Real-time Dynamic Scheduling System for Smart Traffic Control in Intersections

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Abstract

Using AI to enhance the efficency of traffic flow, as well as creating self-driving automobiles has been a prospective future since a long time. Many cities have adopted AI-based systems to face the challenges caused by classical traffic systems. Smart intersections and Advanced Driver Assitance Systems (ADAS) are two of the most prominent changes in the past few years. Most of these systems require many changes in the infrastructure, including installing sensors, expensive servers and chips. We propose a Real-Time Dynamic Scheduling (RDS) system, which relies on cameras, which are seen regularly on intersections, and inter-vehicle communication, eliminating the need for servers. RDS prioritizes emergency vehicles over regular automobiles in intersections, as well as in communicating to ADAS systems to plan accoridingly. We use density-based scheduling for intersections, which allocates green-light time based on the amount of traffic on each road. Additionally, it proposes a solution for emergency vehicles arriving at intersections, both from a safety viewpoint, and an efficiency viewpoint.

Keywords: smart city, ADAS, scheduling, computer vision, connected vehicles

Figure 1 - Image of an Intersection with emergency vehicle approaching

Introduction

Enhancing the efficiency of intersections using Artificial Intelligence (AI) has become an important point of modern urban development, with many cities around the world adopting AI-based systems to address the limitations of traditional traffic management methods. Classical traffic systems, which often rely on fixed timers and manual oversight, struggle to adapt to the dynamic and complex nature of modern traffic conditions. This inadequacy leads to congestion, inefficiency, and increased risks of accidents, particularly in high-traffic areas. By leveraging AI, cities can create smarter, more adaptive intersections that optimize traffic flow, reduce delays, and improve overall safety.

While AI-driven traffic management systems have already demonstrated significant improvements, their performance can be enhanced further by addressing specific, yet critical, scenarios that have a profound impact on traffic efficiency and safety. One such scenario is the arrival of emergency vehicles (EVs) at intersections. In these situations, the intersection must not only prioritize the passage of the EV but also ensure that this prioritization does not lead to conflicts or crashes with other vehicles. This requires a scheduling system capable of dynamically adjusting traffic signals and coordinating with nearby vehicles to create a safe and efficient passage for the EV.

We propose a scheduling system to address this challenge. It manages the transition of traffic signals smoothly, and reduces the possibility of crashes at each intersection. This system uses data from cameras, sensors, and inter-vehicle communication to calculate the optimal timing for signal changes, ensuring that the EV can pass through the intersection without disrupting the flow of traffic or compromising safety. Furthermore, the system communicates these changes to other intersections along the EV’s route, enabling them to plan accordingly and host the EV when it arrives. This coordinated approach ensures that the EV encounters green lights throughout its journey, effectively reducing its waiting time to zero [1, 3]. By minimizing delays for emergency vehicles, this system not only improves response times but also enhances public safety and trust in emergency services.

In addition to the global scheduling system for intersections, we introduce a scheduling policy for real-time Advanced Driver Assistance Systems (ADAS) tasks. ADAS plays a critical role in modern vehicles by providing features such as collision avoidance, lane-keeping assistance, and adaptive cruise control. However, these systems rely on real-time processing of data, and any delays or missed deadlines in task execution can compromise their effectiveness. Our proposed scheduling policy is designed to optimize the allocation of computational resources for ADAS tasks, reducing waiting times and minimizing the likelihood of deadline misses. This ensures that ADAS systems can operate reliably and efficiently, even in high-demand scenarios.

Methods

1. Intersection

Intersections are typically equipped with cameras for security purposes, such as monitoring traffic violations and automating the issuance of fines. These cameras, which are already a ubiquitous feature of modern urban infrastructure, can be leveraged for more advanced applications beyond their traditional roles. By utilizing the existing camera infrastructure, we can detect the arrival of emergency vehicles (EVs) at intersections and gather critical traffic information, such as the number of vehicles on each road. This data can be used to optimize traffic management and enhance the efficiency of intersections.

To quantify traffic conditions, we introduce a normalized traffic quotient for each road. This metric provides a standardized measure of traffic density, enabling the system to make informed decisions about signal timing and prioritization. The normalized traffic quotient for road *i* is calculated as follows:

$$Q_i = \frac{\sum cars(i)}{\sum cars} \tag{1}$$

Where $\sum cars$ denotes the number cars on all roads, and $\sum cars\ (i)$ is the number of cars on road *i*. This equation represents the porportion of vehicles on a specific road relative to the total number of vehicles at the intersection. By normalizing the count of vehicles, we can compare traffic conditions across different roads in a consistent and meaningful way. For example, if Road A has 10 vehicles and Road B has 20 vehicles at an intersection with a total of 50 vehicles, the normalized traffic quotients for Road A and Road B would be 0.2 and 0.4, respectively. This information can then be used to allocate green-light time proportionally, ensuring that roads with higher traffic density receive longer signal phases. The time each road recieves is shown in (2).

$$t_i = Q_i * T \tag{2}$$

Where t_i is the time each road gets, which is proportional to its traffic quotient. The use of cameras for traffic detection offers several advantages. First, it eliminates the need for additional sensors or infrastructure, reducing implementation costs and complexity. Second, cameras provide rich visual data that can be processed using computer vision algorithms to detect not only the presence of vehicles but also specific types of vehicles, such as emergency vehicles. For instance, by analyzing the visual characteristics of an approaching vehicle (e.g., flashing lights, sirens, or specific markings), the system can identify it as an EV and trigger the appropriate prioritization protocols. Alternatively, V2I [3] can be used to identify the EV.

When an EV is detected, the system can dynamically adjust traffic signals to grant the EV right-of-way while ensuring the safety of other vehicles. This involves calculating the EV's estimated arrival time based on its speed and distance from the intersection, and then preemptively switching the signal to green a few seconds before the EV arrives. This approach minimizes delays for the EV while maintaining smooth traffic flow for other vehicles.

In addition to detecting EVs, the cameras can continuously monitor traffic conditions in real time, providing valuable data for optimizing signal timing and reducing congestion. By integrating this information with the normalized traffic quotient, the system can adapt to changing traffic patterns and ensure efficient operation under varying conditions.

In summary, the use of existing intersection cameras for traffic detection and analysis represents a cost-effective and efficient approach to enhancing traffic management. By quantifying traffic conditions using the normalized traffic quotient and leveraging computer vision algorithms to detect EVs, we can create a more responsive intersection control system that prioritizes safety and efficiency.

To further optimize traffic signal management, we propose a dynamic approach to adjusting the signal period based on the total number of vehicles present at the intersection. This adaptive strategy ensures that signal timing is responsive to real-time traffic conditions, enhancing both efficiency and flow. When the number of vehicles is high, the system allocates a larger portion of time to accommodate the increased traffic demand. Conversely, when the number of vehicles is low, the system reduces the total time allocated to all roads, minimizing idle periods and improving overall intersection efficiency.

The signal period T is calculated dynamically using a simple yet effective linear model, which takes into account the total number of vehicles at the intersection. This model is defined in (3).

$$T = \alpha * \sum cars \tag{3}$$

Where α is a constant that estimates the time it takes a vehicle to cross the intersection at a given speed. This linear model provides a sufficiently accurate estimate for determining the next signal period, ensuring that the system adapts seamlessly to varying traffic conditions. The constant α can be fine-tuned based on factors such as average vehicle speed, intersection size, and traffic patterns, allowing for further optimization. n addition to dynamic signal period adjustment, the proposed Real-Time Dynamic Scheduling (RDS) system incorporates preemption to further reduce waiting times. Preemption involves switching the signal for roads with no remaining vehicles to red, thereby prioritizing lanes with active traffic. This ensures that time is not wasted on empty roads, allowing the system to focus on roads with vehicles waiting to pass. By dynamically reallocating time based on real-time traffic data, the RDS system significantly enhances intersection efficiency and reduces delays for all road users.

2. Single EV

When an emergency vehicle (EV) announces its arrival to the intersection communicator using Vehicle-to-everything communication (V2X) [3] protocols, it transmits its current speed and location. This data enables the system to calculate the EV's estimated arrival time. To ensure smooth passage, the system applies a padding mechanism, turning the signal green a few seconds before the EV arrives. This allows traffic on the EV's lane to start flowing, clearing the path for the emergency vehicle [4]. Furthermore, the arrival of the EV is communicated to other intersections along its specified route. By sharing the EV's speed and location, these intersections can dynamically schedule their signal phases to ensure the EV encounters a green light upon arrival. This coordinated approach minimizes delays and optimizes the EV's travel time through the network of smart intersections. The arrival time of the EV at each intersection can be calcluated using (4).

$$\Delta t = \frac{\Delta d}{v} \tag{4}$$

Where Δt is the remaining time until the EV arrives, Δd is the distnace remaining, and v is the velocity of the vehicle. The result of this coordination is that the EV will traverse the intersections as if it was traveling on a straight road, with no intersections.

3. Multiple EVs

When multiple emergency vehicles (EVs) arrive at the same intersection simultaneously, effective scheduling techniques are essential to ensure smooth traffic flow and minimize waiting times for each EV. To address this challenge, we evaluate and compare several classical scheduling algorithms, including Earliest Deadline First (EDF), Least Laxity First (LLF), Round Robin, Priority Scheduling, and Maximum Urgency First (MUF) [5, 2, 6]. Among these, EDF demonstrates notable performance, achieving a low miss rate and optimal execution efficiency [2]. EDF schedules arriving EVs based on their relative deadlines, meaning the EV that arrives first is given the highest priority.

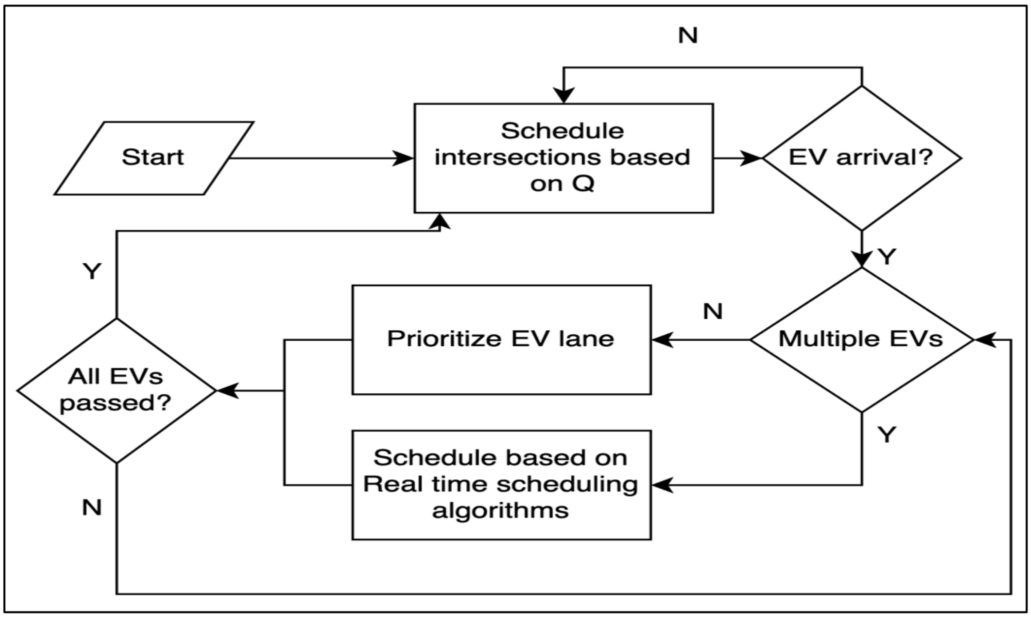

Figure 2 - Flowchart of the RDS

This approach ensures that all tasks (i.e., EV passages) meet their deadlines, making it a highly effective scheduling strategy for time-critical scenarios.

However, while EDF performs optimally in meeting deadlines, there is still room for improvement by considering the permissible waiting time of different EVs. This can be achieved by incorporating the concept of laxity, also referred to as "slack time" in other literature [6]. Laxity represents the amount of time an EV can afford to wait before its deadline is missed. By prioritizing EVs with lower laxity (i.e., those with less slack time), the system can ensure that EVs with tighter deadlines are serviced first, while those with more flexibility are placed in a lower priority tier. This refinement enhances the overall efficiency and fairness of the scheduling process.

Another algorithm, Least Laxity First (LLF), also demonstrates well-rounded performance, effectively balancing the prioritization of critical tasks and the meeting of deadlines [2]. However, LLF faces challenges in distinguishing between hight and low-priority tasks, which can lead to inefficiencies in systems where task priority varies. In our system, this limitation is not a significant concern, as all tasks (i.e., EV passages) hold a similar level of priority. This makes LLF a viable alternative to EDF, particularly in scenarios where minimizing laxity is important.

In summary, while EDF offers optimal performance for scheduling multiple EVs at intersections, incorporating the concept of laxity can further enhance its efficiency. LLF also proves to be a robust alternative, particularly in systems where all tasks share a similar level of urgency. By carefully selecting and adapting these scheduling algorithms, we can ensure minimal waiting times for EVs while maintaining smooth and efficient traffic flow at intersections.Figure 1 shows an overview of the RDS.

In figure 1, the flow of the process in RDS is shown. The system schedules the intersection based on the traffic quotient until an EV arrives, at which point it will shift to EV mode, and schedule the roads based on the EVs that are arriving. The scheduling of multiple EVs is done using either EDF or LLF, both of which perform well for this type of tasks. We simulated the scheduling of intersections based on traffic [1], which yielded positive results, improving the performance when compared to static traffic scheduling. The simulation also incorporated single-EV arrivals, prioritizing it over other lanes, switching the signal in a safe manner, keeping the vehicles inside the intersectoin in mind. A good methodology is to use vehicle-to-vehicle (V2V) communication to inform vehicles ahead of the arrival of the EV. This can help clear the way by ADAS systems, as well as drivers acting as good samaritans. This method is not practical with the technology available in most cars today, but it is only a matter of time before basic V2V communication is implemented in all cars.

Conclusions

The integration of Artificial Intelligence (AI) and advanced scheduling algorithms into traffic management systems represents a significant step forward in addressing the challenges of modern urban intersections. By leveraging existing infrastructure, such as cameras, and employing real-time data analysis, we have proposed a Real-Time Dynamic Scheduling (RDS) system that optimizes traffic flow, prioritizes emergency vehicles (EVs), and enhances overall intersection efficiency. The use of density-based scheduling ensures that traffic signals adapt dynamically to real-time conditions, while the incorporation of preemption and laxity-based prioritization minimizes waiting times for EVs and reduces the risk of collisions. Through the evaluation of classical scheduling algorithms such as Earliest Deadline First (EDF) and Least Laxity First (LLF), we have demonstrated that EDF offers optimal performance for meeting deadlines, while LLF provides a balanced approach for managing tasks with varying slack times. By refining these algorithms to account for permissible waiting times and task criticality, we can further improve the efficiency and fairness of the scheduling process. The proposed system not only addresses the immediate need for efficient EV prioritization but also lays the groundwork for future advancements in smart traffic management. By reducing delays, improving safety, and minimizing infrastructure costs, it offers a scalable and cost-effective solution for cities seeking to modernize their transportation networks. As AI and connected vehicle technologies continue to evolve, systems like RDS will play a crucial role in creating smarter, safer, and more efficient urban environments.

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