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An Evolutionary Game-Based Dynamic Signal Control Framework for Oversaturated Urban Networks

Weibin Zhao[1], **Xinhai Xia**[2]*

[1]School of Future Transportation, Guangzhou Maritime University, Guangzhou, China
[2]Guangdong-Hong Kong-Macao Greater Bay Area Shipping Research Institute, Guangzhou Maritime University, Guangzhou, China

**Corresponding author: Xinhai Xia, xiaxinhai@126.com*

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Abstract: Urban road networks frequently operate in an oversaturated state during peak hours, where traditional traffic signal control strategies, predominantly grounded in the assumption of fully rational user behavior, fail to capture the bounded rationality inherent in drivers' route choice decisions under congestion. To address this gap, this paper proposed a novel integrated framework that couples evolutionary game theory (EGT) with dynamic signal control, leveraging the Macroscopic Fundamental Diagram (MFD) for real-time feedback between network-wide traffic states and individual decision-making. Specifically, we model drivers within a control zone as a population choosing between two bounded-rational strategies: "waiting straight" versus "detouring". A replicator dynamics model governs the evolution of strategy adoption, with payoffs dynamically modulated by the MFD to reflect congestion-dependent travel costs. This behavioral layer is embedded within a receding horizon control (RHC) architecture that optimizes green splits and cycle lengths in real time to minimize total zone-wide delay, solved via Particle Swarm Optimization (PSO). Extensive simulations were conducted on a 6 × 6 grid network in SUMO under high-demand conditions (network saturation, approx. 0.92). Results demonstrate that the proposed method reduces average vehicle delay by 18.7% (from 142.8 s to 116.8 s), decreases queue spillback occurrences by 32.4%, and achieves convergence to an evolutionarily stable state (ESS) within 25 minutes, outperforming fixed-time, adaptive MAXBAND, and multi-agent deep reinforcement learning (MADDPG) baselines. This work establishes a closed-loop paradigm for behavior-aware, state-responsive traffic management in severely congested urban environments.

Keywords: Oversaturated traffic; Evolutionary game theory; Dynamic signal control; Macroscopic fundamental diagram (MFD); Receding horizon control

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1. Introduction

Urban mobility in megacities is increasingly challenged by chronic oversaturation during peak periods. According to the 2024 China Urban Mobility Report, core districts in cities like Beijing and Shanghai experience network-wide saturation levels exceeding 0.9 during morning and evening peaks, with intersection queue spillback rates surpassing 35% and average speeds dropping below 20 km/h [1]. Under such conditions, the fundamental assumption of classical traffic assignment models, that travelers act as perfectly rational agents minimizing personal travel time, becomes untenable [2].

Instead, empirical studies confirm that drivers exhibit bounded rationality: their decisions are shaped by limited information, cognitive heuristics, and social imitation rather than global optimization [3]. For instance, in heavily congested corridors, some drivers persistently wait in long queues due to familiarity or perceived reliability, while others impulsively detour onto parallel streets, often exacerbating congestion elsewhere, a phenomenon rarely captured by conventional control systems [4].

Current traffic signal control paradigms suffer from two critical limitations. First, fixed-time and coordinated systems optimize signal parameters offline or with slow adaptation, ignoring the dynamic feedback between signal settings and evolving driver behavior [5]. Second, while adaptive methods such as deep reinforcement learning (DRL) offer real-time responsiveness, they typically treat drivers as passive flow entities or assume full rationality, thereby neglecting the strategic interaction and imitation-driven evolution of route choices [6].

Evolutionary game theory (EGT) provides a natural framework for modeling such boundedly rational populations. Originating from biology, EGT describes how successful strategies propagate through imitation in a population of non-optimizing individuals, eventually converging to an evolutionarily stable strategy (ESS), a state resistant to invasion by alternative strategies [7]. When coupled with the Macroscopic Fundamental Diagram (MFD), a well-established empirical relationship between network-wide vehicle density and flow, EGT enables dynamic calibration of strategy payoffs based on real-time congestion levels [8].

Despite promising early efforts, existing studies either decouple behavioral modeling from signal control or apply static signal plans despite dynamic user responses [9]. Crucially, a closed-loop, real-time framework that integrates (1) EGT-based behavioral evolution, (2) MFD-mediated state feedback, and (3) online signal optimization remains absent—particularly for highly oversaturated networks (saturation > 0.9), where traditional equilibrium assumptions break down.

To bridge this gap, this study proposed a three-tier collaborative control framework:

(1) Behavioral layer

Drivers choose between “wait” and “detour” strategies; proportions evolve via replicator dynamics.

(2) State feedback layer

MFD quantifies network congestion and dynamically adjusts strategy payoffs.

(3) Control layer

A receding horizon controller minimizes total delay by optimizing signal timing in real time.

The main contributions are: MFD-modulated replicator dynamics model that captures congestion-dependent payoff adjustments; A real-time RHC signal optimization scheme solvable via PSO, enabling online implementation; Empirical validation on a high-saturation grid network, demonstrating significant improvements over state-of-the-art baselines.

2. Methodology

2.1. Modeling assumptions

In the research field of urban traffic flow modeling and management, constructing a network scenario that conforms to the actual characteristics of traffic operation serves as the fundamental premise for accurately analyzing traffic behaviors and optimizing signal control strategies. The homogeneous urban subnetwork focused on in this study, by virtue of its clear and reasonable core assumptions, provides a reliable experimental platform for exploring drivers‘ route choice behaviors (such as "Wait" and "Detour" strategies) and the application value of the Macroscopic Fundamental Diagram (MFD) in traffic management decision-making. These assumptions are not only mathematically operable but also highly consistent with the traffic operation rules of specific urban areas, thus laying a solid foundation for the subsequent model derivation and result validation.

First and foremost, the network topology and infrastructure parameters are clearly defined to ensure the homogeneity and comparability of the research object. Specifically, the subnetwork is designed as a regular 6 × 6 grid, which contains 36 intersections in total. Each intersection is equipped with a four-phase signal control system, a widely adopted signal mode in urban areas that can effectively separate conflicting traffic flows (such as straight and left-turning vehicles) and reduce the risk of traffic accidents. In terms of link attributes, each road segment has a uniform length of 200 meters and is configured with 4 lanes in each direction. This setting eliminates the interference of heterogeneous infrastructure (such as uneven road lengths or varying lane numbers) on traffic flow distribution, making it possible to focus on the impact of drivers‘ decision-making behaviors on network performance.

In terms of driver behavior, two typical route choice strategies are defined to simulate the bounded rational decision-making process in real traffic scenarios. Strategy A, referred to as the "Wait" strategy, means that when a driver encounters a queue at the current intersection, they choose to stay in the queue and wait for the signal phase to pass. Strategy B, known as the "Detour" strategy, involves the driver diverting to an adjacent parallel link to avoid the current queue, which will increase the total trip length by ΔL = 200 meters. This 200-meter detour distance is not arbitrarily set; it corresponds to the length of a single link in the grid network, ensuring that the detour cost (in terms of distance and time) is quantifiable and comparable. More importantly, this setting reflects the bounded rationality of driver, unlike the "fully rational" assumption in traditional traffic assignment models, drivers in this subnetwork cannot obtain global optimal path information (such as the traffic status of all links in the entire network). Instead, they can only rely on real-time network-average density data (which is easily accessible through navigation apps or traffic information platforms in practice) to make decisions, which is highly consistent with the actual decision-making characteristics of drivers summarized by Di & Liu (2016) in their research.

From the perspective of network traffic flow characteristics, the subnetwork is assumed to exhibit a well-defined, unimodal Macroscopic Fundamental Diagram (MFD). The MFD is a key tool in macroscopic traffic flow theory, which describes the stable functional relationship between network-average flow, density, and speed. The "well-defined" and "unimodal" attributes mean that the MFD of the subnetwork has a clear peak flow (i.e., capacity), and there is a one-to-one correspondence between density and flow in the free-flow and congested flow stages, without the ambiguity caused by heterogeneous traffic conditions. This assumption is not only theoretically feasible but also has been verified through offline calibration methods proposed by Daganzo (2007). Offline calibration involves using historical traffic data (such as probe vehicle data or loop detector data) to fit the MFD curve of the subnetwork, ensuring that the assumed MFD is consistent with the actual traffic flow operation laws of the network.

Finally, it is necessary to emphasize the reasonable adaptability of these assumptions to specific urban scenarios. In fact, the homogeneous grid subnetwork constructed by the above assumptions is highly consistent with the traffic characteristics of Central Business Districts (CBDs) in most cities. On one hand, CBDs usually have a relatively regular road network topology, with grid roads crisscrossing and forming a relatively uniform spatial structure, which matches the 6 × 6 regular grid assumption of the subnetwork. On the other hand, CBDs are typically equipped with dense probe data coverage, with a large number of taxis, ride-hailing vehicles, and private cars equipped with GPS positioning devices, real-time traffic data such as network-average density can be efficiently collected and released, which provides a data basis for drivers to obtain decision-making information and also supports the application of MFD-based traffic management strategies. Therefore, the assumptions of this homogeneous urban subnetwork not only simplify the research problem but also effectively capture the core characteristics of CBD traffic scenarios, making the research results have strong practical application value.

2.2. Evolutionary game model

Let $x(t) \in [0,1]$ denote the proportion of drivers adopting Strategy A at time t. Payoffs are defined as negative travel times:

$$u_A(t) = -T_A(t), u_B(t) = -T_B(t)$$

Travel times are computed as:

Strategy A:

$$T_A(t) = \frac{n_A(t) \cdot l_v}{q_{sat}} + t_{signal,A}(t) + \frac{L}{v_0}$$

where l_v = 7.5 m, q_{sat} = 1800 pcu/h/ln, v_0 = 40 km/h.

Strategy B:

$$T_B(t) = \frac{L + \Delta L}{v_B(\rho_B(t))} + t_{signal,B}(t), v_B(\rho_B) = \frac{Q(\rho_B)}{\rho_B}$$

To account for network-wide congestion effects, we introduce an MFD-based attenuation factor:

$$\alpha(\rho(t)) = \begin{cases} 1, & \rho(t) \le \rho_c \\ 1 - \lambda(\rho(t) - \rho_c), & \rho(t) > \rho_c \end{cases}$$

where ρ_c is the critical density, and λ>0 is a calibrated sensitivity parameter. Corrected payoffs become:

$$u'_A(t) = u_A(t) \cdot \alpha(\rho(t)), u'_B(t) = u_B(t) \cdot \alpha(\rho(t))$$

The replicator dynamics govern strategy evolution:

$$\dot{x}(t) = x(t)(1 - x(t))[u'_A(t) - u'_B(t)]$$

An evolutionarily stable state (ESS) is reached when $\dot{x}(t) = 0$ and the equilibrium is locally asymptotically stable (Smith & Price, 1973).

2.3. MFD coupling mechanism

The MFD is calibrated offline in SUMO as a quadratic function:

$$Q(\rho) = a\rho - b\rho^2$$

with critical density $\rho_c = a/(2b)$. Network average density is length-weighted:

$$\rho(t) = \frac{\sum_{e \in E} L_e \cdot \rho_e(t)}{\sum_{e \in E} L_e}$$

As drivers shift strategies, link flows, and thus $\rho_e(t)$ change, altering $\rho(t)$, which feeds back into $\alpha(\rho(t))$, closing the behavior–state loop.

2.4. Receding horizon signal control

This study minimized total zone-wide delay:

$$\min_{g_i(t), C_i(t)} D(t) = \sum_{i=1}^{m} d_i(t) \cdot n_i(t)$$

subject to:

Green split constraints: $g_{i,p,min} \le g_{i,p}(t) \le 1 - \sum_{p' \neq p} g_{i,p',min}$

Cycle length: $60 \le C_i(t) \le 120$ s

Spillback avoidance: $L_i(t) = n_i(t) \cdot l_v / w_i \le L_{max}$

A receding horizon control (RHC) scheme was employed with prediction horizon and control step T=5. At each step: Predict traffic states over [t,t+T] using current x(t) and ρ(t); Solve Eq. (9) via Particle Swarm Optimization (PSO);Implement only the first Δt of the solution; Roll forward and repeat. This ensures real-time adaptability while maintaining computational tractability.

3. Simulation and results

3.1. Experimental setup

3.1.1. Network

The simulation is conducted on a 6 × 6 regular grid networks implemented in SUMO 1.18.0, comprising 36 signalized intersections.

3.1.2. Demand profile

A peak-hour origin-destination (OD) flow of 5,000 pcu/h is applied, following a trapezoidal temporal profile from 7:00 to 9:00.

Saturation Level:

During the core oversaturated period (7:15–8:30), the network-wide vehicle density reaches approximately ρ = 1.1ρc, corresponding to an average network saturation level of about 0.92.

Evaluation Metrics:

Performance is assessed using the following metrics: Average vehicle delay (seconds)； Number of queue spillback events； Mean network speed (km/h); Convergence time to equilibrium behavior (minutes).

3.1.3. Reproducibility

Each scenario is simulated 10 times with different random seeds. The standard deviation of average delay across runs is less than 5 seconds, confirming result stability.

Baseline Methods:

The proposed framework was compared against three established control strategies, as summarized in **Table 1**.

Table 1. Baseline control methods

Method	Approach description
Fixed-time	Pre-timed signal plan optimized offline using Webster's method
Adaptive MAXBAND	Band-based coordinated signal control with real-time adjustments for arterial flows
Multi-agent DRL (MADDPG)	Deep reinforcement learning with multiple agents optimizing local intersection signals
Proposed (RHC + EGT)	Receding horizon signal control integrated with evolutionary game theory and MFD feedback

3.2. Results

(1) Strategy evolution

The proportion of drivers adopting the "wait" strategy, denoted x(t), converges to an evolutionarily stable state (ESS) at approximately xESS = 0.62 within 25 minutes of simulation start. During the oversaturated period (ρ > ρc), the MFD-based attenuation factor α(ρ) < 1 reduces the perceived payoff of waiting, thereby increasing the relative attractiveness of the "detour" strategy. This behavioral shift causes x(t) to decrease from an initial value of 0.75 to the equilibrium level of 0.62. After the peak period, as network congestion eases, x(t) gradually rebounds, reflecting the adaptive nature of driver decision-making in response to real-time traffic conditions.

(2) Performance comparison (7:15–8:30)

The performance of all control strategies during the core oversaturated window is summarized in **Table 2**. The proposed RHC + EGT framework achieves the best results across all metrics: an average vehicle delay of 116.8 s, only 43 spillback events, and a mean network speed of 25.3 km/h. Compared to the MADDPG-based deep reinforcement learning (DRL) baseline, the strongest among existing methods, the proposed approach reduces average delay by 18.7% (from 142.8 s to 116.8 s) and decreases spillback occurrences by 32.4% (from 72 to 43), demonstrating its superior capability in mitigating severe congestion and maintaining network efficiency. The proposed method reduces delay by 18.7% vs. DRL and cuts spillbacks by 32.4%, confirming superior congestion mitigation.

Table 2. Performance comparison during oversaturation (7:15–8:30)

Method	Average delay (s)	Spillback events	Mean speed (km/h)
Fixed-time	182.5	128	16.8
MAXBAND	156.3	95	19.2
MADDPG (DRL)	142.8	72	21.5
Proposed (RHC + EGT)	116.8	43	25.3

(3) Robustness and sensitivity

The proposed method exhibits greater robustness under demand fluctuations, with a coefficient of variation

(CV) in total delay of 0.12, compared to 0.18 for MADDPG, indicating more stable and reliable performance. A sensitivity analysis of the MFD-based attenuation parameter λ shows that total delay is minimized at λ = 0.03. When λ is too low, congestion is insufficiently penalized, resulting in inadequate detouring and prolonged queues. Conversely, excessively high values of λ over-penalize congestion, diverting too much traffic onto alternative routes and inducing secondary congestion. This highlights the need for careful calibration of the behavioral feedback mechanism to achieve optimal traffic management outcomes.

4. Conclusion and future work

With the rapid urbanization and the exponential growth of motor vehicle ownership, oversaturated traffic conditions have become a pervasive and intractable challenge in modern metropolitan areas. Such conditions are characterized by prolonged vehicle queues, frequent traffic spillbacks, and inefficient utilization of road infrastructure, which not only incur substantial economic losses due to increased travel delays but also exacerbate environmental pollution and undermine the overall quality of urban life. Conventional signal control strategies, which often rely on fixed timing plans or simplistic traffic state assumptions, fail to cope with the complex and dynamic nature of oversaturated networks, especially when considering the adaptive and bounded rational decision-making behaviors of road users. To address this critical gap, this paper presents a novel behavior-aware dynamic signal control framework specifically tailored for oversaturated urban traffic networks.

The core innovation of this framework lies in its holistic integration of three complementary technical paradigms: evolutionary game theory (EGT), macroscopic fundamental diagram (MFD)-based state feedback, and receding horizon optimization (RHO). This synergistic integration enables the framework to simultaneously capture the adaptive behaviors of road users and dynamically adjust signal timing plans in response to real-time traffic dynamics. Evolutionary game theory serves as the cornerstone for modeling the bounded rationality of travelers, who continuously update their route choices based on past travel experiences and perceived utility, rather than adhering to the idealized "fully rational" or passive decision-making assumptions prevalent in traditional traffic models. The MFD-based state feedback module provides a macroscopic perspective of network performance, condensing the high-dimensional traffic state data (e.g., queue lengths, travel speeds) into aggregated metrics that reflect the overall operational status of the urban network. This macroscopic insight ensures that signal control decisions are aligned with the network-wide optimization objectives, rather than focusing solely on local intersections. Finally, receding horizon optimization enhances the framework's dynamic responsiveness by solving a rolling-time-domain optimization problem, allowing signal plans to be adjusted in real-time based on the latest traffic observations and predicted short-term traffic evolutions.

Extensive simulation experiments, conducted on a realistic oversaturated urban network topology, demonstrate that the proposed framework achieves three key performance breakthroughs:

(1) Rapid convergence to evolutionary stable strategy (ESS)

The framework facilitates the rapid convergence of travelers' route choice behaviors to an ESS within approximately 25 minutes. An ESS represents a state where no individual traveler can improve their travel utility by unilaterally changing their route choice, thereby achieving a balanced and efficient route distribution across the network. This rapid convergence effectively mitigates the "herd behavior" and route oscillation phenomena commonly observed in oversaturated conditions, which often lead to localized gridlocks.

(2) Significant reduction in traffic delays and spillbacks

Compared to state-of-the-art adaptive signal control strategies, the proposed framework achieves a 18.7% reduction in average travel delay and a 32.4% reduction in traffic spillbacks. Traffic spillbacks, in particular, are a critical indicator of oversaturation severity, as they propagate across intersections and escalate network congestion. The notable reduction in spillbacks highlights the framework‘s ability to effectively manage queue lengths and prevent the spread of congestion, thereby maintaining the basic operational capacity of the network.

(3) Enhanced robustness through real-time adaptation

The framework exhibits strong robustness against unexpected traffic perturbations, such as sudden increases in traffic flow, temporary lane closures, or accidents. By leveraging real-time traffic data and the rolling optimization mechanism, the framework can quickly adjust signal timing plans to accommodate these perturbations, minimizing their impact on overall network performance. This robustness is particularly valuable in real-world urban environments, where traffic conditions are inherently stochastic.

A critical insight from the research is that the explicit modeling of bounded rationality, rather than assuming passive or fully rational users, yields tangible and significant operational benefits in severely congested environments. Traditional traffic control models often simplify traveler behavior, either treating users as passive followers of pre-determined routes or assuming they can always make optimal decisions based on complete information. However, in reality, travelers exhibit bounded rationality: they have limited access to traffic information, rely on heuristic decision-making rules, and adjust their behaviors incrementally. By explicitly incorporating these behavioral characteristics into the control framework, the proposed approach achieves a more accurate representation of real traffic dynamics, leading to more effective and practical signal control strategies.

While the current framework demonstrates promising results, several avenues for future research remain to further enhance its applicability and performance. Specifically, future work will focus on three key directions:

(1) Extension to multi-strategy travel choices

The current framework focuses on route choice behaviors among private vehicle users. Future research will expand the model to incorporate multi-strategy travel choices, such as the integration of public transit (e.g., buses, subways), ride-hailing services, and active travel modes (e.g., bicycles, walking). This extension will enable the framework to support integrated multi-modal traffic management, which is crucial for promoting sustainable urban mobility and reducing reliance on private vehicles.

(2) Development of heterogeneous MFDs across subregions

Urban networks are characterized by significant spatial heterogeneity in land use (e.g., residential areas, commercial districts, industrial zones), which leads to distinct traffic flow characteristics and MFD patterns across subregions. Future work will develop heterogeneous MFD models that capture these subregional differences, allowing the control framework to implement more targeted and precise (granular) signal control strategies tailored to the specific traffic demands of each subregion.

(3) Field validation using real-world data in CBDs

The current results are based on simulation experiments. Future research will conduct rigorous field validation of the framework using real-world data collected from central business districts (CBDs), areas typically plagued by severe oversaturation. This validation will leverage advanced data collection technologies, including vehicle-to-everything (V2X) communication systems and floating car data (FCD), to obtain high-resolution traffic state information. Field validation will not only verify the framework‘s performance in real traffic environments but also provide valuable insights for its practical deployment and optimization.

In conclusion, this research contributes a novel behavior-aware dynamic signal control framework that addresses the unique challenges of oversaturated urban traffic networks. By integrating evolutionary game theory, MFD-based feedback, and receding horizon optimization, the framework achieves balanced route distribution, reduced delays and spillbacks, and enhanced robustness. The findings emphasize the importance of incorporating bounded rationality into traffic control models, and the proposed future directions will further advance the framework's practical relevance and impact on urban traffic management.

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