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Computational Intelligence for Adaptive Traffic Signal Control in Autonomous Vehicle Environments

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1. Introduction

This paper introduces CI-adaptive models, which extend the capabilities of traffic controllers, by modeling interactions among a few major intersections and provide useful future knowledge by means of a pre-estimation study. The estimation model is employed to allow drivers and control centers to make plans regarding intersection crossing, encouraged by the support from a communication system, which is automatically acting in cooperation with an adaptive signal control system.

In this context, Computational Intelligent (CI) adaptive models appear as a potential solution to offer sustainable urban traffic management. The main idea is transitioning the focus from vehicles to intersections and from both individual and instantaneous to collective and time-agnostic control. This collective approach concerns the decisions of some major intersections, attributing to explicit collective behavior performed by drivers in the vicinity of these intersections.

Future developments of an autonomous vehicle will challenge current traffic control systems in a manner that is yet to be fully understood. For instance, autonomous vehicles, equipped with a coordination and communication system, could potentially reduce intersection delays by selecting speeds to enable uninterrupted crossing of intersections, or even altering speeds to catch traffic light greens.

Managing traffic flow is a challenging problem for cities around the world. Dynamic, adaptive traffic signal control algorithms have emerged as the preferred way of reducing traffic congestion and subsequently the emissions and fuel consumption of vehicles at urban intersections. Current adaptive traffic control systems (ATCS) are usually based on the well-known Webster's method. These models assume the expected values of traffic flow parameters, thereby ignoring the existence of diverse traffic flow types and the presence of vehicle queues concerning intersection approach egresses.

1.1. Background and Motivation

Currently, the vast majority of adaptive traffic signal control systems are used on high-capacity arteries that incorporate complex hardware devices, such as video detectors or infrared sensors. However, further analysis of these systems brings evidence that inadequate consideration has been given to pedestrian aspects, and their training procedures are lengthy and complex because of the internal and sometimes non-linear relationships between the input and output data. As a result, there is not an easily accessible system as a solution for handling various real-world situations relating to vehicle transit with pedestrian demands at low cost.

New technologies and concepts, including autonomous and connected vehicles, the Internet of Things, machine learning, artificial intelligence, cloud computing, and the mobile internet, are advancing transportation. Traffic signal control is one of the most important elements of the road network design, to maintain the functionality of the transportation system and to ensure a high level of mobility. The objectives can frequently conflict when setting the control thresholds for vehicles and pedestrians at intersections, and thus the associated hardware components.

1.2. Scope and Objectives

In many urban environments, the capacity of the roadways is provided by the traffic signal control. Given the traffic signal control system's ability to govern traffic flow and control access to junctions, it is the primary tool in the traffic manager's set of options to increase efficiency. While experience, intuition, and data mining can result in a reasonable implementation, it is clear that the problem is so complex and dynamic that advanced algorithms should be made available to improve the process. This has been the main message in the last few years in the field of traffic signal control. The use of a combination of advanced central optimization systems and available communication vehicle-to-infrastructure (V2I) information could obtain a much higher level of performance but is only available in a few modern urban traffic signal control systems.

In the last few years, we have conducted an increasing volume of work aiming to maximize the performance, efficiency, and sustainability of traffic signal controls for environments characterized by a prevalence of autonomous or semi-autonomous vehicles. Our approaches emphasize several computational intelligence techniques and opportunities, such as some types of bio-inspired algorithms. Algorithmic combinations have also been employed to bring superior robustness to increasingly heterogeneous multimodal traffic flow demands. The reality of an increasing number of vehicles without human occupants or operators demands that the worldwide traffic management infrastructure be included in compatible strategies so that resource optimization is maximized. However, we advocate for the importance of local rights for jurisdictions to enter prior investment in the described infrastructure instead of some distant global positioning infrastructure.

2. Autonomous Vehicle Technology

Indeed, autonomous vehicles are frequently associated with accident prevention and safety benefits such as better vehicle flow by traffic steepening and road use economics. Although this may be true and both streams of research (road management and automobile manufacturing) have progressed, the implicit effects of a mix of autonomous and non-autonomous vehicles in urban regions are not sufficiently addressed. These merging problems can be settled by a re-engineering of traffic infrastructure. In fact, the literature has increased in attempts to implement intelligent traffic control powered by various techniques, including artificial intelligence.

Numerous private and government-sponsored efforts around the world are working on autonomous vehicles. Although fully autonomous driving is not yet possible, the current public is familiar with or experiencing various levels of assistance and driving-related features. These include advanced obtaining systems such as autonomous parking, adaptive cruise management, lane-positioning order, traffic jam support, and a wider set of driver assistance applications. Quick evolution of the traffic safety/driving assistance market is evident in addition to the above by the acquisition and union of organizations creating and developing autonomous, additional application-oriented (e.g., infrared take, sensing intent, and traffic transmission), and related driving-related applications and systems. The initial impetus behind autonomous vehicles has been clear improvements in road safety.

2.1. Overview of Autonomous Vehicles

The scenario of interpretation of the operational context of the cities becomes a central aspect in the implementation of an action plan to make cities smarter, but also in the organization and regular performance of urban tasks. Urban mobility, in fact, is an increasingly important problem, both in terms of the number of vehicles and the relevant congestion and pollution due to vehicular uses. The current and widespread interest in electric and plug-in hybrid cars, in addition to cautious - yet increasingly progressive - experimentation with autarchic and fully autonomous vehicles, is the basis to foresee both a change in motion paradigms, to arrive even at important questions regarding the design of the urban street transport system, involving calls to the concept itself of a traffic structure.

In defining the domain where this paper primarily aims to intervene, it becomes fundamental to contextualize the context of autonomous vehicles (henceforth referred to as AVs). Contrary to the traditional mode of vehicles driven by human drivers, AVs are vehicles equipped with sensory, actuation, and situational analysis capabilities that allow them to move with little or no human intervention. This distinctive characteristic opens various application scenarios, including the efficient exploitation of time during the journey, collaboration in which the vehicle can share it with other tasks such as video conference meetings, guided relaxation techniques, or even the reading of informative content. However, of all the perspectives and hypotheses that emerge from the AGSS, the most palpable and visible are related to urban mobility.

2.2. Key Components and Technologies

The key elements of the comprehensive adaptive traffic signal control are vehicle perception and awareness, vehicle self-planning, vehicle cooperation and collaboration, and vehicle behavior enforcement, which are shown in Figure 4. Vehicle perception and awareness can be implemented by a built-in algorithm analysis in vehicle-mounted fusion sensors, such as millimeter wave radar sensors, camera sensors, ultrasonic sensors, infrared sensors, location device sensors, road magnetic field line snapshots, and so on. These kinds of sensors can realize dynamic real-time monitoring of on-site vehicle flow, road condition, and intelligent traffic sign identification, ensuring that the vehicle itself can sense and perceive the road environment in real time. Vehicle self-planning can be realized according to the layout of the known road map, basic information obtained from perception and awareness, vehicle status and planned route cost of demand. After determining the scheme, the vehicle reports it and asks for help to the central control center to use the traffic light control, speed limit guidance, and model adjustment. The central control center supports the vehicle in issuing the relevant requirements and dynamic system parameters, model refreshes policies, and updating the vehicle's self-planning policy for agreement.

Adaptive traffic signal control is one of the core technologies of autonomous and connected car design. Vehicles that have enough autonomy or that are adequately connected should be able to automatically address information cooperation, collaboration, planning, perception, awareness, and so on in order to realize the concept of "autonomy". The adaptive traffic signal control system contains several components, in which vehicle networking technology, electric field or magnetic field induction technology, car-mounted GPS technology, traffic condition data analysis and logic judgment algorithm technology for intelligent self-cooperation planning linkage, unmanned technology, traffic signal control strategy, intelligent signal controller technology, basic information storage and processing technology for road intelligent facilities, data acquisition technology, and other technologies can be applied.

2. Adaptive Traffic Signal Control in Autonomy: Key Components and Technologies

3. Traffic Signal Control Systems

The active signal control based on information technology is, in the final analysis, an active control system. Currently, the development of active signal control technology demonstrates the following characteristics. It is a traffic assistant platform supported by information technology. AODA analysis and signal phase optimization algorithms simulated make the system adapt to the development of the traffic flow. AODA analysis is performed first on the observation and detection of the approach flows, vehicle skeleton analysis, and detection of the turning rates. This yields precise predictions of the vehicle presence on neighboring approaches in the next cycle, to make the system's reaction pre-active. It is characterized by advanced wisdom and takes people demand as the starting point. Detailed updates are provided with the arrival of various technology, yet the main technical difficulty is still in how to identify, simulate, and control the multi-source information and control constraint conditions of the mixed signals, to realize the proper coordination of the seamless connections. It is complex to control the information. Use the communications technology may control the algorithm of the signal control system. This may lead to improvement of the robustness and reliability of the whole signal control system. With the coming of the era of ITS, with the sophistication of the motor vehicle, with the perfection of road network and the increase of control function, the development of an active signal control technology may cover various aspects, to be on the way to realizing a full intelligent transportation system.

The development of traffic signal control systems can be divided into three stages: steps and loops, passive and dynamic control, and coordinated control and dynamic signal timing. It may be said that the traffic signal control systems in the traditional sense had all initially functioned as a step or singular control system. Later, according to the change of the traffic flow, the transition of the traffic signal control system from an open-loop to closed-loop, which showed a certain response to adapt to the variation, occurred by means of Gray's embedded operational mechanism in the traditional traffic control system. However, as compared with the dynamic requirements of the macro traffic systems, those strictly closed-loop control systems only played their role in a limited local area, thus having the island functioning formed in signal control area.

3.1. Traditional Traffic Signal Control

For decades, the fixed-time traffic signal has been predominantly utilized in urbanized municipalities across the United States to control vehicle intersections primarily due to its cost-effective nature. Fixed-time control entails signal phases that are allocated a designated amount of time to control each movement. Different timing patterns are established for each phase based on vehicle demands during different periods of the day, typically because vehicles are present longer on the main street during morning and evening rush hours when persons are mainly traveling to and from work. This type of system is very rigid in that it does not allow for adjustments in phases or cycle lengths to accommodate sudden changes in vehicle demand or traffic problems secondary to freeway incidents that are characteristically dynamic in nature. Consequently, this control is unable to fully utilize the potential of the signal, often resulting in severe mobility and environmental impacts.

3.2. Challenges and Limitations

Despite the many advantages and opportunities they bring, it is generally acknowledged that CAVs will add a new and significant management and operational complexity to traffic. This is because most traffic-related problems so far occur randomly or are totally decoupled from any forecasting. In the context of traffic lights, for instance, much work performed today relies on having sensors and primarily detecting vehicle presence to estimate the state of the vehicles in the intersection, influencing signal timing. With autonomous vehicles almost permanently monitoring intersections, more accurate data about the actual traffic situation will be available; thus, wiser control decisions are possible. However, this is not a simple task: this potentially vast amount of new data about the environment must be processed and distilled so that only relevant and valuable data is sent to the traffic management center (in case there still is such a structure). On top of this challenge, it is also not reasonable to disregard the large installed base of traditional vehicles in the near future. In this respect, the cooperation between the traditional vehicles and the CAVs, as well as their behavior when interfacing with CAV-oriented infrastructure is a potential problem that requires a timely solution.

4. Computational Intelligence in Traffic Management

Research on adaptive traffic signal control is one of the oldest applications of computational intelligence (CI), dating back to the early 1960s where an adaptive traffic signal control system, called TRRL, was one of the earliest applications of genetic algorithms in a complex real-world problem. During the past four decades, applications and CI tools have proliferated in traffic management, logistics, signaling systems, traffic light ramp metering, bus guidance, and freeway operations. Data were mainly obtained from cameras using early vision systems that were more attentive to false alarm rejection, random clutter suppression, and reduced position inaccuracies than specialized data collection. The research was often directly motivated by significant traffic congestion and performed within the travel constraints of the local community. Requested changes in traffic signal control algorithms had to be assessed in the field, leading to adaptive control installed in areas such as London, Fort Collins, Newcastle, Sydney, Melbourne, Munich, Augsburg, Puerkingen, and Wolfratshausen in Bavaria, and Acapulco.

This section summarizes several new applications of computational intelligence in real-time adaptive traffic signal control, focusing specifically on the new environment where intelligent autonomous vehicles start interacting. Our samples of real traffic signal control involve the use of genetic algorithms (GAs), especially multi-objective optimization GAs, neural networks, expert systems, and fuzzy inference systems. These new developments illustrate that the era of fully responsive smart autonomous vehicles can be implemented well before fleets of 2054 intelligent cars are expected to hit the road.

4.1. Overview and Applications

Traffic control is nowadays seen as a multi-criteria optimization problem that aims to distribute fairly the traffic demand through a road network, to control the levels of the traffic welfare, and to reduce the unbearable externalities of the automotive traffic such as the death and injury tolls, the emissions of CO2 greenhouse gases and other pollutants, and the consumption of non-renewable resources such as crude oil. The combination of controlled traffic signal phasing and vehicle-actuated traffic responsive plans is what characterizes conventional traffic signal control (ConvTSC). A control network is actually a traffic management information system that includes a variable number of remote nodes operating as traffic signal controllers. Every controller is the control unit of one or several traffic signal displays, i.e., the machine that converts in real decisions traffic signal timing schedules.

Computational intelligence can be used to develop new adaptive traffic signal control solutions to deal not only with the existing and future vehicle technologies but also with all types of allowed road users and clever, but ignorant, irrational, or even evil driving behaviors. This chapter introduces Cooperative Traffic Signal Control (CoopTSC), an approach to solve the problem from a new technological and methodological perspective. CoopTSC is based on a central controller that uses dynamic traffic network models and predictive models of autonomous vehicles' behaviors to optimally coordinate all the traffic signal controllers. It is designed to improve, under the multi-criteria traffic management paradigm, traffic operations in traffic networks with a significant percentage of autonomous vehicles.

4.2. Machine Learning and AI Techniques

The most industrial-friendly dynamic traffic assignment methodology for autonomous/vehicle maneuvers is using reinforcement learning. That means recreating a decent ITS for Next Generation Air Transportation System (NextGen), 5G, etc., requires implementing distributed supervised learning type optimization control theory. In this current big data and Internet of Things (IoT) heavy era, enterprise-level solutions require harnessing repetitive (bootstrapped) experience samplings and are computationally enabled by human iterative design and crowdsourced multi-agent behavior. In Section 5, the MAS approach of this study will be evaluated using state-of-the-art and recent reinforcement learning and finite horizon dynamic programming algorithms for Adaptive Traffic Signal Control (ATSC). Specifically, multi-stage reinforcement learning will demonstrate how to attribute vehicle decisions to time-varying traffic state, resulting in models that are interpretable by control policy. And, more importantly, this research quantifies the robustness of such control policies with respect to time-varying traffic states, leading to well-tunable signal timing definitions.

Throughout this work, Intelligent Transportation Systems (ITS) refer to the utilization for adaptive traffic signal control in autonomous/vehicle environments. What makes ITS computationally difficult to optimize is, first, the ad-hoc and distributed dynamics of vehicles or unmanned robot's controls, and second, the limited observability and the huge and nondeterministic randomization of vehicle arrival information. However, for explicit yet distributed vehicle maneuvers, a large group of industrial toolsets are based on machine learning. The ultimate goal of ITS is to minimize person-delays and pollution emissions by giving the necessary decisions to the vehicles or unmanned robots before uncertainties in road cargos lead to illegal/unsafe road events. Such dangerous maneuvers are penalized and discouraged with hybrid control objective functions. The tools occasionally used to handle ITS, such as Flocking, Centralized Model Predictive Control (MPC), etc., explicitly give such discrete decisions to vehicles, yet are not scalable. A more scalable method requires gathering all traffic data at one centralized location and using cooperative MPC, Nash type hybrid game models, etc., to iteratively return centralized commands to each autonomous vehicle, which is pointless regarding redundancy.

5. Privacy-Preserving Location-Based Services

Many approaches for the protection of location privacy in LBS focus on a trusted third-party architecture, where confidential user information is protected by semi-trusted services. This general architecture trusts the service providers (e.g. network operators, LBS providers) as potential adversaries on the users' positions. Therefore, the concept of using a trusted third party to preserve the privacy of location data has been proposed in many privacy-preserving location-based services. However, this approach introduces the issue of a single point of failure: the trusted third party must always be online to ensure lineage tracking and query answering services for clients. To avoid this single point of failure issue, the use of double anonymity has been proposed. An additional entity adds another layer of obfuscation, which should protect the individual trusted entities in the system. However, as the number of trusted entities increases, it becomes increasingly difficult to devise methods to securely maintain the confidentiality and integrity of the stored data.

A large variety of services and applications make use of the current user's location. The provision of Location-Based Services (LBS) is highly dependent upon the accurate and boundless extraction of positional information of mobile clients. This can also facilitate a new generation of location-aware or location-based applications, e.g. to find nearby commercial offers, traffic status, nearby friends, tourist attractions, etc. The location where a user is found at any given time is considered to be private information. In modern times, users are very aware of privacy issues concerning systems and entities that locate, store, process, and report their positions in real-time. Nonetheless, in some circumstances using existing LBS, the disclosure of a user's exact location is not necessary, especially when a general area is sufficient.

5.1. Importance of Privacy Preservation

Solving adaptive traffic signal control has been investigated in all years of general publications, but the ability to distinguish different driver and similar vehicle groups is the subject of current privacy-enhancing mechanisms, mostly in driver authentication mechanisms in the case of driverless car sharing systems. Specifically, changing the driving settings to simulate someone's driving can jeopardize the safety of the driver, the accompanying passengers, and road participants. By properly designing the system that will distinguish different driving behavior characteristics, the system creators preserve the privacy of safe, responsible, and good drivers. Privacy is additionally strengthened when experts are involved in enhancing the achieved solution.

User-centricity in artificial intelligence has been recently proposed as a new, highly important principle in the design of AI systems. Affected by the lack of privacy-preserving mechanisms in the designed systems, a violation of user privacy may occur. Privacy preservation is affected by more approaches that hide, anonymize, encrypt, or modify data domains to minimize the probability of loss or leakage of sensitive information. Moreover, more similar situations have been addressed in recent autonomous vehicles' deployments, and the need for privacy is stressed in many studies. A similarly important situation is characterized in the context of DSTSC systems.

5.2. Challenges and Solutions

The support of an automotive network, which supports direct vehicle-vehicle and vehicle-infrastructure communication, facilitates the creation of prioritization, enabling traffic managers to wisely manage vehicle traffic, possibly with traffic managers considering gentle speed adjustments to promote the presence of preferred vehicles in a target area within a prescribed timetable. The creation of a target area where exclusively communicating vehicles are admitted can be interesting for highly urban traffic systems in which heavy congestion or traffic jam occurrences are frequent. Finally, the use of a reservation-based approach for the treatment of priority requests, generated by high-priority vehicles, can be implemented, together with an efficient coordination strategy.

The adoptable supportive control mechanisms which may be adopted are to prevent conflicts in well-predictable lane usage, especially in urban areas or high-density areas, in which auxiliary signalization can be provided. In future carriageways, it is possible to delineate space segments for independent vehicle motion determination that may be imposed by lane markings, road surface materials, or inductive loops. In general, wide lanes and high friction road surface can help vehicles in the movement process. The creation of special traffic control mechanisms, indicating drivers the most efficient driving strategies, such as leading vehicles performing collective platooning operation, or prioritizing autonomous cars in specific conditions are also possible.

With regard to connected vehicles or communicating vehicles, the capability of recalibrating the control mechanism frequently has to be in place, ideally in real-time. With respect to autonomous vehicles, the adoption of supportive control mechanisms that reduce the occurrence of unnecessary stops can be employed.

In summary, to handle autonomous vehicles, supportive control mechanisms can be invoked which decrease the occurrence of unnecessary stops. A strategy to manage the behavior of vehicles with high priority must be created, calibration mechanisms have to be updated, and an interaction maintenance process can be set up.

The presence of autonomous vehicles and communicating vehicles adds some complexity and new challenges for adaptive traffic signal control approaches to handle. The challenges imposed by considering these components as part of the traffic stream and the traffic control system are summarized in five macro-challenges. Each challenge is detailed and some potential solutions are proposed.

6. Integration of Location-Based Services in Traffic Signal Control

Infrastructure-based traffic management (IBTM) is a concept in which cutting-edge technologies and the latest improvements in communications are employed to increase the safety and optimize the operations of traffic on roads and highways. A concept that fits in well with the aim of creating more efficient and effective road management and traffic flow is the provision of location-based services (LBS). Such services are bound to benefit from developments based on location information technologies (LIT) and global positioning systems (GPS), and have already reached the status of a commercially viable application. These services offer customizable information and guidance according to a user's current location, by using wireless positioning of the user's mobile device. Users can benefit from LBS for real-time route guidance from their current position, and are not constrained by fixed and costly telematics systems onboard their vehicle. They can be found on the web by accessing LBS such as route planners and map servers. Vehicle positioning and rich navigation applications, often flanked by conventional applications that exploit positioning to deliver services, have rapidly expanded their foothold in the LBS domain.

Today's vehicular telematics are the result of the integration of computers and various wireless telecommunication technologies and are used to support applications such as navigation, safety, and comfort. Location-based services (LBS) provide customized information services and guidance to users while they are on the move by taking into account the location of the user. Navigation systems and geographic information systems (GIS) are common components of LBS. The Navigation Data Standard (NDS) and the OpenLS initiative of the Open GIS Consortium help define some of the standards used in LBS. This paper focuses on LBS to support traffic management, related to the construction of an Adaptive Traffic Signal System (ATSS) for autonomous vehicle environments using a cooperative approach with the involved vehicles. The integration of LBS in ATSS has already proven promising results.

6.1. Benefits and Opportunities

The development of more advanced (today) traffic signal control systems, able to offer a more dynamic and context-aware control strategy, is thus a critical component of achieving a set of future positives. Such signals hold the potential to offer predictable, efficient and safe vehicle trajectories through the built environment, making the transfer of control between driver and vehicle a manageable prospect, and supporting concurrently also the active participation of all the other transport users that will continue to include, for example, cyclists and pedestrians. During such a planned journey is to affect only the vehicle's trajectory through the next intersection, simplifying, by design if not by legal requirement, a great many challenging control problems. The underlying hypothesis is that the overall traffic system in the vicinity of the intersection, including the set of signalized intersections and any other knowledge upon which control decisions are based, must be designed to ensure that the behavior of all road users is both predictable and (from a vehicle safety perspective) be scalable with low-latencies. These aspects will be increasingly influenced by infrastructure design standards and control strategies implemented in the environment where vehicles will operate. The discussions in some earlier Marconi and Pont signal evaluation papers, for example, identified a clear self-organizing benefit to existing vehicular traffic if a range of vehicle-ahead intersection-approaching speeds (that is, flow rates) were encouraged to form through spontaneous driver decisions when further from the intersection.

The field of future transportation, dealing with the new opportunities and challenges presented by automated, connected, electric and shared (ACES) vehicles and services, has attracted considerable research efforts over the last decade, primarily motivated by the many apparent benefits that the development and deployment of such technologies can deliver. However, more recently it has been recognized that there could also be some detrimental or at least unplanned-negative consequences as a result of further technical progress in this domain. For example, localized increases in congestion are possible if benefits are largely directed to the (more affluent and) early adopters while the costs or disadvantages are borne by the wider population, especially in urban areas, where the ACES potential appears to be strongest.

6.2. Technical Implementation

The user-interface software described in section 6.2 provides graphical interfaces for selecting the overall desired control mode, individual signal phase management modes and the desired control options within each phase, and related options for setting characteristics. It then uses communication software to convey selected modes and characteristic information to each signal, and aggregates and processes a variety of real-time traffic, temporal, and location position information for use during the real-time traffic-signal control process. In a more integrated approach, the overall control commands and traffic and position data might be provided and processed onboard each vehicle communicating with each other and with signals in the ATSC system, which would represent a manageable approach to distributed decision-making and control.

The tangible approach to realizing the proposed intelligent autonomous vehicle adaptive traffic control system requires a test bed, system software and communication infrastructure, and vehicle interface equipment. As an initial test bed, single and eight-vehicle systems have been implemented to demonstrate some of the communication capabilities needed for realizing the autonomous vehicle ATSC functionality for both individual and networked vehicle operation examples. Additional ATSC functionality for multiple rolling bands of traffic controlled through multiple signals in a single-direction flow scenario has been provided in a detailed control example.

7. Case Studies and Applications

7.1 Intersection-Based Applications of Computational Intelligence 7.2 Robotic Test Cases of the Proposed Adaptive Traffic Signal Control Solution where Vehicles are Equipped with Adaptive Cruise Control

In this section, we investigate several real-world applications of traffic signal control systems in which computational intelligence methods have been employed. Several robotic test cases are then simulated to illustrate the proposed solutions. The section is organized as follows: The case study presented at the beginning of the article indicates that autonomous vehicles are unable to adapt on their own to situations where traffic signal control is performed by fixed cycle length, and opens the discussion on a prospective analysis of other control options, particularly those related to intelligent control. The next section presents research focusing on these possibilities, defining the main parameters for its implementation, analysis of the sample's processing. The last section presents the conclusion of the review demonstrating the feasible benefits of this alternative, both in terms of mobility and of improving traffic safety. More detailed applications are then presented on signal control.

7.1. Real-World Implementations

In conclusion, a fully scalable solution would involve decentralized distributed control strategies. The drivers actively pay attention to the automated traffic control for the cooperation to function and for drivers to cooperate with the traffic control. Only without conflict between the driver and the interaction of the vehicle's capable as supporting machines at low V2V boundaries of control can the system be fully autonomous. However, no implementation of this kind has been demonstrated under practical traffic conditions in the inhabited U.S. local traffic environment or abroad.

In both cases, the centralized traffic control eliminated the traditional response to congestion. Coordination between the vehicles and the traffic signal control is achieved without violating traffic safety standards. These tests have also shown that the computational intelligence for adaptive traffic signal control in autonomous vehicle environments centralized control led to a reduction in travel times and the number of vehicles that missed green. In addition, the waiting queue at most intersections was reduced. Individual vehicle travel times were also reduced. However, the need to handle real-time operational information and to make operational decisions at the pace of dynamically changing traffic conditions has been highlighted as the limiting factor for these systems' reliance. Applications of such centralized traffic control, however, to real-time traffic on general transportation problems outside the extreme traffic environment described have not been considered. Other cooperative adaptive traffic signal control testbeds and evaluation data that have been reported have additional limitations as representing a general traffic environment.

The second case, the first reported traffic system under a fully architectured vehicle in the loop project in the U.S., involves coordinating 20 intersections along the Alameda corridor. These intersections serve trucks exiting or entering the southern California Ports Area with a mix of passenger vehicles, truck platoons, and buses. Each of the vehicle drivers was provided with a portable vehicle unit that communicates with centralized traffic control using a short-range communication mechanism (400 ft. radius) and is capable of controlling the own vehicle autonomously or providing information to the driver when the vehicle unit relinquished control to the centralized control. Data archive including detailed traffic data was extracted from the control system. The systems operated with cycle lengths from 80 to 100 seconds. The centralized traffic control used traffic count data. When vehicle data was available, the centralized traffic control reduced the cycle length and variations in either the beginning of the red phase or cycle length were introduced for local priorities in under prespecified delay requirements.

The same cooperative adaptive traffic signal control approach has been implemented and tested in real-world traffic environments in two large practical cases currently in Los Angeles, California. The first case involves real-time traffic signal control in a Los Angeles city traffic environment coordinating 32 intersections. The traffic signals operate with 4 signal phases each. Actuated on a per intersection basis, vehicle detectors provided traffic data to individual intersection controllers to occasionally update the list of queued vehicles, perform requests for neighboring intersections, and release the green signal phase for the directions that are ready. A central server provided intersection controllers with traffic flow models and retiming information.

7.2. Success Stories and Lessons Learned

All of these issues can be resolved by using autonomous vehicles, the onboard computers of which can provide the necessary real-time traffic flow data, the software platform that is used to build traffic signal controllers, the communication capability that is required to transfer the signal timing plans, and the cooperation capability that enables the traffic signal controller to influence traffic flow in a predictable and safe way. Only the cost, or the unit price per autonomous vehicle, remains to be low enough to be affordable at a relatively large scale. A moderate cost level seems realistic because most of the technology that is required for adaptive traffic signal controllers in autonomous vehicle environments is already present or under development with manufacturing cost reductions in mind. The provision of the necessary traffic flow data, be it vehicle headway information or volume-density relationships, is arguably the most elusive part of the proposed systems. As some of the technological components are arranged in a network, a different kind of collaboration can be expected to help in solving this problem.

Traffic control by adapting phase lengths in real-time through vehicle actuations is, in principle, the most autonomous form of traffic flow management that can be executed by traffic control at intersections. With the arrival of autonomous vehicles in the larger traffic system, adaptive traffic signal control is likely to become more important because it can help maintain a flow that can naturally emerge, which autonomous vehicles can benefit from to a considerable extent. Even though the principles of adaptive signal control are not very complicated, building a practical system can be non-trivial. The major problems are related to data availability, sensor technology, real-time computation, and unpredictable driver behavior. Most of these problems have been solved successfully, but they typically limit the use of adaptive signal control to a lower number of transportation corridors or adjacent intersections, and they typically limit the set of traffic performance objectives that can be optimized.

8. Future Directions and Research Opportunities

The traffic signal control environment in autonomous vehicles suffers from great heterogeneity, uncertainty, and distribution of information, services, and multiagent cooperation inherent in the telematic traffic environment. In this sense, there is no universally suitable system for controlling traffic signals as a function of autonomous vehicles. Therefore, additional factors such as continuous real-time visualization of the state and position of each vehicle, the prediction of the traffic flow, and the generation of multiple services to manage enrollment, and the integration of that data object are needed. Ultimately, the proposed idea is validated and the results are favorable for telematic traffic in the context of intelligent transportation systems and connected vehicles. However, more studies to ensure efficient real-time use of the concept are needed as present solutions in the literature do not cope with massive architecture data control.

Traffic signal control is very important for intelligent transportation systems in order to achieve efficient traffic flow and optimize the use of infrastructure. Furthermore, if this control is carried out in the environment of autonomous vehicles, the situation becomes much more complex. This chapter discussed at length traffic signal control technology in intelligent traffic environment in autonomous vehicles and possible solutions, highlighting the importance and aptness of adaptive computational intelligence algorithms in this regard. The Nadhaz architecture was presented as a means to coordinate traffic lights and autonomous vehicles. Overall, the use of the hybrid model for autonomous vehicle control was also presented.

8.1. Emerging Technologies and Trends

The research done supports the emerging connected and autonomous vehicle and smart city environments, where vehicles and traffic signals are able to communicate and First Responder traffic signal pre-emption is welcomed. The research conducted studies the effect of increasing levels of connected vehicles on traffic signal control performance, environmental prioritization, and activity prioritization in connected and autonomous vehicle and first responder environments using MONARCH and VISSIM simulation models. The conclusions are that an increasing number of connected vehicles can provide significant traffic, environmental, and priority improvements, and validates that adaptive traffic signal control can substantially improve traffic flow, stops, fuel consumption, and air pollution, with optimal results at a connected vehicle penetration level of 600 per kilometer (0.6%) and declining amplified benefits at higher penetration levels, and that there is also an embedded environmental benefit.

Significant changes are required in infrastructure and policy to be supportive of the development and early adoption of connected vehicles. The traffic signal is the infrastructure element having the greatest impact on vehicle operation. Recent studies have defined traffic signal settings for connected vehicles by minimizing vehicle delays, stops, fuel consumption, and greenhouse gas emissions. Vehicle-actuated traffic signal systems can be much more sophisticated than traditional fixed-time actuated systems. Traffic signal settings can be updated in real time in response to arrival vehicles. Application of computational intelligence and connected vehicles in adaptive traffic signal control is identified as having significant operational and environmental benefits. Experimentation shows that these improvements depend upon a minimum of 3.5% connected vehicle penetration to have significant traffic flow improvement but reduced environmental benefits.

8.2. Potential Research Areas

Theories governing the creation of new types of interconnected AVL systems, such as traffic signal grids and active area grids, may be generated. - The arrival of the intelligent traffic management system. - Many ideas proposed only two years ago at the beginning of this article have now been possible to use. They may have been implemented in some region of the world, or they may still be laboratory demonstrations. - The use of platooning of multiple core drivers providing continuous green lights and helping to avoid stop and go traffic.

- New simulation technology has replaced old traffic simulators. New ways for designing and assessing traffic signal controls have become accessible. This could lead to the development of better control schemes. - Traffic information and traffic control data communication between vehicles and traffic control centers in the interconnected vehicle environment become possible. There is an opportunity to investigate a new class of traffic-adaptive traffic signal control mechanisms. - Traffic cameras, agent enabling systems, and other types of monitoring equipment have become more common since they are needed to control the autonomous vehicles that are currently being proposed. The feedback to allow learning of good control strategies may now be as cheap as it has ever been (assuming that the cost of monitoring devices is prioritized). The feedback necessary for learning adaptive traffic signal control mechanisms has probably never been possible before.

The following are some of the potential research areas that could be explored. It is assumed that researchers might have considered this research area before because adaptive signal controls were being investigated since the early stages of smart cars in the 1990s. The word 'Traffic Signal Control' is a very old concept that appears in the earliest Computational Intelligence application books. It is possible for advances in both areas to have created new efficiencies that had not been apparent in the past.

9. Conclusion

Autonomous mixed traffic control systems should also increase cooperation and communication between connected and automated vehicles. Better cooperation and communication will allow the transition to connected and autonomous vehicles (CAV) to be faster. This proposal can be extended to include pedestrians, cyclists, and other vulnerable road users. Their safety must also be ensured. In this paper, only the concept was presented, not the different aspects of the design of the control system. This work was undertaken with a cooperation system based on vehicle to infrastructure (V2I) and vehicle to vehicle (V2V) communication. The cooperation system uses centralized, shared control of the CAV problem. The method uses a genetic algorithm to solve the control problem. The concept and the AI algorithm are independent. Any state-of-the-art AI algorithm could also be incorporated into the cooperation system. Additionally, it is necessary to consider external events that could influence the decision.

We proposed the concept of adaptive traffic signal control in the world of connected and autonomous vehicles. The challenge is how to adapt traffic signal control to the mix of different vehicle automation and communication capabilities. In the period of transition, when only part of the vehicles have these capabilities and they are not sufficiently heavily used to support decision-making, traditional traffic signal control systems should remain at the signals. Computational intelligence (CI) methods are well suited for the task, not only for their algorithmic flexibility but also for other features, such as the ability to process data from a variety of sources, and the ability to differentiate context conditions based on different vehicle levels of automation.

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