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Traffic Management Systems: A Comprehensive Literature Review

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Abstract: ***The traffic systems used are fixed timing signals, which are programmed and can't adjust to changes in traffic, and loop inductive systems, which have been criticized for their limited foresight. Inefficient, traditional traffic management systems lead to traffic congestion, which further leads to economic losses, fuel wastage, and worsens air quality. This review looks at intelligent traffic management solutions through the integration of Artificial Intelligence and the role of IoT in better deployment of AI in urban settings. The review also particularly looks at how IoT systems through a variety of sensors and other infrastructure. This review also looks at an AI model-SURTRAC- that shows real world potential and reduction in waiting times. This review calls for the need for AI implementation into traffic systems and tries to point out research gaps that need to be addressed.***

Keywords: Traffic Management Systems, Traffic Control, Fixed-Timing Systems, Inductive-Loop Systems, Artificial Intelligence (AI), Traffic Prediction, Traffic Optimization, Reinforcement Learning, Computer Vision, IoT-Based Systems, Traffic Monitoring, SURTRAC, Traffic Congestion, Emissions, Urban Mobility, Sustainability.

1. Introduction

With more people moving into cities throughout the world, it has placed a record-high strain on existing transportation infrastructure with increased traffic congestion, longer travel times, increased fuel consumption by vehicles, and a surge in the emission of greenhouse gases globally. Fixed traffic light schedules, which majorly rely on static, are preprogrammed signal timing cycles or basic inductive loop detection mechanisms. They inherently lack the ability to adapt and real-time responsiveness. This ability is necessary to effectively manage dynamic and unpredictable traffic conditions of most cities today. This fundamental problem impacts the day to day lives of commuters and leads to frustration and lost productivity, costing an economy billions of dollars. Traffic congestion is speculated to cost around 1.5 lakh crore rupees a year to the four major cities of India- Mumbai, Kolkata, Delhi, and Bengaluru [1]. It also hinders the delivery of life-saving emergency services, such as an ambulance, which should be delivered within an urgent timeframe.

2. Methodology

In order to locate sources, I began with general searches on sites like Google Scholar. I made broad searches using terms like "Traffic Management Systems," "Traffic Control," and "AI in Traffic" to simply get a sense of what studies were out there. This assisted me in locating primary research papers that had been commented upon by other experts. Based on these initial results, I created more focused keywords such as "Fixed-Timing Systems" or "Reinforcement Learning Traffic Optimization" to search on more specialist academic databases. Furthermore, employed a tactic known as "Snowballing". In this technique I scanned the references of good articles to discover further useful research. All keywords were selected because they align with the aim of this review.

I chose sources for their relevance to understanding traffic control, its problems, and new solutions like AI and IoT. Every source had to directly support the purpose of this review and answer the research questions. Only original research papers were included, and any work based on other people's research was removed. All sources also had to come from academic journals that were peer-reviewed. I also made sure the journals were typical for their field and looked for the most recent articles, generally not going back further than 2007, as this is a newer field.

When I examined the information in the articles, I looked for evidence that proper research methods were followed. For studies with numbers (quantitative data), I checked for large and diverse groups of participants. I also made sure the data collection directly addressed my research questions and was presented clearly. For studies with descriptions (qualitative data), I reviewed how the information was collected and the details about the participants to ensure the research was trustworthy and accurate.

3. Results and Discussions

3.1 Fixed-Timing Systems

Fixed timing traffic signals are found all over the world today, being the most commonly used type of traffic signal in today's world. They make the use of preset timings to determine when to signal the drivers and control the flow of traffic. These systems are rudimental, simple, and low maintenance and can be easily installed. However, fixed timing traffic signals cannot adapt to real time changing flow of traffic. Traffic conditions are ever changing; fixed timing signals simply cannot match the real flow of traffic [2]. Additionally, the lack of resonance of the timings and traffic conditions creates major bottlenecks and inefficiencies in the flow of traffic. For instance, cars may wait at red lights when there are no vehicles crossing or green lights may stay on even when all of the vehicles have cleared. As a result, these systems prove to be inefficient by preventing roads from being completely utilized.[3]

3.2 Inductive-Loop Systems

Inductive-loop systems are considered superior to fixed timing traffic signals as they can be adapted based on vehicle presence. Inductive based loop systems make the use of loop wires embedded in the road that detect vehicles as they pass over them. Detection of vehicles helps in changing timing changes appropriately, making these systems much more responsive than fixed time systems [4]. However, this system also does have its drawbacks. These systems have limited foresight and aren't able to forecast traffic flow. Due to this lack of foresight these systems can't engage and adapt to the entire roadmap of a city and its traffic flow: disabling it to interact with nearby intersections and making it harder to prevent traffic jams.[5]

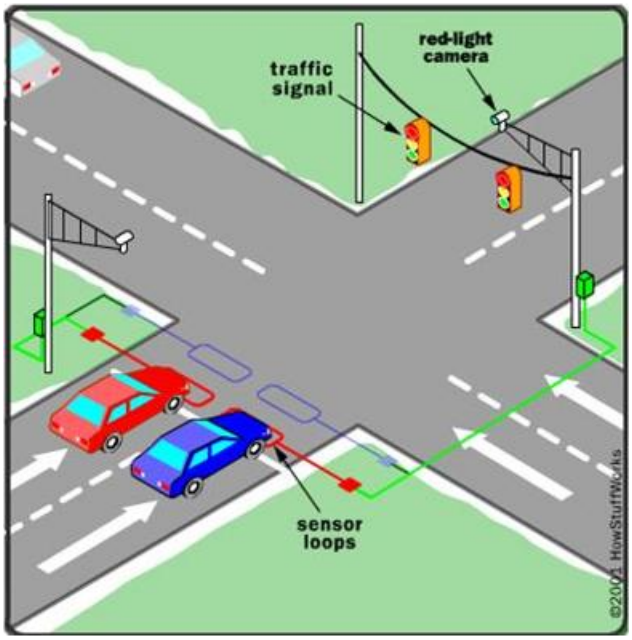

Figure 1: Inductive loop systems [4]

3.3 Challenges of Current Systems

Many cities continue to heavily depend on older traffic systems (inductive-loop and fixed timing signals) causing a plethora of issues, mostly connected to urban mobility and sustainability.

One of the most prominent challenges of traffic jams is delays. At its core, the problem stems from the incapability of our current systems to adapt and adjust to traffic in real time. Its inability to respond and adapt makes congestion, specifically during peak hours. Consequently, commuters lose out on time which could have been better spent elsewhere. Long travelling also leads to loss of productivity and quality of life. Delays can reduce work output and cause stress. Furthermore, our current system's unreactive nature causes them to simply respond rudimentarily rather than proactively adapting and attempting to anticipate traffic to prevent congestion in the near future, weakening their ability to manage complex traffic scenarios.

The inefficiencies of our current traffic systems lead to higher time spent on vehicles on the road, requiring higher fuel consumption. Cars are often left idle on the road. Additionally, constant stopping and starting causes even more extra fuel to be consumed as engines need more energy to reach a certain speed. Higher fuel consumption directly corresponds to the release of harmful emissions such as: CO, NOx, and various hydrocarbons. This worsens urban air quality and harms the environment. It acts counterproductive against cities' efforts to make it more sustainable and eco-friendly.[6]

Traffic congestion and Traffic flow bottlenecks incur huge economic costs as well, rooting from the limitations of our current traffic systems. Time wasted by commuters on travelling acts as an opportunity cost, wherein the time could be better spent on work or other activities. Long travelling hours also catalyze burnout in commuters and make them experience fatigue. Additionally, firms are also to bear higher costs of excess fuel consumption, longer travelling times incurring labour costs, and delayed deliveries. Delays in deliveries particularly disrupt supply chains and adversely affect consumer satisfaction. [7]

Finally, the slow movement of emergency vehicles poses critical concerns as it is a major safety issue. Traditional methods of prioritizing vehicles include the sirens and manual priority by traffic operators and traffic police departments. These may not be as effective as manual overrides require too many resources and sirens may not be reliable in every scenario. These methods lack smart and predictive capabilities. The result is that critical help can arrive late, which can be life-threatening.[8]

4. AI & Machine Learning in Traffic Management

With the limitations and drawbacks of traditional traffic management, researchers and city planners are exploring more enhanced solutions such as Artificial Intelligence (AI) and Machine Learning (ML), which offer advantages over older traffic systems.

4.1 AI for Traffic Prediction and Optimization

AI has the ability to handle large, complex datasets, can analyze complex patterns that can't easily be sighted by humans, and give meaningful insights. AI could possibly be trained on historical data fed to its about a particular location or area, additionally integrate real time data as well, collected via the combination to multiple sensors, GPS, and IoT systems[9]. The training of the AI model will allow it to manipulate the traffic flow through signals and allow real time signal optimization, making continuous changes to signal timings to clear routes and possibly interacting with multiple intersections at once to minimize delays and prevent congestion. The model can also intervene earlier.[10]

4.2 Reinforcement Learning for Adaptability

Machine Learning can be used as a smart solution to control traffic, specifically Reinforcement Learning (a specific Machine learning technique) acts as a method for real time

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signal management. Reinforcement learning can work by a model interacting with a traffic system, possibly simulated, and receiving negative or positive feedback based on its choices and actions. This allows an AI to make optimal traffic control decisions with continual improvement over time based on one primary goal: minimizing traffic delays. [11]

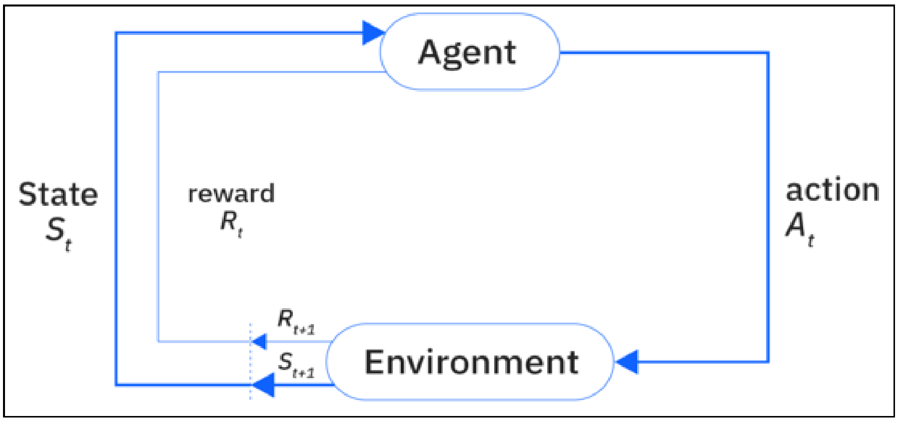

Figure 2: RL training process [12]

4.3 Computer Vision for Object Detection

Computer vision could help the model utilize Reinforcement Learning to its maximum capability by using real-time video streams at intersections. The computer vision could detect and classify many objects on the road, using YOLO algorithms, such as vehicle types-cars, trucks, and buses- or even pedestrians and cyclists. This is often superior to traditional sensors since it offers a 3- dimensional perspective and can consider multiple variables such as- speed, vehicle type, no of vehicles etc, allowing for more detailed datasets. [13]

4.4 Examples of AI in Traffic Management

Benefits of AI traffic management systems has over time become increasingly evident, causing an increase in adoption of such systems globally. Singapore has been one of the leaders in the adoption of AI management systems since it is essential to its densely populated urban areas. Singapore's CRUISE project predicts congestion hotspots and notifies the authorities about it, upon which action is taken [14]. Los Angeles, too, has integrated adaptive AI based signals and smartly acts to change traffic conditions [15]. Barcelona uses IoT-based systems that provide the city with large datasets that are processed by AI algorithms. The implementation of such systems has led to a 15-25% reduction in average waiting times.[16]

5. IoT-Based Traffic Management Systems

While AI algorithms may optimize traffic control, they heavily rely on IoT systems to interact with the real world. IoT acts as the backbone of smart traffic management solutions as they enable real- time data collection. IoT systems create an ecosystem of various sensors, cameras, and other input devices to collect traffic data continuously.[17]

5.1 Role of IoT in Data Acquisition

IoT systems make use of various sensors to monitor traffic flow using multiple parameters. They make use of low-cost microprocessors, similar to Raspberry Pi, and attach them to different sensors to collect readings on road capacity, vehicle speed and roach occupancy. Additionally, the development of specialized sensors and special hardware specifically for intelligent traffic management systems create scope for a more accurate and diverse datasets.

5.2 IoT Sensors for Traffic Monitoring

IoT and sensors are very important in the context of traffic monitoring since sensors give data on various different parameters. Such data would be needed in order to train the AI models and in the future training.

Any number of IoT sensors can be placed to measure parameters of traffic movement. This can either be accomplished by low-cost microprocessors or computers, when fitted with suitable sensor modules can be made to gather information on traffic flow, speed of vehicles, and occupation of the road. There may also be creation of tailored solutions, like specially built sensors that are tailored for monitoring traffic. Special hardware can deliver even more detailed and precise data, such as vehicle type, axle load, and environmental factors like temperature and air quality. It is possible for governments and companies to create their own sensors if they wish to utilize the capabilities fully and discover more kinds of data, making diversity of data variables possible and enabling maximum utilization of special hardware.[18]

5.3 Adaption and Real-Time Adjustments

The real-time data constantly supplied by the network of IoT devices is the critical input for advanced AI algorithms, which can then process this data and make highly educated decisions about the dynamic adjustment of traffic signal timing [19]. The IoT-based system deployed at Barcelona is a case in point for this collaboration. In this system, signals can adjust virtually in real time to changes in actual traffic volume picked up by IoT sensors placed around the city. The network's responsiveness makes it possible to manage the traffic flow much more fluidly and efficiently that directly leads to the drastic waiting time reductions witnessed in the city.[20]

6. Case Study: SURTRAC

SURTRAC is an AI model developed by The Robotics Institute at Carnegie Mellon university. SURTRAC is an adaptive AI designed to control urban traffic and reduce emissions, fuel wastage, and traffic congestion in a city. SURTRAC approaches this problem through a decentralized method, where SURTRAC employs a multiagent paradigm and makes every intersection an intelligent entity. Its primary purpose is to optimize the flow of traffic in an urban grid-like network of routes. This distinguishes itself by using independent, local decision makers that communicate with its neighbour agents at different intersections, allowing this system to be highly scalable.

SURTRAC's , at its core, operates through a "schedule-driven process". Each intersection's AI agent has a "scheduler" service that constantly receives information from multiple sensors at the intersection, indicating its occupancy, and also receives information from other intersections about incoming traffic. This allows the agent the function dynamically and allocate green signal timings, approaching the problem of congestion as a single machine scheduling problem. Future schedules are recomputed frequently, from 1 second to 0.1 second.

SURTRAC's architecture consists of multiple systems coordinating with each other. This includes: Communicator, Detector, Executor, and Scheduler services, sensor integration (e.g.-Traficon video detection), and control execution via interfaces with traffic signal controllers (e.g., 170 controllers running Wapiti firmware). The Executor oversees the controller when it's running in free mode, fine-tuning the phase settings and handling failures by using default time durations and moving average forecasts.

SURTRAC's effectiveness was proven in a nine-intersection East Liberty, Pittsburgh pilot (triangular grid, 382 ft avg. intersection distance). Compared to existing coordinated-actuated/free mode plans across 12 high-volume routes over four daily periods, SURTRAC achieved substantial improvements.Overall the travel times dropped by more than 25%, average speeds went up by 34%, stops decreased by over 31%, and wait times were cut by more than 40%. Emissions also fell by 21%. Mid-day saw largest gains (11 of 12 routes improved); rush/evening periods showed 8 of 12 routes improved. This means about 247 gallons of fuel and 2.25 metric tonnes of emissions are saved every day and add up to roughly 588 metric tonnes of emissions that are avoided each year. It really shows how much potential SURTRAC has to make a big difference.[21]

7. Conclusion

This review explores the limitations of traditional traffic systems-fixed-timing and inductive-loop traffic systems-and their inability to adapt to real-time conditions and manage congestion. While AI, machine learning, and IoT , show progress through their predictive capabilities, real-time optimization, and enhanced data acquisition, there are many research gaps such as- limited foresight of AI models and ethical concerns integration of AI may bring.

Future research, due to currently limited knowledge, should focus on and address:

a) The need for standardized evaluation metrics for AI-driven systems- studies in the future need to develop a standard method for evaluating AI models to allow continuous measurement of the effects and performance of different models.
b) (b)The scalability of decentralized approaches- Research must cover scalability issues with decentralized systems, like SURTRAC, especially when deployed over larger, more complex urban settings
c) (c)Diverse and specialized IoT sensors- there is a need to develop sensors for increased real time data capture, allowing models to be trained better.

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