Analyzing the Impact of AI-Driven Traffic Signal Control on Reducing Congestion and Improving Road Safety

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Abstract

A considerable proportion of road traffic congestion is generated by the inefficient control of traffic signals at road intersections. We propose an artificial intelligence-driven, adaptive traffic signal control approach to reduce traffic congestion, as well as improve road safety by accommodating the unsignalized movement of vulnerable road users. Specifically, we adopt a curriculum learning mechanism, in which the overall AI-driven traffic signal control problem is separated into multiple sub-optimized problems dealing with different scenarios trapped in the training data, and the learned results are gradually sampled and added to the training data for global problem optimization. We evaluate our work through large-scale simulations, and the results demonstrate the clear and consistent improvement of AI-driven traffic signal control in reducing congestion, where the longer the traffic volume peak, the more significant this improvement can be observed. More interestingly, our approach dramatically reduces road conflicts between traffic participants across different intersection scenarios and hence improves road safety as well.

Keywords: *AI-driven traffic signal control, adaptive traffic management, road traffic congestion reduction, intelligent traffic systems, road safety improvement, curriculum learning in traffic control, sub-optimization in traffic scenarios, vulnerable road user safety, unsignalized movement accommodation, global problem optimization, traffic volume peak management, intersection safety enhancement, large-scale traffic simulation, dynamic traffic signal timing, conflict reduction in intersections, real-time traffic data utilization, machine learning in traffic control, traffic participant coordination, scalable traffic optimization, AI-powered road safety.*

I. INTRODUCTION

As traffic congestion arises as one of the most pressing urban challenges, transportation agencies are seeking technology-based solutions to manage and optimize city streets. City traffic management and mobility often require quick, effective, and efficient traffic signal control. In recent years, research efforts have been largely devoted to designing advanced traffic signal control systems. Traffic signal control defined at an intersection level, also known as cycle-based traffic signal control, is the most widely used method in the world. More than 85% of urban traffic junctions are regulated by pre-timed or actuated signal control systems. However, cycle-based traffic signal control systems can only operate independently and locally, which inevitably leads to stop-and-go movements and increased travel times.

Conversely, optimization-related research that incorporates a networked approach to signal control has been relatively underdeveloped. Real-time traffic congestion and mobility problems are often treated at a macroscopic level without regard to the influence of personalized navigation. Thus, traffic signal control is inherently insufficient due to its inadequacy in synchronizing platoon movements through neighboring traffic signals. Moreover, the necessity for ecology and sustainable urbanism increases the importance of traffic control in reducing emissions. Although traffic control systems have been integrated with emission estimation models, the performance of cycle-based traffic signal control remains unsatisfactory since it cannot place spatial constraints on certain problematic roads for emission reduction.

Fig 1 AI used to Solve Traffic Management

➢ *Background and Rationale*

With the rapid urbanization now occurring throughout the world, traffic congestion has become a concern worldwide. Especially since the 1960s, urban-specific population, and private car volume have increased, and the construction of basic urban facilities such as public transportation, which can cope with the increased transportation needs, has not kept pace with the rise in transportation requirements. Many areas have encountered extreme traffic congestion, with the number of vehicles on the road far exceeding the capacity of a region's road network. For several reasons, it has been found that many planned traffic improvement projects did not achieve the desired goals. For example, the shortage of supervisors makes the traffic signal network difficult to operate properly, which has also caused a decrease in local capacity. Additionally, some adaptive signal control systems provide very limited reductions in queue lengths and travel time, which did not result in appreciable benefits. Especially in developing countries, with economic growth and urbanization acceleration, people traveling on the roads have become the biggest obstacle to human social life. These problems have caused heavy losses in economic and social life. Therefore, it is urgent to develop a practical system that can adapt to a variety of traffic conditions within a reasonable budget to reduce traffic congestion and improve road transportation safety.

Equation 1 : Traffic Flow Rate at an Intersection:

$$Q = \frac{N}{T}$$

Q: Traffic flow rate (vehicles per unit time)

N: Number of vehicles passing through the intersection

T: Total time period

➢ *Research Aim and Objectives*

- *Title: 1.2. Research Aim and Objectives*

With this shaping work to set out a viable methodology for optimizing road traffic signal control, our research aims to contribute to the development of a more sustainable and efficient transport system by proposing a novel AI-driven solution for optimizing city-scale traffic signal control. We also study how this novel methodology could help reduce congestion, improve the utilization of road infrastructure, and perhaps, more intriguingly, improve road safety at the same time. The submission also has the following objectives:

To conduct a thorough review of the current status of traffic signal control systems and related optimization work that informs on the state of the art in the domain, particularly about agents' learning, urban traffic congestion, and road safety improvement when taking a 360-degree approach to the problem. - To develop a methodology that includes an agent model simulating the decision-making capabilities of vehicles in a simple urban road network with low to moderate congestion levels in varied traffic light configurations, allowing the impact of different vehicle shape configurations, traffic density levels, speed of the vehicle, junction synchronicity, and interchange movements on congestion mitigation, road infrastructure utilization efficiency, fuel consumption, and pollutant emissions. - To ensure the reliability of the proposed methodological framework, we integrate the agent model into a simulation environment.

The focus of this paper is on developing new methodologies for optimizing traffic signal control in large cities, combining multiple deep learning models to identify precisely how to develop deep learning models for traffic signal control that work well with only a small number of real training samples relative to the excessive number of training samples the model supports.

II. LITERATURE REVIEW

To optimize the operation of ramp metering signals, a control algorithm for managing traffic signals was designed, based on the evaluation of road traffic conditions. This took into account the volume of entering cars, the state of the road, the condition of the main road traffic, and the status of the road segment. The rules for the interaction of the designed control algorithm in special cases were disclosed. The procedure for setting the input parameters of the control algorithm was implemented arithmetically. The necessity of expanding the range of operating input parameter values and the number of conditions for the development and functioning of the algorithm was substantiated to improve its efficiency.

To assess the impact of AI-driven control on the intensity of the main traffic flow and the total number of vehicles in queues after leaving the investment, simulation modeling techniques for the operation of road infrastructure facilities were substantiated. It is established that under uncertain and variable conditions of both the intensity of the main flow of cars and the volume of cars entering the flow of the original investment, implementing approaches to adaptive control of the signal action allows for more effective use of the investment. The results of analyzing traffic signal control mechanisms in the opposite direction, combined with developed optimization techniques, enable the assessment and improvement of the efficiency of road infrastructure use.

➢ *Current Challenges in Traffic Signal Control*

Traffic signals are designed to balance traffic flow through an intersection and are essential for the safe and efficient movement of both vehicles and pedestrians. Nonetheless, traditional traffic signals work by optimizing a fixed-time assignment, often failing to adapt to real-time conditions such as changes in travel demand or accidents. Consuming signals that only provide fixed-time designs has been proven to be worse than other dynamic systems that are out there in the sense that they fail to accommodate a much-needed adaptation. The inflexibility of static control strategies makes poor choices of signal plans and thus results in opportunistic congestion. If no immediate solution can be synthesized, the congestion caused by outdated signals will only exacerbate. Furthermore, an increase in the probability of vehicle collisions is also assumed to be associated with specific dispatch policies, whether they be inflexible or out of date.

Reducing traffic congestion is a costly and crucial problem. It is crucial because congestion substantially increases travel times and incentivizes drivers to make inefficient choices. And it is costly because solving congestion problems often involves building expensive infrastructure, which does little to address the existing challenge. It has been estimated that big cities in the U.S. will lose almost $200 per person by 2039 as a consequence of the economic expenses due to traffic congestion. Finally, the global CO_2 emissions due to city traffic congestion increase from 7.0 to 56.8% when compared to that in free-flowing traffic.

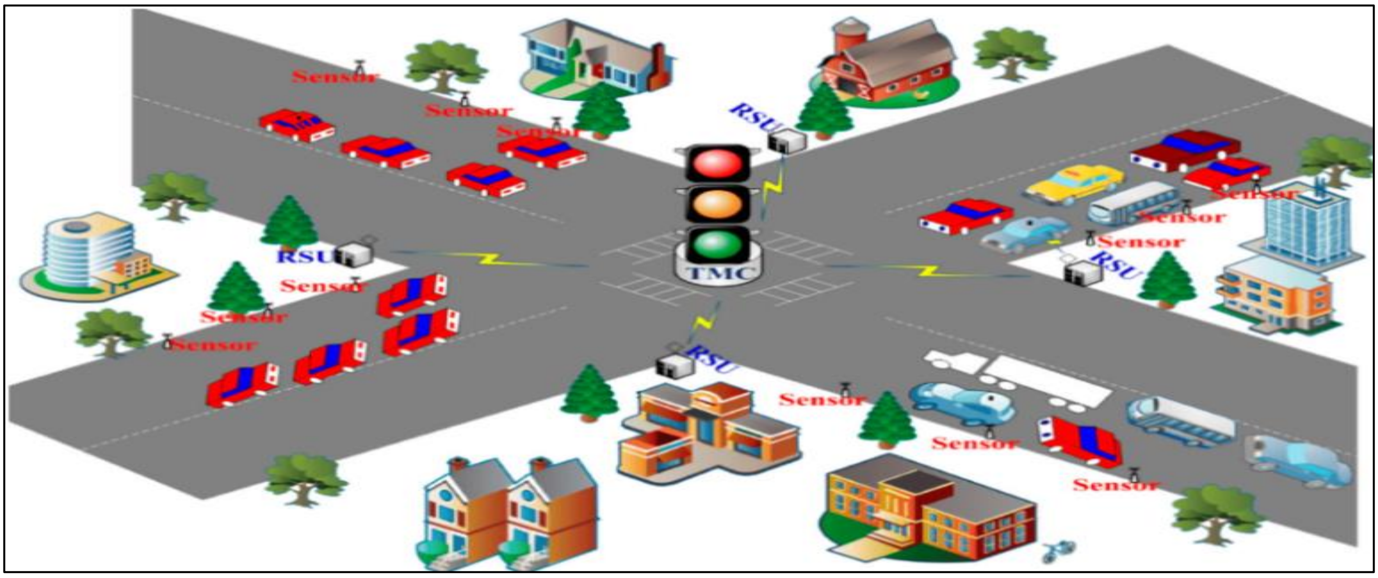

Fig 2 A Survey on Urban Traffic Management System Using Wireless Sensor Networks

➢ *Advancements in AI and Traffic Management*

I would like to discuss the issue regarding the modern technology of AI applied to video traffic monitoring systems. While AI is now a popular term and we can hear many AI solutions in all spheres of traffic management every day, it must be understood that the real AI task for in-traffic monitoring is not about finding all the vehicles (knowing their type and features); it is about vehicle tracking through multiple camera zones (updating vehicles and their attributes). It is a more challenging and important AI task, the solution to which could be a powerful and scalable decision support tool at any traffic control center. Real improvement of the traffic control process could be achieved by using AI-based tools to solve complex tasks such as the definition of travel time on specific routes by sections of the road network, or by transferring vehicles through specific road intersections. These are just a few of the control tasks that are not currently supported by the existing tools and cannot be solved by simple informative traffic diagrams, even those built based on dynamic traffic models. These tasks cannot be solved within the existing time horizon of several minutes. Thus, transportation control practice, despite the application of various traditional and modern intelligent systems, still uses an enormous amount of mostly passive, non-actionable information; even such critical information sources are largely not used. Simulation models remain a common tool for long-term strategic decision analysis and land creation and can be useful for understanding travel time reliability characteristics of different road network designs, but they do not help to estimate the real number of vehicles on the road at the same time to support supervision and control activities.

III. METHODOLOGY

We use a two-stage approach to estimate the effects of AI-driven traffic signal control on traffic delays and safety. First, we estimate the effect of introducing AI-driven traffic signal control on the total hours of traffic delay experienced at each intersection during business hours. To account for the contemporaneous changes at intersections that changed control mode around the time the pilots became operational, we estimate the following equation:

$$DI,d = \Sigma K\text{-}12k= -12\delta k Pilotd(r) + \Theta PBOThoursd + XtX + CdC + \Sigma\tau + \gamma + \mu + \Omega t + \epsilon d$$

Where I indexes intersections; d indexes days; DI,d = accumulated hours of traffic delay on day d in business hours at intersection i; Pilotd(r) = 1 if the rth pilot is operational on day d, 0 otherwise; PBOThoursd = hours between 10 a.m. and 2 p.m. on day d; K = 12 (K = 5) when r = 1 without (with) reaching the smart coordination; X includes daily precipitation, snow depth, and temperature; and Ωt are date (level) fixed effects. The parameter of interest is δ−12, which measures the change in delays that occurred immediately following the introduction of AI-driven traffic signal controls relative to the level after reaching the full smart traffic signal coordination function. The number of pilots is large enough to capture the collective impact of the pilots under consideration. The coefficients, therefore, are the average treatment effect of the treatment on the treated. Furthermore, we include interaction effects between Treatment and PTRT in the equation to focus on the effect at different levels of implementation. In the second stage, we focus on how AI-driven traffic signal control intervention affected intersections that completed the smart city transportation infrastructure: travel time, intersection capacity utilization, and red light running.

➢ *Data Collection and Analysis Techniques*

This study makes use of two data sources coming from real-world deployment of AI-based traffic signal control systems. The data used for learning the model and simulating real-world traffic conditions was collected from the operation of the AI-based traffic signal control systems deployed at 133 junctions in two cities and provides sensors' traffic counts, time domain, and control plan information for these 133 junctions. The data serves as the real-world benchmark dataset, providing traffic flow with a frequency of 15 minutes.

In this paper, two separate scenarios were considered. Scenario 1 used the data to learn and fine-tune the deep neural networks and later simulated the sensor data to have a traffic flow per second. We then used the real-world traffic flow for the same junctions and the Intersection Control Model to recast the traffic flow into something interpretable for our planning and safety model - the three-second rule observed by drivers in that region. The link exists because red-light running is shown to have a high correlation to congestion, especially with the underlying traffic signal control. In a similar vein, congestion is, on its own, a very well-correlated indicator of when crashes are more likely to occur. Scenario 2 used a subset of sensor data provided to learn and fine-tune the planning and safety model and used this to evaluate the potential of using the traffic signal control system to improve the traffic safety performance of the adherent junctions.

Equation 2 : Average Waiting Time Per Vehicle:

$$W_{\text{avg}} = \frac{\sum_{i=1}^{N} W_i}{N}$$

W_{avg}: Average waiting time per vehicle

W_i: Waiting time for vehicle i

N: Total number of vehicles

➢ *Case Study Design*

In our study, data-driven analysis of signal control policy is provided by using data from more than 200 high-accident concentration intersections in the city of Riyadh, Saudi Arabia. We have contributed a novel data-driven analytics platform that can facilitate more accurate and objective policies or decisions for accidents and congestion relief. Over 70% of the total accidents in Riyadh are at intersections, and this provides a real opportunity for a traffic management solution. The proposed data-driven analytics could provide recommendations based on observed data analysis and hence facilitate more coordinated traffic management strategies, such as more objective decisions on signal settings, detour routes, or traffic calming solutions. The main goals of signal control are to reduce delay, minimize stops, decrease congestion levels, and improve safety conditions. In response to these goals, the traffic signal control problem has attracted significant interest from both academia and industry. Traffic signal control is known to have a significant impact on intersection efficiency and may lead to beneficial outcomes such as decreased travel delays, improved safety, increased capacity, reduced fuel consumption, and reduced transfers to the environment. The typical traffic control approach is either pre-timed or actuated. Pre-timed control requires the pre-determination of the cycle length and green timing for a signal set, which is then used to control the traffic irrespective of the real-time traffic conditions. In contrast, actuated control refers to a sensor-activated control policy that adapts the signal timing to traffic demands at an intersection. Although actuated control provides some adaptability to specific intersections, it fails to address potential inter-intersection links or connections. The joint optimization problem of control on multiple interconnected intersections, to honestly reflect the interdependencies among the signal settings, is known as signal coordination and has been less extensively studied for practical application in real-world scenarios. Several signal coordination and control strategies have been proposed both on theoretical and empirical models.

IV. RESULTS AND ANALYSIS

➢ *Objective Evaluation of SCOOT and PAWS*

In this paper, we use the comparison of SCOOT with an academic optimization engine to analyze the effectiveness of AI-based traffic signal control versus conventional signal control techniques. The installed optimization engine was used to perform the optimization of traffic signal control plans of the Main Road of Sham Shui Po, bypassing Shek Kip Mei and Tai Hang Road, which was located at Sham Shui Po, from 7:00 to 10:00 and 16:00 to 19:00 during weekdays. Besides, we set some realistic control constraints and utilized a system to check and modify route movement in case of the occurrence of several invalid route movements. After that, we ran the optimized cycle starting time and the phase order by SCOOT for 30 minutes. Finally, the numbers of guest vehicles that traveled across the performed area under the SCOOT method and the modified method were recorded. We compared the difference in the effectiveness of traffic signal control between the SCOOT signal control method and the modified signal control method.

- *The Evaluation of SCOOT Signal Control Method*

As we know, all discussions made by the conference delegates we are mentioning consisted of experienced experts from many countries in the world. We may have views and experiences, but this combination of experience and background is very special. These have led to interesting initial findings of studies of such an organization. The SCOOT signal control method is considered the intensified method to deal with the dynamic traffic control problem in adaptive traffic signal control. In the present work, SCOOT is employed to assign effective cycle length, and phase order, and plan to monitor the traffic link provisionally and respond to real-time traffic flow. To analyze the performance of SCOOT, we record the traffic status condition during the rush hours at the experimental intersections.

➢ *Quantitative Impact on Congestion Reduction*

One of the most widely publicized benefits of traffic signal control is to reduce traffic congestion. Both of our field deployments aimed directly to reduce congestion. Our field deployment of the AI-driven and the inductive-loop detector traffic signal control solutions did not make use of the camera data of the previous queue length in the notification feature, so this field deployment is even better than a standard important validation. When road traffic demand at an intersection becomes close to capacity, the queue length will no longer be indeterminate. The peak-hour traffic capacity of an intersection can maintain a constant average queue length of about two vehicles throughout the green time.

We first defined peak hours as the hours during which the links' queue lengths would increase during the green and decrease during the red if the signal timings were to stay constant throughout the peak hour. During our field study, we observed that the queue length of a cycle was frequently clear once a light turned back to green. We therefore selected the first two cycles of a peak hour, assuming that both selected cycles would experience the same queue length. Using a sample of an equal number of the first and the second cycles during the pre-implementation and the implementation in phase 1, we evaluated the queue length reduction of the AI-driven traffic signal control.

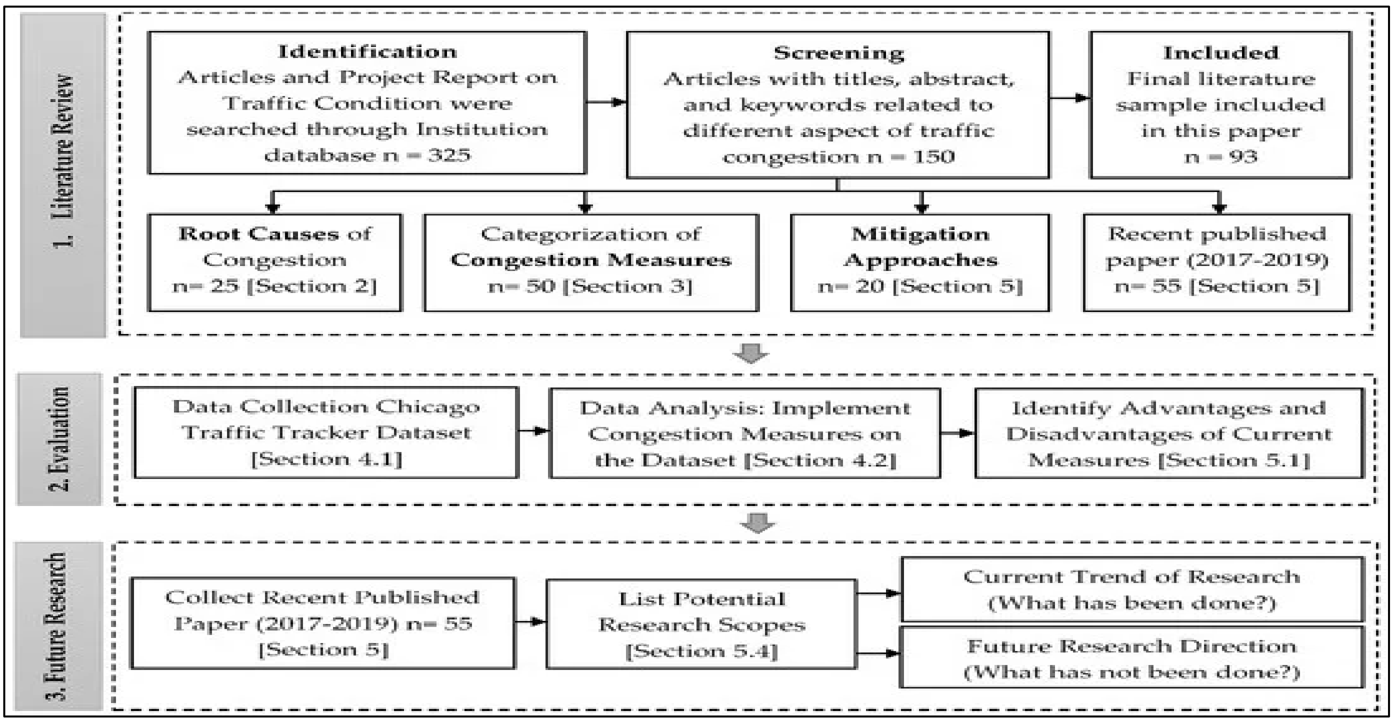

Fig 3 Road Traffic Congestion Measures towards a Sustainable and Resilient Transportation System

➢ *Qualitative Impact on Road Safety*

Traffic violations can cause crashes. One major violation behavior is running red lights at intersections. It often induces conflicting and dangerous behaviors, and this is shown as a chain of traffic events. Our AI-based real-time dynamic traffic signal control could not only reduce the waiting time but also cut down the start-moving delay in both vertical and horizontal directions through cycle length adjustment. Additionally, the dynamic transition adjustment could prevent the entering flushing between edge buffer time zones and entering scrambling between arrival-dependent phase termination zones. When vehicles' moving reservation time for red start moving is comparatively low, that means the head moving delay time could be expected to accomplish the minimum and then provide green time for the other non-dominant directions. The green time waiting for vehicles to start following in the red clearance interval can sink the queue at a faster speed and thus completely release this prepaid preempted green, which further reduces the vehicles' start moving delay and decreases queue length. Besides reducing congestion and improving both vehicles' and pedestrians' travel time in the mixed traffic environment, the number of potential red-running vehicles could be reduced, enhancing pedestrian safety.

Benefiting from the results of waiting time and cruising time, the system can program a reasonable stage split to allocate more green time for vehicles at a determined gap time. AI helps to abolish phase margin and carries out accurate stage packets with enough green time to release the vehicles. The relative action of quick restarting and preempted stopping undoubtedly stabilizes the vehicles' moving speed within the traffic system, decreases the possibility of traffic accidents and improves road safety, particularly at pedestrian crossing areas. Intersection sight distance is the sight distance directly related to the ability to safely cross the intersection from a standing start position. Vehicular crash data have identified the crash-prone crossing site as a highly variable attribute, so the decisions to use additional sight distance come with a cost, usually measured in the value of lost opportunities for commercial development at the approach.

V. DISCUSSION

We analytically prove the performance of the proposed AI-driven optimization scheme under a traffic junction and discuss the conditions under which it outperforms other analytical methods, including the longest queue-first dispatching and the phase design in the cycle. By using real-life data in a city, we find that the proposed scheme increases traffic flow, and reduces total travel time and emissions. In addition, the performance of the proposed scheme is maintained at a certain level as the volume of traffic flow increases. Furthermore, we analyze the impacts of some significant parameters on the proposed scheme by simulation.

In this paper, a city-level optimization scheme for signal control at isolated signalized intersections is proposed, which is based on reinforcement learning. With the specific structure and identification process, the computational cost of the system and the required computation are reduced by a large margin, which applies to city-level signal control. Also, a parameter sensitivity analysis on reinforcement learning is carried out and the proposed method is proven to be effective against simulation results. More specifically, the load-balanced traffic scenario is given more consideration and has achieved encouraging results under this novel scheme.

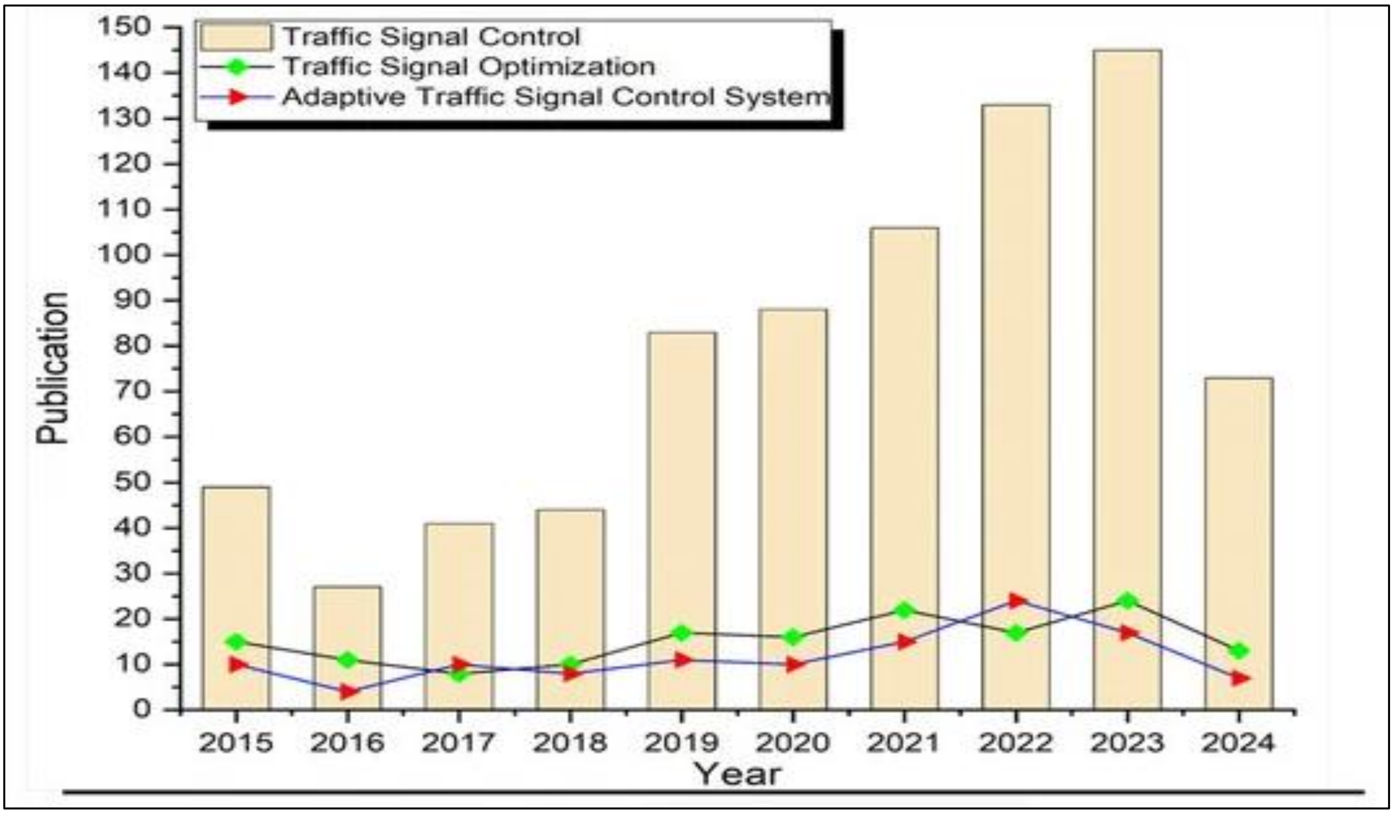

Fig 4 Artificial Intelligence-Based Adaptive Traffic Signal Control System

➢ *Implications for Urban Planning and Infrastructure*

Despite the significant progress in AI and data-driven traffic signal control, the vast majority of the research uses datasets from a very limited number of intersections, and insights from testing the techniques on larger test domains are largely absent. We highlight this limitation by developing a multi-intersection, city-scale network model and environment and use a large-scale traffic flow microsimulation model with comprehensive urban development and activity pattern components for generating the evaluation environment. Our suite of urban environment models represents the diversity of real-world behavior within city-scale geographic scales. The full diversity of urban-impacting influences, including the interaction between transportation and urban planning that contribute to causes of urban congestion and increased risks of accidents, is incorporated in an agent-based, city-scale traffic modeling and urban development simulation framework.

Revised signal selection optimization formulation with mixed integer programming techniques operates efficiently on even larger traffic network sizes. We evaluate AI optimization testing methods by tracking urban sustainability behavioral simulation outputs. Evaluation results using these next-generation simulation models demonstrate potential significant emission, congestion, and thus many times safety improvements. Safety benefits are measured in terms of data that directly observe potentially dangerous traffic conflicts between vehicles and unprotected road users. The current body of research does not provide cities, metropolitan organizations, and regional planning associations tools capable of measuring the potential urban impacts of these planning practices. This research is essential to understand the opportunities in responding to the urbanization movement with refined policies and emerging priorities backed by established technology.

VI. CONCLUSION AND FUTURE DIRECTIONS

Intelligent transportation systems implemented using the Internet of Things have become attractive technologies for traffic efficiency, and intelligent traffic signal control is a promising method for solving traffic congestion. This study proposed a deep reinforcement learning model that was designed to learn the estimated or true state to produce a control command. The simulations showed that with reasonable settings, the AI-based approach could reduce the average waiting time by 24.85%, the average queue length on the left side of the junction by 26.93%, and the average queue length on the right side of the intersection by 8.16%. The proposed approach showed great potential in solving dynamic traffic signal control problems. The influence radius for queue detection is the most critical factor based on the investigation. More information about the traffic state will allow the training models to estimate the traffic demand or true state in advance and produce the best traffic signal control command as much as possible.

In the future, more advanced demand estimation models, such as those based on deep learning and cost-effective hardware should be integrated to provide more information about the traffic demand. To consider multi-junction coordination, a deep reinforcement learning model that can consider communication and monitor competing junctions is necessary. Using the smart and communication feature, the traffic signal controller can make smooth decisions by choosing the green-all phase to fully cut waiting time or using a short green phase followed by a green-all phase to ensure the clearance of queued vehicles. Privacy concerns should be considered when designing control systems according to video cameras, GPS, and other observation equipment. Control systems should be designed such that no camera can be used to track a distance of over 50 m. Magnets and GPS should be removed after the travel demand disappears to protect civilian privacy. Cameras do not record video; instead, they snap photos based on the induction signal of vehicle channels. Only the operation status of all channels at the time point is stored in binary form, and the photos are immediately covered. High efficient embedded computing units should be used to further support these efforts.

Equation 3 : Signal Timing Optimization (Cycle Time):

$$C = \frac{1.5L + 5}{1 - \sum_{i=1}^{n} y_i}$$

C: Optimal cycle length (in seconds)

L: Total lost time per cycle

y_i: Flow ratio for phase i

n: Number of phases

➢ *Summary of Findings*

In this study, the effectiveness of AI-driven traffic signal control is evaluated in mitigating urban congestion and improving road safety. The dataset used in this study consists of real-time traffic conditions at three intersections. The first intersection has traffic signals controlled by a traffic police officer, and the other two use AI-driven traffic signal control. Two models are built to predict the traffic time series of different intersections, where the first model utilizes the historical section and road topological feature, and the second model uses the real-time traffic condition feature. The results show that deep learning models are effective for predicting the traffic time series of different intersections, and real-time traffic condition-based models are more accurate. The results also indicate that the use of real-time feature information can robustly improve prediction accuracy and traffic signal control effect, proving that upgrading traffic signal control from pre-defined time intervals to a real-time controlled approach is beneficial for reducing urban congestion and improving road safety.

The results of this study are very valuable for practical urban traffic signal control practices. However, this is a preliminary study considering only a few intersections. In future work, we will deploy our method on more intersections or in a connected vehicle-coupled infrastructure environment. Furthermore, it is sensible to incorporate more faceted features into the model related to the enhancement of the prediction and control accuracy.

➢ *Recommendations for Further Research*

Although the current research is an attempt to identify and analyze the opportunities and threats related to the application of AI technologies in controlling traffic lights, the results obtained can be expanded and supplemented in many ways. First, the research did not take into account the weather conditions under which the neural network was trained, reducing the likelihood of errors at different times of the year, especially in some regions with changing weather conditions. This omission causes additional risks, the recognition of which could increase the practical value of the current study. Second, the insufficient size of the dataset and the diversity of details limited the possibility of learning tasks and comparing them with the task of conducting full macroeconomic research, and the level of practical recommendations was low. Using more diverse training data to simulate infrastructure improvements and weather conditions allows for more accurate training of the neural network.

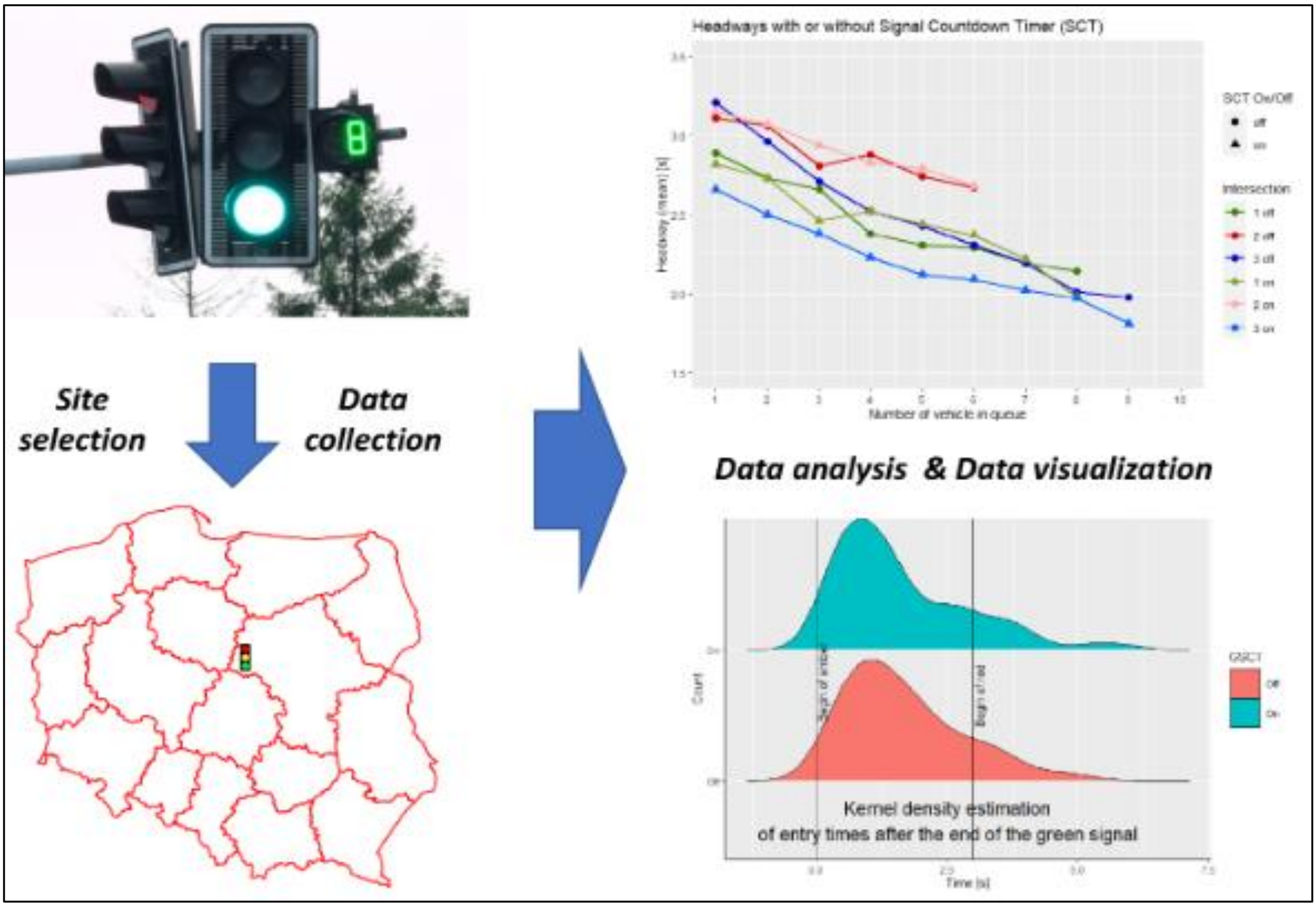

Fig 5 Impact of Countdown Signal Timers on Driving Behavior and Road Safety

Because the current model does not consider the saturation setting of traffic lights or the probability of conflict between vehicles and pedestrians, it is important to expand it to communicate a specific green time for each traffic lane while ensuring effectiveness. Theoretically, it is possible to teach the model to communicate the estimated route length so that issuing and changing green signals is easier. However, in this case, it is not possible to make maximum use of the basic capabilities of a standard decentralized traffic control system, such as the optimization of each intersection at the same time. Therefore, it is reasonable to improve the existing traffic control schedule. The aforementioned reviews and modeling schemes should therefore be supplemented to increase the control quality.

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