregions as agents but assumed fully aligned objectives, neglecting conflict under oversaturation.

These efforts underscore game theory's promise but reveal a gap: no existing model explicitly incorporates strategic autonomy, interest misalignment, and equilibrium-driven adaptation in dynamic subarea reconfiguration.

1.2 Research Significance

1.2.1 Theoretical innovation

This study reconceptualizes control subareas not as passive execution units but as rational, utility-maximizing agents. We establish a game-theoretic framework—"subarea autonomy ↔ system equilibrium"—that fills the void of "missing subject initiative" in urban traffic control literature[5]. By embedding concepts like Nash equilibrium and Pareto optimality into a context-specific utility function, we formalize trade-offs between local efficiency and systemic cooperation, particularly under extreme events like the Canton Fair.

1.2.2 Practical application value

We design an adaptive, closed-loop control mechanism—"real-time sensing → strategic gaming → equilibrium execution"—that improves response speed by over 55% compared to static methods in oversaturated scenarios. Validated via VISSIM and field trials in Tianhe and Pazhou, our model outperforms benchmarks in total delay, queue length, and throughput, offering a deployable solution aligned with Guangzhou's ITS roadmap[6].

1.2.3 Research scope

This paper addresses four core tasks: (1) formalizing the problem with realistic assumptions grounded in Guangzhou's traffic dynamics; (2) constructing centralized (cooperative) and decentralized (non-cooperative) game models; (3) analyzing equilibrium properties and validating performance via simulation and field tests; and (4) proposing a phased, standardized implementation strategy tailored to Guangzhou's governance and infrastructure landscape.

2 PROBLEM FORMULATION AND MODEL ASSUMPTIONS

2.1 System Boundaries and Decision Behavior

Consider an oversaturated urban network in Guangzhou comprising n intersections and l links, initially partitioned into m control subareas $S=\{S_1,S_2,\ldots,S_m\}$. Two constraints govern valid partitions:

Connectivity: Any two intersections within a subarea must be linked via a path in the road network graph $G=(V,E)$, accounting for complex topologies (e.g., river crossings, commercial district branches).

Scale: Each subarea contains 2-5 intersections. Fewer than 2 limits synergy; more than 5 exponentially increases signal optimization complexity.

Each subarea acts autonomously, selecting from three strategies based on real-time metrics $q_i(t)$, $Q_i(t)$, and $T_i(t)$:

(1) Maintain status quo (stable flow, $D(t)\leq 1.0$);

(2) Request merge with adjacent subareas if $Q_i(t)>Q_{max}$ (e.g., 75% of link length, reduced to 70% in business districts);

(3) Split proactively if $D(t)<0.8$ or scale exceeds 5 intersections.

2.2 Objective Function and Key Variables

The utility of subarea i is defined as:

$$U_i=-C_i+\lambda\sum_{j\in N(i)}\phi(C_j) \tag{1}$$

where C_i is the local control cost:

$$C_i=\alpha\cdot T_i+\beta\cdot Q_i \tag{2}$$

with: $T_i=\frac{0.52}{1-q_i/C_i^{cap}}$ (HCM2016-adjusted delay for Guangzhou), α=32 CNY·h/(pcu·veh) (2024 Guangzhou travel time value),β=55 CNY/m (queuing risk, reflecting accident and economic loss in commercial zones).
The collaborative benefit from neighbor j is:

$$\phi(C_j)=\gamma\cdot\left(T_j^{pre}-T_j^{coop}\right)\cdot\alpha\cdot q_j$$

where γ=1.3 for commercial zones (e.g., Zhujiang New Town), 1.2 for cross-river links, and 1.0 otherwise. The weight $\lambda\in[0,1]$ reflects the subarea's concern for system welfare.
Key model parameters are calibrated using empirical data from Guangzhou's traffic monitoring infrastructure, as summarized in Table 1.

Table 1 Model Parameters and Calibration Values for Guangzhou's Oversaturated Network

Symbol	Meaning	Unit	Value / Range
N	Number of intersections	—	12 (Tianhe CBD benchmark)
ρ	Demand-to-capacity ratio	—	1.3 - 1.9 (oversaturated regime)
qth	Queue length threshold	m	48 (business districts)
λ	Collaboration weight	—	0.2 - 0.9 (event-adaptive)

2.3 Modeling Assumptions

Agent rationality: Subareas maximize utility using real-time data from Guangzhou's 5G+edge computing platform.
Partial information symmetry: Adjacent delay and queue data are shared via the Traffic Bureau's platform, but internal cost parameters (α,β) remain private.
Persistent oversaturation: Analysis focuses on $D(t)\in[1.3,1.9]$, excluding off-peak or extreme weather.
Feasible strategies: Merges require connectivity; splits yield subareas ≥2 intersections.

3 GAME MODEL CONSTRUCTION AND SOLUTION

3.1 Centralized Cooperative Game Model

The central authority (Guangzhou Transport Administration) minimizes total network cost:

$$\min_{\{x_{ij}\}} Z=\sum_{i=1}^{m'} C_i' \tag{3}$$

subject to:
Connectivity: $\forall u,v\in S_k,\exists$ path $u\to v$ in G;
Scale: $2\le S_k\le 5$;
Oversaturation: $Q_i\le Q_{max}$;
Binary decisions: $x_{ij}\in\{0,1\}$.
A genetic algorithm solves this NP-hard problem:
Chromosome: binary vector of length $\binom{m}{2}$;
Fitness: $f=1/(\delta\cdot Z)$, with δ=1.2 for core zones;
Operators: tournament selection, single-point crossover (p_c=0.75), site mutation (p_m=0.06);
Termination: 120 generations or fitness change <1.2% over 15 gens.
Applied to Tianhe CBD ($n=12,m=4$), the optimal partition $S^{=}\{S_{12},S_{34}\}$ yields $Z^{=}$13,280 CNY/h—31.6% lower than static zoning.

3.2 Decentralized Non-Cooperative Models

3.2.1 Stackelberg game (central guidance)

The leader (Transport Bureau) sets λ and incentive μ to minimize total delay:

$$\min_{\lambda,\mu}\varepsilon\cdot T_{total}(\lambda,\mu) \tag{4}$$

where ε=1.3 during the Canton Fair. Followers (subareas) maximize:

$$U_i^1=-\frac{C_i^1+C_j^1}{2}+\lambda\sum_{k\in N(i,j)}\phi(C_k^1)+\mu\cdot\gamma \tag{5}$$

Backward induction yields equilibrium. Particle Swarm Optimization (PSO) with c_1=1.8,c_2=2.0 finds optimal $\lambda^{=}$0.65, $\mu^{=}$950 CNY/h, achieving T_{total}=4,520 h·pcu/h—30.7% better than static.

3.2.2 Nash game (peer-to-peer autonomy)

Each subarea i selects $s_i\in\{\text{maintain,merge,split}\}$ to maximize U_i, given others' strategies. Equilibrium satisfies:

$$U_i(s_i^{*},s_{-i}^{*})\ge U_i(s_i',s_{-i}^{*}),\quad\forall s_i' \tag{6}$$

Solved via Iterated Best Response (IBR), convergence occurs in 9 iterations, yielding Z^{Nash}=19,150 CNY/h—44.2% above centralized optimum but 1.4% below static.

4 RESULTS ANALYSIS AND VALIDATION

4.1 Performance Comparison

VISSIM simulations (12 intersections, D=1.6) show (Table 2):

Table 2 Comparative Performance of Subarea Coordination Strategies

Model	Total Delay (h·pcu/h)	Max Queue Length (m)	Adjustment Frequency (/h)	Total Cost (CNY/h)
Centralized	4,280	41.8	1.1	13,280
Stackelberg	4,520	47.6	2.4	14,650
Nash	5,520	64.9	5.1	19,150
Static	6,380	88.7	0	19,420

Findings: Centralized excels in efficiency but lacks agility; Stackelberg balances delay, frequency, and robustness; Nash is highly responsive but inefficient.

4.2 Sensitivity Analysis

Demand intensity: At D=1.8, Nash delay increases by 108.5% vs. 68.7% for centralized.
Collaboration weight: When $\lambda>0.6$, merge probability ↑42%, queue ↓27%.
Subarea size: Optimal at 2-5 intersections—cost drops 9.3% from size 3→5, while management overhead declines.

4.3 Robustness Testing

Data noise (±20%): Nash delay fluctuates only 4.8%; centralized varies by 15.6%.
Communication delay (30s): Nash convergence extends by 21.5%; centralized by 62.6%.

4.4 Field Validation

Field trials conducted in Tianhe Central Business District and Pazhou from May to June 2024 demonstrated significant operational improvements under the proposed control framework. Peak-period vehicle delay was reduced by 26.9% on weekdays and 30.6% during the Canton Fair, reflecting strong adaptability to both routine and event-driven demand surges. Maximum queue lengths decreased by 48.4%, effectively mitigating spillover and blocking at intersections. Additionally, green time utilization increased by 40.9%, indicating more efficient signal allocation, while network throughput rose by 23.6%, confirming enhanced capacity under oversaturated conditions.No spillover-induced accidents occurred in pilot zones.

5 MANAGEMENT IMPLICATIONS AND IMPLEMENTATION STRATEGY

The proposed traffic management system operates as a real-time, closed-loop framework with four integrated layers. The perception layer fuses data from geomagnetic sensors, cameras, and radar at one-minute intervals to monitor traffic states[7]. Based on this input, the decision layer automatically selects an appropriate game-theoretic coordination mode—Stackelberg for high-density core areas to prioritize system-wide efficiency, and Nash for suburban zones to enable localized responsiveness. The execution layer implements optimized signal plans in real time and activates emergency measures, such as red-light shortening, during incidents[8]. Finally, the feedback layer continuously assesses performance and triggers re-optimization whenever observed gains fall below a 6% improvement threshold over a 15-minute window, ensuring sustained operational effectiveness.
To maintain consistency and institutional coherence, the system embeds standardized operational rules and a collaborative governance structure. Subarea merging is automatically initiated when spillover rates exceed 18% in core districts or 15% in suburban areas—thresholds calibrated to local infrastructure and safety standards. Governance is carried out through a tripartite partnership: the Municipal Traffic Bureau provides regulatory oversight and traffic data; academic institutions (including SCUT and GZMTU) contribute model validation and algorithmic refinement; and local ITS firms handle system integration, edge computing, and field maintenance. This arrangement ensures that the system remains technically robust, context-sensitive, and institutionally sustainable in daily operations.

6 CONCLUSION AND FUTURE WORK

6.1 Key Contributions

We demonstrate that game-theoretic subarea adjustment significantly enhances control efficacy in oversaturated networks. Stackelberg equilibrium offers the best compromise for cities like Guangzhou, balancing efficiency, adaptability, and robustness.

6.2 Limitations

Homogeneous subarea assumption ignores heterogeneity (e.g., freight vs. passenger corridors).
Subarea partitioning and signal timing are decoupled.
Limited adaptation to extreme weather.

6.3 Future Directions

Heterogeneous agent models with differentiated utility functions.
Joint optimization of subarea structure and signal timing via bilevel programming.
V2X integration for predictive subarea adjustment.
Deep learning-enhanced emergency protocols for typhoons and mega-events.

COMPETING INTERESTS

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