Intelligent Multi Agent Systems Based Traffic Simulation for Adaptive Traffic Regulation Using Dynamic Message Signs

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***Abstract*— Traffic congestion remains a critical challenge in urban mobility, necessitating adaptive and intelligent regulation strategies. This paper presents a novel, generic framework that integrates a Multi-Agent System (MAS) layer within a traffic simulator to optimize traffic flow through simulation-driven decision-making. The proposed system allows Dynamic Message Signs (DMS) to function as autonomous agents that assess congestion levels, exchange information, and collaboratively determine rerouting strategies. Unlike conventional approaches, our framework enables agents to negotiate multiple rerouting strategies offline, test them in simulation, and store the most effective ones in a learning module. When congestion occurs in real-world conditions, the agents perform a similarity check within their learning module; if a matching scenario is found, the best prevalidated strategy is immediately applied, eliminating the need for real-time simulations. Otherwise, new rerouting strategies are generated and tested offline for future optimization. The framework ensures that only reliable and effective strategies are deployed, leading to more adaptive and data-driven traffic regulation. Preliminary simulation results demonstrate significant reductions in total waiting time, highlighting the efficiency of integrating MAS-based learning into traffic management systems.**

I. INTRODUCTION

Traffic congestion has become one of the most concerning challenges in modern transportation networks, significantly impacting urban mobility, environmental sustainability, and economic productivity. As cities continue to grow and vehicle ownership rises, the increasing demand on road infrastructure leads to prolonged travel times, higher fuel consumption, and escalated greenhouse gas emissions. Studies have shown that congestion not only affects individual commuters but also imposes substantial costs on economies due to lost productivity and excessive fuel consumption [3]. The inefficiencies caused by traffic congestion necessitate the development of intelligent, adaptive solutions to optimize road network utilization.

Traditional approaches of congestion management, such as road expansions and centralized traffic control systems, often fall short due to high implementation costs, infrastructure constraints, and the inability to dynamically adapt to real-time traffic conditions. While traffic navigation applications, such as GPS-based rerouting, provide alternative routes to drivers, they rely on internet connectivity, smartphone accessibility, and user compliance. Moreover, such solutions do not guarantee globally optimized rerouting strategies, as they typically operate at an individual driver level, potentially shifting congestion rather than resolving it.

To overcome these limitations, there is a growing interest in infrastructure-based traffic regulation using Dynamic Message Signs (DMSs), also known as Variable Message Signs (VMS), digital road panels capable of displaying real-time traffic information. Unlike smartphone-based navigation applications, DMSs provide universal accessibility to all drivers, ensuring that rerouting recommendations reach road users without requiring additional devices or internet access. However, conventional DMSs are often passive tools, relying on centralized traffic control centers for updates rather than autonomously adapting to evolving traffic conditions.

This work proposes a proof-of-concept for an open framework that leverages DMSs as intelligent, autonomous agents for decentralized traffic regulation. The framework integrates Multi-Agent Systems (MAS) and traffic simulation-based learning, enabling DMSs to dynamically assess congestion levels, communicate with neighboring agents, and make rerouting decisions that optimize overall traffic flow. Instead of relying on predefined rerouting strategies, the proposed system allows DMS agents to learn and refine their decision-making process over time, ensuring that suggested rerouting solutions are tested and validated through simulation before real-world deployment. This study is part of a broader research project investigating the exploitation of DMS for traffic congestion management. Our previous works [1], [9] focused respectively on the trust management mechanisms for cooperative ITS and the potential of DMS networks for congestion alerting. In contrast, the present paper introduces a novel architecture that empowers DMSs to act as autonomous agents capable of decentralized, simulation-driven rerouting decisions. The key innovation lies in combining MAS coordination, offline learning, and real-time decision-making within a single, adaptive framework. The key contributions of this work include:

- A MAS-based architecture where DMSs operate as intelligent agents capable of monitoring traffic conditions and making independent rerouting decisions.
- A simulation-driven learning approach, where DMS agents refine their strategies through controlled testing before applying them in real-world scenarios.
- A proof-of-concept implementation, demonstrating how integrating MAS with traffic simulation enhances adaptive traffic regulation and congestion mitigation.

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The remainder of this paper is organized as follows: Section 2 provides an overview of related work. Section 3 details the proposed framework, including the design of the MAS-based DMS, and simulation-based traffic regulation. Section 4 describes the simulation scenarios and the obtained results. Finally, section 5 concludes the paper.

II. Related Works

Traffic congestion regulation in Intelligent Transportation Systems (ITS) has been extensively studied, with approaches generally relying on infrastructure-based solutions and adaptive traffic control systems.

Wireless Sensor Networks based systems have been widely explored as a foundation for real-time traffic regulation. Yousef et al. in [5] proposed a WSN-based adaptive traffic control system, where Traffic Sensor Nodes (TSNs) collect data on vehicle count, speed, and queue lengths. This enables dynamic traffic assessment and real-time optimization of signal control, significantly reducing congestion. Similarly, Lilhore et al. in [6], introduced a Machine Learning and IoT-based Adaptive Traffic Management (ATM) system, integrating wireless sensors, accelerometers, and motion detectors for traffic monitoring and accident detection.

Adaptive traffic control systems were adapted to dynamically adjust signal timings and rerouting strategies based on real-time traffic conditions. Kapapula and Mittal proposed an adaptive traffic control system using infrared sensors, which detects vehicle density and adjusts signals accordingly in [4]. More advanced approaches integrate machine learning algorithms to predict traffic flow and optimize signal control. Moumen et al. developed an adaptive traffic light system utilizing a random forest regressor model in [7]. In addition, Deep Reinforcement Learning (DRL)-based approaches have been explored for real-time traffic optimization. In [8], Mushtaq et al. combined DRL and Smart Re-routing (SR) techniques to balance traffic load across the network.

DMSs, VMSs, are widely adopted infrastructure-based solutions, providing real-time traffic guidance to drivers. Brocken and van der Vlist examined the deployment of VMS on Amsterdam's Ring Road, demonstrating its ability to influence driver behavior by dynamically suggesting route alternatives in [2]. However, Song et al. in [10] highlighted that driver response to DMS messages varies significantly, emphasizing the importance of message clarity and strategic placement.

While infrastructure-based DMS and adaptive control systems have been widely studied, most existing approaches rely on either static rerouting mechanisms or centralized control strategies, which may not guarantee optimal traffic distribution. Furthermore, while machine learning-based adaptive systems improve efficiency, they lack cooperation with different intersection to oversee the status of neighboring areas. To the best of our knowledge, only Mushtaq et al. in [8] considered the status of adjacent routes for rerouting. However, they relied on In frastructure-to-Vehicles (I2V) communication for information transmission. This solution requires drivers to have connected vehicles, and internet access. This is not always practical, as not all drivers have access to such technology.

Most current traffic regulation solutions suffer from a key limitation: they do not guarantee that rerouting strategies will improve overall traffic conditions, as they suggest rerouting paths without evaluating their long-term impact on other road segments. This can lead to unintended consequences, such as increased congestion at alternative routes or bottlenecks at intersections.

To overcome this issue, we propose a simulation-based learning approach where DMS agents experiment with different rerouting strategies before implementing them in real-world conditions.

III. Proposed Framework

Dynamic Message Signs have traditionally been used as static traffic information displays, providing drivers with general warnings about congestion, accidents, or road conditions. However, existing DMS implementations rely heavily on centralized traffic management centers, limiting their adaptability and responsiveness to real-time traffic fluctuations. In this work, we propose a distributed, intelligent DMS framework, where each sign operates autonomously, continuously monitoring traffic flow and making informed rerouting recommendations.

As presented in figure 1, our approach integrates a Multi-Agent System layer within a traffic simulation environment, allowing DMS agents to test different rerouting strategies in a controlled setting before deploying recommendations in real-world scenarios. By training agents through simulation, we ensure that rerouting suggestions effectively alleviate congestion rather than inadvertently worsening traffic conditions at adjacent intersections or road segments.

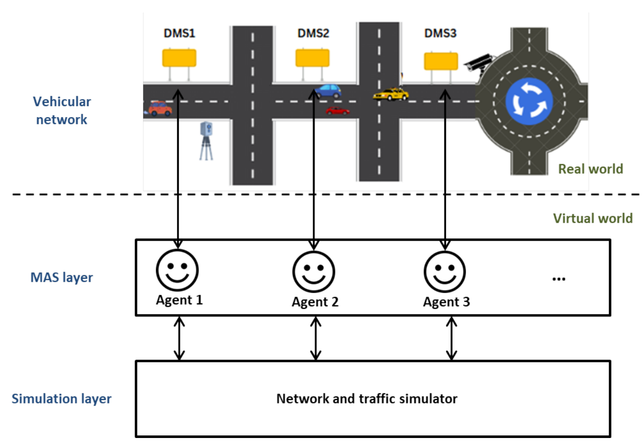

Fig. 1. Proposed framework

A. Multi-agent system based DMS

DMSs are digital panels designed to disseminate real-time traffic information and rerouting recommendations to alleviate the traffic congestion [9]. These signs leverage their autonomy and reactivity to collect and process traffic data independently, without requiring intervention from centralized traffic management systems. Equipped with internet connectivity and possess enhanced computational, communication, and storage capabilities compared to vehicles and traditional roadside units (RSUs), enabling them to dynamically adapt their displayed messages based on evolving traffic conditions [1].

In this system, each DMS operates as an individual agent capable of gathering traffic data, communicating with neighboring agents, and making decentralized rerouting recommendations. The road network is represented as a graph, where:

- Nodes correspond to DMS agents, positioned at key locations such as intersections or highway exits.
- Edges represent road segments, defining the connectivity between different DMSs.
- Neighboring DMSs are those directly connected by a road segment, enabling local collaboration in traffic regulation.

As presented in igure 2, each DMS agent has three functional modules. These modules work together to ensure efficient congestion management in a decentralized manner. In what follows, we define each module:

- **Communication module:** This module allows DMS agents to exchange information with their neighbors to build a more comprehensive understanding of network-wide traffic conditions. Each agent regularly shares its local traffic state, enabling neighboring agents to anticipate potential congestion before it propagates further. By leveraging historical data and trend analysis, agents can differentiate between normal traffic fluctuations and exceptional disruptions, such as accidents or road blockages. This collaborative communication ensures that decisions are not made in isolation but are instead informed by a broader traffic context.
  Agents work in an offline mode to test different traffic scenarios and propose rerouting strategies in the occurrence of congestion. To determine the best rerouting strategy, agents engage in a negotiation protocol, allowing them to evaluate various strategies collaboratively. Once multiple strategies are determined through negotiation, they are injected into the traffic simulation to assess its efficiency using metrics such as total waiting time of vehicles and the number of vehicles without any waiting time. The most effective strategies are then stored in the learning module for future reference, ensuring a diverse set of rerouting solutions is available for different traffic conditions.
- **Decision-Making module:** This module is responsible for evaluating potential rerouting strategies and selecting the most effective option for congestion mitigation. When a traffic congestion event occurs in real-world conditions, the DMS notifies its assigned agent. The agent then performs a similarity check within its learning module to determine whether a comparable scenario has been previously analyzed in offline mode. We can employ any similarity technique, such as cosine similarity, to estimate the distance between the scenarios parameters. If a match is found, the most effective stored rerouting strategy is immediately sent to the DMS for real-time implementation. If no similar scenario exists, indicating a completely new congestion pattern, the agents negotiate and test new rerouting strategies in the simulator. However, in this case, the agents do not send the decision to the DMS immediately; instead, they observe how the congestion evolves over time.
  The agents then compare the results of their simulated rerouting strategies against what actually happened in the real-world scenario using performance metrics such as total waiting time. if the simulated strategy would have been more efficient, it will be added to its module.
- **Learning module:** The learning module is responsible for continuously improving the agents' decision-making over time. Instead of following static rerouting rules, this module allows agents to learn from past interactions and previous simulation results. By analyzing historical congestion events and evaluating the effectiveness of multiple previously tested rerouting strategies, the agents dynamically update their knowledge base.
  When a new traffic congestion pattern occurs, the agents first check for similar stored scenarios. If a match is found, they use the previously validated rerouting strategies. If no match is found, new strategies are negotiated and tested offline, and their real-world impact is observed before making final decisions. The learning module then compares simulation results with real-world outcomes using key performance metrics such as total waiting time. Only rerouting strategies that prove more efficient than real-world congestion evolution are retained, ensuring that only the most effective and reliable strategies are stored for future use. This allows the agents to refine their decision-making over time by maintaining a repository of multiple successful rerouting scenarios, which can be leveraged in future decision-making. This ensures that only reliable and efficient rerouting solutions are used for future occurrences of similar congestion patterns, thereby enhancing the robustness of the system.

B. Simulation-based traffic regulation

Real-world traffic regulation strategies, such as dynamic traffic lights and centralized rerouting mechanisms, are often deployed without a thorough evaluation of their impact on the broader road network. In some cases, modifying traffic flow at one intersection may inadvertently create congestion at nearby intersections, worsening overall traffic conditions. Moreover, testing different rerouting strategies in a live traffic environment is not only impractical but also poses significant risks, as ineffective solutions may increase delays and disrupt urban mobility.

To address these challenges, our approach leverages traffic simulation as a controlled environment for evaluating rerout-

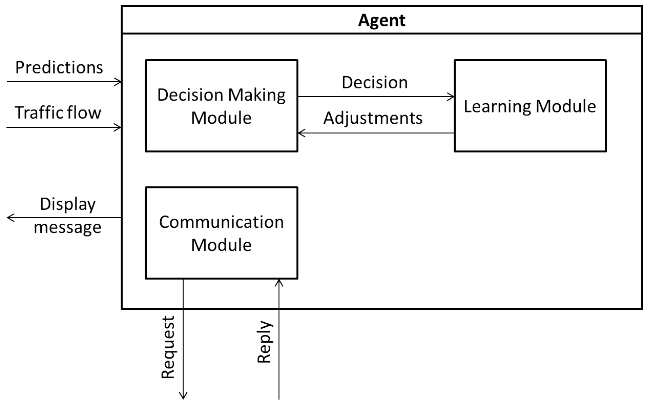

Fig. 2. DMS agent architecture

ing strategies before deploying them in real-world scenarios. Simulation enables us to test multiple scenarios, compare different rerouting strategies, and determine the most effective approach without causing real-world disruptions. This ensures that traffic regulation decisions are data-driven and optimized for overall network efficiency.

To enhance the realism and effectiveness of the simulation, we integrate a MAS layer within the traffic simulator. Each DMS is represented as an agent, capable of sensing real-time traffic conditions, exchanging information with neighboring agents, and making decentralized rerouting decisions. The MAS-enhanced simulator allows us to experiment with different rerouting strategies, oversee their effects on the entire network, and identify the most effective solutions, using metrics such total waiting time, and overall flow, before applying them in practice.

In fact, our framework introduces a two-phase rerouting strategy combining offline learning and real-time decision-making.

- **Offline Learning Phase:** Agents work offline to analyze various traffic scenarios and test different rerouting strategies. A negotiation protocol is employed to collaboratively determine the best rerouting plan. Each proposed strategy is evaluated in a simulation environment, where its efficiency is assessed based on key metrics such as total waiting time, the number of vehicles without waiting time, and congestion dispersion. The best-performing strategies are then stored in the learning module of the agents for future use.
- **Real-Time Decision Phase:** When DMSs detect a traffic congestion using their embedded sensors, each DMS notifies its agent [1]. Thus, each agent performs a similarity check within its learning module, and if a similar traffic pattern has been encountered before, the best pre-tested rerouting strategy is immediately applied. If the scenario is completely new, agents negotiate new rerouting strategies and inject them into the simulator for testing. However, agents will not notify their DMSs about their agreed strategy as there is still no guarantee that it will be efficient, but instead observes how congestion evolves over time. Agents then compare the real-world congestion outcome with the results of their offline simulations. A simulated strategy is stored for future use only if it proves more effective than real-world traffic behavior. This ensures continuous learning and adaptation.

When congestion is detected, DMS agents initiate simulations to evaluate multiple rerouting strategies. The decision-making process is iterative: agents test different rerouting alternatives, analyze their impact on traffic flow, and select the strategy that optimally reduces congestion. By integrating simulation-based learning, DMS agents are not limited to predefined rerouting rules but can dynamically adapt their decisions based on the evolving traffic conditions.

A key advantage of our approach is the ability to store and reuse successful rerouting strategies for future decision-making. Each time a traffic scenario is simulated, the resulting rerouting strategies and their effectiveness are recorded in the learning module. When a similar traffic pattern occurs in the future, the MAS can reference its stored knowledge and apply the most effective strategy based on past experiences.

If a completely new traffic scenario emerges; one that does not closely resemble any previously encountered case; the MAS initiates new simulations to explore potential solutions. This ensures that the system remains adaptive and continuously improving, as agents refine their decision-making over time by combining stored knowledge with real-time simulation-based experimentation.

IV. SIMULATION AND RESULTS

To validate our proposed framework, we conducted simulations within a real-world urban traffic network. It is important to note that we did not implement a negotiation protocol in this study, as its design is beyond the scope of this paper. Instead, we employed simpler rerouting strategies as a proof of concept to evaluate the efficiency of our MAS-based approach, focusing on the integration of MAS within the traffic regulation framework.

The performance of the MAS-based DMS framework is compared against a baseline scenario with no DMS control, where vehicles follow their predefined routes without any rerouting suggestions. In the proposed MAS-based approach, DMS agents autonomously monitor traffic conditions, communicate with neighboring agents, and dynamically adjust rerouting strategies using the learning-based decision-making module.

A. Simulation setup

The experiments are carried out using Simulation of Urban Mobility (SUMO), an open-source microscopic traffic simulator.

The simulation environment is constructed using a real-world road network extracted from OpenStreetMap (OSM), covering approximately 9 km × 4.8 km area, as presented in figure 3. The selected area is characterized by high traffic density and multiple intersections, making it an ideal testbed for evaluating the impact of adaptive rerouting strategies. The road network is preprocessed to ensure realistic connectivity, lane configurations, and traffic signal placements. The red dots indicate the locations of the DMS agents, strategically positioned along the two main highways, near key junctions where the road splits. These placements are chosen to maximize rerouting efficiency, ensuring that drivers receive timely congestion updates and alternative route suggestions before reaching critical decision points. To represent realistic traffic dynamics, we generate vehicle demand using a combination of historical traffic data and synthetic demand modeling. Vehicles are assigned departure times, routes, and speeds based on empirically observed traffic patterns. The simulation period covers peak congestion hours, ensuring that the system is tested under high-load conditions where rerouting decisions have the most significant impact. Each simulation involved 52,309 vehicles, with vehicle insertion following a structured 4-hour peak congestion period. To incorporate DMS-based decision-making, we implement a MAS layer within the SUMO simulation. Each DMS agent is positioned at strategic locations, such as intersections and highway exits, where rerouting decisions can influence overall traffic distribution. The agents operate autonomously, continuously monitoring traffic conditions and exchanging information with neighboring DMSs.

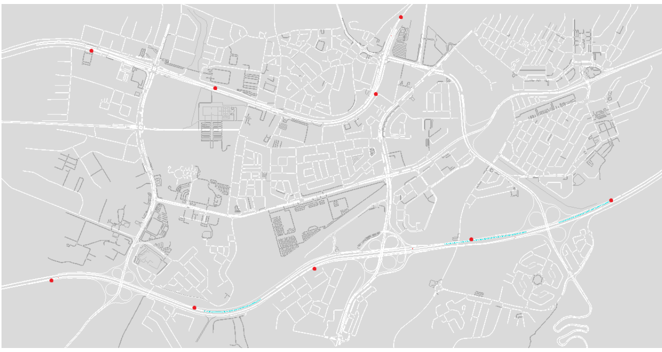

Fig. 3. Simulated area

The MAS layer is developed using JADE (Java Agent Development Environment), a widely used framework for multi-agent system simulation. The DMS agents interact with SUMO through TraCI (Traffic Control Interface), allowing them to dynamically influence vehicle routing decisions in response to detected congestion. The communication between agents follows a decentralized approach, where each DMS processes local information and coordinates rerouting decisions collaboratively.

B. Results

This section presents the results obtained from the conducted simulations, evaluating the performance of the MAS-based DMS framework in mitigating traffic congestion. The framework was tested under two different rerouting strategies:

- Full-duration rerouting: Rerouting was active for the entire congestion period.
- Half-duration rerouting: Rerouting was active only during the first half of the congestion period.

For each scenario, three different simulation runs were conducted:

- Version 1 (V1): Baseline scenario with no DMS intervention, where vehicles follow their predefined routes without any adaptive rerouting.
- Version 2 (V2): Rerouting applied to 10% of vehicles.
- Version 3 (V3): Rerouting applied to 50% of vehicles.

The effectiveness of the MAS-based DMS system was assessed through total waiting time (TWT) and average trip duration. The results showed a clear reduction in TWT, by 68% in V2 and 29% in V3. This indicates that activating rerouting for the entire congestion period significantly enhances traffic flow, reducing the time vehicles spend in near-stop conditions.

Similarly, when rerouting was limited to only half the congestion period, results showed that the TWT dropped by 72% in V2 and by 38% in V3. This confirms that even partial rerouting contributes to congestion mitigation, though to a lesser extent than full-duration rerouting.

Moreover, we observed the traffic flow improvements by observing time savings between the different simulation executions in full-duration and half-duration rerouting , respectively. For instance, the results showed positive values indicating time savings using full-duration rerouting. We also noticed a skewed distribution towards positive values, demonstrating that the majority of vehicles experienced notable reductions in waiting time, confirming the efficiency of continuous rerouting in alleviating congestion. In contrast, for the half-duration rerouting, the results showed a more dispersed distribution. While most vehicles still experienced waiting time reductions, the variation in results suggests that limiting rerouting to only half the congestion period may not provide consistent improvements across the entire network. This variation in effectiveness could be attributed to the abrupt termination of rerouting, which may have caused a resurgence of congestion in certain areas.

The obtained results confirm that the MAS-based DMS framework significantly outperforms conventional traffic regulation methods by enabling adaptive, decentralized rerouting strategies. The reduction in total waiting time and the increase in rerouting efficiency highlight the framework's ability to dynamically respond to traffic conditions and distribute congestion more effectively.

However, the results also indicate that rerouting may lead to unintended delays for some drivers, as evidenced by the increase in maximum waiting time for individual vehicles in V3. In fact, we noticed minor increase in total trip duration in V3 compared to V2, suggesting that while the framework enhances network-wide congestion management, its direct impact on individual travel times remains marginal. This highlights the importance of optimizing rerouting intensity, ensuring that traffic is distributed efficiently without unnecessarily extending travel distances.

V. CONCLUSIONS

In this paper, we proposed a proof-of-concept framework for traffic congestion regulation using Multi-Agent Systems integrated with Dynamic Message Signs. Unlike conventional centralized traffic management systems, our approach enables decentralized, adaptive decision-making, where DMS agents autonomously assess real-time traffic conditions, exchange information with neighboring agents, and apply simulation-driven rerouting strategies.

A key feature of our framework is the integration of an offline learning mechanism, allowing agents to negotiate multiple rerouting strategies in a controlled simulation environment. The most effective strategies are stored in the learning module and retrieved when similar traffic congestion patterns occur. This eliminates the need for real-time simulations in known scenarios, enabling rapid response and reducing computational overhead. When new traffic conditions arise, agents conduct offline simulations to generate new rerouting strategies, which are validated against real-world outcomes before being stored for future use.

The experimental evaluation provided preliminary results demonstrating that the MAS-based DMS framework effectively reduces total waiting time and improves overall traffic efficiency. The findings indicate that full-duration rerouting yields more stable and consistent congestion relief, while partial rerouting, though still beneficial, introduces more variability in waiting times. These results highlight the need for an optimal balance in rerouting intensity to ensure that congestion mitigation strategies remain effective without causing localized inefficiencies. Despite these promising outcomes, the current study has certain limitations. The results suggest that while full-duration rerouting achieves significant improvements, aggressive rerouting can introduce unintended inefficiencies. This emphasizes the importance of dynamic and context-aware rerouting strategies, ensuring that rerouting decisions account for broader network effects rather than focusing on localized improvements alone.

While our simulation results are promising in a dense urban area, further experimentation is needed to assess how well the approach performs across diverse environments, including rural networks, multi-level interchanges, and highways. As this work represents a proof-of-concept, current research is focusing on injecting more complex techniques within each module and extending the simulation to cover a wider range of traffic scenarios, including varying congestion levels, different network topologies, and real-world datasets.

In future works, we aim to explore the integration of reinforcement learning (RL) into the decision-making process, to further enhance the adaptability of DMS agents. Unlike our current rule-based learning module, RL would allow DMS agents to continuously optimize rerouting policies by learning from the rewards which are associated with traffic outcomes. This could improve adaptation to dynamic and previously unseen traffic patterns.

Finally, from a deployment perspective, implementing this framework in real-world conditions involves practical considerations such as sensor infrastructure, communication bandwidth, and the computational capabilities of DMS units. Although initial costs may be significant, especially for large-scale rollouts, the long-term benefits of improved traffic efficiency and reduced congestion are expected to outweigh these investments. Hybrid deployments, where MAS-based DMSs coexist with existing centralized systems, could serve as a feasible transitional solution.

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