

Research Title:

Global Traffic Management for Zero Transportation Externalities

Primary Investigator:

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1. **Background:**

The development of real-time scheduling algorithms addresses critical challenges in managing intersections effectively. Consequently, managing and scheduling traffic becomes crucial. By optimizing traffic flow, societies can increase the overall efficiency of transportation systems, reduce travel times, and improve the economy by facilitating the movement of goods and services. Additionally, it helps to ensure the safety of drivers, passengers, and pedestrians on the roads. By regulating traffic flow, societies can reduce the risk of accidents and minimize the impact of congestion on emergency services. Finally, efficient traffic management can improve air quality by reducing the time cars spend idling in traffic, thus reducing emissions.

Recent advances in Artificial Intelligence (AI) and Large Language Models (LLMs) offer promising directions for further enhancing such systems, enabling adaptive decision-making, anticipating congestion, and dynamically adjusting control strategies based on real-time traffic patterns.

Overall, this work not only enhances the efficiency of transportation management but also improves user experience by reducing travel times and promoting sustainability through minimized fuel consumption, while laying the groundwork for future AI-augmented traffic control systems.

2. **Objectives:**

(1) Define and demonstrate an academic prototype for infrastructure supporting Travel Route Scheduling with prioritized situations and/or vehicles and/or platoons. Including an academic paper. (2) Define and demonstrate an academic prototype for infrastructure supporting dynamic signs according to AI recommendations. Including an academic paper. (3) Define and demonstrate an academic prototype for a multi-agent LLM-based traffic management framework capable of globally optimizing traffic flow across a road network. Including an academic paper.

3. Tasks Achieved:

(1) Define and demonstrate an academic prototype for infrastructure supporting Travel Route Scheduling with prioritized situations and/or vehicles and/or platoons. Including an academic paper. (2) The development of this research direction is ongoing. We are collaborating with Israel Roads (NETIVEI ISRAEL) toward completing this objective and advancing the proposed framework toward practical implementation. (3) Define and demonstrate an academic prototype for a multi-agent LLM-based traffic management framework capable of globally optimizing traffic flow across a road network. The corresponding research paper is currently in preparation. We also plan to integrate and evaluate the proposed system within the Israel Roads platform.

4. Summary of Results:

- a. **Schedule emergency situations:** The main idea of this subject is to find a routing and timing for vehicles and allowing emergency vehicles to pass through the network. And prioritize them as needed. The ability to prioritize certain vehicles in the road network opens the door to further benefits, for example, prioritizing platoons, which can motivate their formation.

Thus, during each time unit, the algorithm considers the following principles: (a) minimization of travel time, (b) continuous travel, and (c) priority. It identifies the path that requires the least time to travel from the source to the destination without stopping at intersections, while maintaining the priority mode.

Related work: A detailed overview of the related work be found in [2].

Outline of the algorithm: First, we construct a scheme represented by a map of the area as a weighted and directed graph. The nodes represent intersections, the edges represent the lanes, and the weight assigned to these edges represents the transit time.

From this initial scheme, we build the conflicts graph CG as follows, each node in this graph consists of three key components: (1) A dynamic list, denoted as ML , which describes the movements at the node. Where each element within this list contains the following information: the vehicle's unique identifier ($idVehicle$), the time of arrival at the intersection (at), and the direction from which the vehicle entered the intersection ($direction$). (2) A conflict's function, denoted as $c(node)$, which identifies the nodes with which this node conflicts. (3) The duration of time required to cross the intersection, denoted as y . (4) For any vehicle v , let $v.priority$ be the priority level of v represented by an integer. (5) Let VQ be a priority queue of vehicles ordered by time of entry into the road network and prioritized by $v.priority$ for any vehicle v .

To dynamically schedule vehicles as they enter and exit the road network, we maintain two queues: one for vehicles to schedule, VQ , and another for vehicles that have already been scheduled, SQ . This allows us to reschedule vehicles as needed.

The algorithm works by removing the reserved slots of all vehicles of lower priority before scheduling a vehicle, and then inserting them to the front of the queue in the order they entered the road network. This will ensure that they will be rescheduled before we schedule the next vehicle and in their original order.

We achieve this by dividing SQ into two temporary queues, TSQ and TVQ , where TSQ contains vehicles of equal or higher priority, and TVQ contains vehicles of lower priority. We then apply the rescheduling operations to the vehicles in TVQ in the order they appear in that queue, and use TSQ as the new SQ .

b. Vehicle Platoons:

A platoon of vehicles is defined as a group of cars moving in the same direction as a selected car, called a representative vehicle, and at a distance from each other that is less than a given threshold. When dynamically managing traffic, there are known benefits in forming vehicle platoons [3], especially for autonomous driving, the vehicles in the platoon can autonomously follow the representative vehicle which may be driven by a human, thus making autonomous driving easier and safer, as the representative vehicle driving human can cause the whole platoon to stop in case of emergency. Furthermore, fuel efficiency gains can be made by platoon vehicles [4], among other benefits.

The important tasks of platoon formation and management have been extensively studied, and many different solutions have been proposed. To mention a few, in [5], for example, a formal model of vehicle platooning is presented. The strategies of platoon formation are presented in [6]; in these strategies, the vehicles are evaluated for platoon membership as they enter the road network. Various methods for platoon formation are also presented in [4,7,8,9] and many other sources.

Prioritizing platoons in the scheduling encourages vehicles to form platoons. The priority is determined by the simultaneous schedule assignment policy for all vehicles that are part of a platoon.

Such a policy yields a high priority that seems like a correct and simple solution, but this approach may create a major problem: starving other vehicles when a platoon passes through a junction. Suppose that a lengthy platoon was formed (as we hope) and that the representative vehicle in this platoon began crossing the junction, due to the prioritization of all vehicles in the platoon above the rest, they will all be scheduled instead of the other vehicles waiting to cross, therefore the platoon vehicles will be assigned adjacent spots in the junction schedule, which will cause them to pass through the junction while blocking traffic continuously. The situation is exacerbated when vehicles dynamically join the platoon before the current junction. It therefore has the potential to create an endless stream of vehicles that closes that junction to all other vehicles. For this reason, the following approach is taken.

For any given platoon, mark the representative vehicle r and assign all information about the platoon it leads (such as the number of vehicles and

destination) to it. Then, push it to the front of the queue of vehicles to be scheduled, VQ . Modify the algorithm above such that when r is passed to it, the algorithm sees that r is a platoon representative and reserves slots for the entire platoon that r leads. To accommodate this, the algorithm above that chooses the junction for the vehicle to route through must be modified to check if there are enough slots in the junction's schedule to accommodate the entire platoon. If there are, the algorithm will reserve slots for all vehicles in the platoon and remove them from VQ , leaving one slot space between each vehicle so that other vehicles can pass between the platoon vehicles. This ensures the junction is not entirely closed off. Leaving one slot between each pair of platoon vehicles is a possible solution, but the optimal number and placement of such slots within a platoon remain open questions and are a topic of further research. There are two key aspects to consider when making this decision. One is how many slots should be left as a margin between two adjacent platoon vehicles, and the other is whether to count slots occupied by non-platoon vehicles towards this margin.

- c. **Dynamic road instructions:** The main idea a comprehensive system for dynamic traffic management that optimizes traffic flow by considering real-time conditions and predicting future scenarios, leveraging dynamic digital twins and advanced agent frameworks.

The Algorithms analyze real-time traffic data to determine efficient routes for vehicles, considering factors like congestion, road closures, and accidents. This generates optimal navigation instructions, enhancing travel efficiency and minimizing congestion on busy routes.

Related work a detailed overview of the related work be found in [2].

Outline of the algorithm: Real-time data is collected from vehicles and roadside sensors. This data is then processed by digital twins using agents assigned via the A2A protocol. The agents analyze the information and suggest traffic policy updates. These updates are simulated using the SUMO simulator to predict their impact. If the results are favorable, the changes are deployed through dynamic digital signage. Policy updates include speed limits, distance gaps, and even more complex or uncommon rules, such as reserving lanes or setting directions for platoons or emergency vehicles.

The SUMO simulator models traffic flow and evaluates the algorithm's performance under varying traffic loads. The results are used to refine policies and ensure both reliability and fairness. More specific algorithms will be developed during the second year of the project, as outlined in the proposal under the designated second year objectives.

This work was presented in 7th Summit on Gender Equality in Computing.

Vision of “zero externalities”:

This work provides a technological contribution to the Smart Transportation vision of achieving Zero Externalities. While it does not explicitly mention “Zero

casualties, Zero delays, and Zero environmental harm”, there are connections to these concepts within the text.

Zero Casualties: The proposed system enhances safety through adaptive traffic policy updates powered by real-time data, agent-based decision-making, and cloud-based digital twins. By dynamically responding to road conditions, driver behavior, and unexpected events, the system helps mitigate risk across transportation modes. This supports the creation of a resilient, responsive road system that reduces fatalities and serious injuries.

Zero Delays: To improve travel efficiency and reduce gridlock, algorithms constantly analyze live traffic conditions. They take into account factors like congestion, road closures, and accidents to then suggest the quickest and most effective routes for vehicles. Improving travel efficiency contributes to the goal of zero delays.

Zero Environmental Harm: Driving at a consistent speed significantly is related to environmental impact. It saves fuel by minimizing inefficient acceleration and braking, which means fewer pollution emissions like CO₂ are released. By optimizing transportation and reducing fuel consumption, there is potential to minimize environmental harm, aligning with the goal of zero environmental harm.

While the work does not address pedestrians the global scheduling and slot reservation concepts, and challenges discussed within are related to the future implementations that achieve the objectives of zero casualties, zero delays, and zero environmental harm in the context of transportation management.

5. Conclusions:

In conclusion, this work presents an integrated approach to intelligent traffic management that prioritizes emergency vehicles, minimizes travel time, and maintains continuous traffic flow through dynamic scheduling and routing algorithms. Furthermore, a solution was presented to utilize the mechanism to accommodate and incentivize the formation of vehicle platoons.

Additionally, the research has established a framework for AI-enhanced transportation management that combines existing optimization and scheduling algorithms with hierarchical multi-agent architectures, Digital Twins, and Large Language Models. The proposed approach enables transportation systems to respond dynamically to changing traffic conditions while considering multiple objectives, including travel time, throughput, safety, priority, fairness, and sustainability. The ongoing development of Intelligent Programmable Roads and predictive lane-direction management further extends the framework toward proactive, adaptive traffic control.

6. Significance:

This work demonstrates a novel and practical solution to urban traffic congestion by integrating priority-based scheduling with real-time data processing and dynamic policy adaptation. Its ability to handle emergency scenarios while maintaining fairness and efficiency highlights its potential for real-world

deployment. By combining proven scheduling algorithms with AI-based decision-making and Digital Twins, the framework has the potential to improve traffic efficiency, enhance the management of emergencies and unexpected events, and make better use of existing road infrastructure. The planned collaboration with Israel Roads provides an opportunity to move the research from academic simulation toward practical evaluation and future real-world deployment.

7. References:

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