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Autonomous Vehicles on the Smart Roads: Challenges and Potentials

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ABSTRACT

Self-driving vehicles and smart roads are not new concepts. These ideas have been discussed for many years, but for much of this time, the required technology was not available to make them a reality. Just recently has our technology caught up to our ideas, and we are beginning to see progress towards the realization of the automated highway system. The transition to a completely automated highway system is still in progress, which still leaves many questions to be answered as well as novel solutions to be presented. Using modern research papers to formulate a sound basis in current automated highway systems research, novel solutions are presented for various problems still existing in the field.

Keywords: autonomous vehicles, queuing system, dynamic traffic control, automated highways, automated urban networks

Introduction

The idea of automated roadways is not a new one; however, the lack of capable technology hindered the progress of this idea for much of its life. It is only recently with modern computing equipment that intelligent vehicles and highways can be tested and refined. The goal of these systems is to increase efficiency and safety on highways and urban transportation networks. These benefits would affect many aspects of life, including decreased energy consumption and travel time. In this research, we first review the recent literature on the emergence of intelligent transportation systems. Additionally, we discuss how the emergence of intelligent systems will play a role in the future of transportation engineering. Issues of hetero- and homogeneous- traffic safety, control, and implementation were presented for further discussion to produce innovative ideas on how to fix the problems of highway/network efficiency and safety.

Problems such as merging systems procedures, intra- and inter-communication systems between vehicles and vehicle-infrastructure, and the transition into a fully automated traffic system were the main focuses throughout the reviewed literature. However, these are global problems from which more specific issues aim to be solved through different logistics. In this research, a set of traffic control and management strategies is proposed to improve the performance of urban networks in connected environments. The first proposal is a first-in-first-out traffic control strategy for increasing the capacity of smart intersections. The second proposal is an optimal routing strategy for autonomous vehicles to reduce the traffic congestion in urban networks. Finally, the potentials of real-time speed control at the perimeter of urban networks for enhancing the integrated system performance are demonstrated.

Concept of Smart Roads

The concept of smart roads dates back to the 1930s (Ackerman, 2016; Vanderbilt, 2012; Weber, 2014). In 1960, the *New York Times* published an article on the practicality of automatic driving on highways with a central-control system (Ingrahams, 1960). Since then, extensive research has been conducted on the operation and control of driverless cars and their potential impacts on the safety and efficiency of traffic flow (Fukunari & Malmborg, 2009; Mladenovic & Abbas, 2013; Peng & Tomizuka, 1993; Rajamani & Shladover, 2001; Roncoli et al., 2014; Shladover, 2000, 2005; Zeng et al., 2012; Zohdy et al., 2015). However, only until very recently have advances in wireless communication, high-performance processing, and artificial intelligence made it possible to turn the concept of the autonomous vehicle (AV) into reality. Currently, the automobile industry increasingly strives to develop AV prototypes. Many major manufacturers, such as Audi and BMW; newly-born companies, such as Tesla and Local Motors; and technology companies, such as Google and Apple; have ongoing programs to introduce their own AVs by 2025 (Kockelman et al., 2017; Shi & Prevedouros, 2016).

The National Highway Transportation Safety Administration defines four levels of automation for vehicles (NHTSA, 2013). Level 0 and Level 1 technologies include preliminary driving assistance systems, such as cruise control, lane-centering, lane-keeping, collision-warning, blind-spot monitoring; and electronic stability control. These technologies improve road safety and make driving more convenient. In Level 2, vehicles have the capability to operate automatically in specific conditions. For example, Level 2 vehicles may operate on highways without drivers' physical engagement. However, drivers are still solely responsible for monitoring roads and safely operating vehicles. Level 3 automation takes full control of vehicles, although operation may still have to be transferred back to drivers on some occasions with adequate transition times. Finally, in Level 4, vehicles are completely driverless.[1]

Advocates for intelligent vehicles and automated highway systems believe that increases in both highway capacity and safety on existing infrastructure can be achieved through technological advancement. Varaiya (1993) outlines various control theories on how an Intelligent Vehicle Highway System can be implemented to reach the aforementioned goals. Varaiya (1993) also introduces the "platooning" concept where vehicles are grouped together in order to increase highway capacity. In addition to platoons,

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[1] Society of Automotive Engineers (SAE) also defines six levels of driving automation, from Level Zero (no automation) to Level 5 (full vehicle autonomy) for consumers. (SAE, 2016).

control systems for both the vehicles and highways are presented. These systems are divided into architectures present in the individual vehicles and the overall highway network. A simple experiment was conducted using a two-car platoon to observe the performance of the proposed control system. The results of this research show the positive impacts of implementing the proposed platooning strategy.

In contrast, Shladover (2000) explores the gaps between conventional transportation systems and fully automated systems. The paper proposes a guided plan that can be followed to convert the current system to a fully autonomous one. The sequence of steps covers planning and technology needed for both individual vehicles as well as the overall network. The deployment strategy begins with vehicle technologies, such as adaptive cruise control. Subsequent steps build upon this (i.e., vehicle-to-vehicle communication) and eventually lead to infrastructure changes, such as dedicated lanes to accommodate these more intelligent vehicles. A major obstacle in the progress toward an automated system is the adoption of these emerging technologies by major shareholders in the transportation realm, such as state and local governments.

Horowitz and Varaiya (2000) achieved full implementation of an automated highway system. Their research showcases a culmination of the California PATH program with an emphasis on the highway system’s control architecture. The control architecture consists of different layers. Each layer controls a different aspect of vehicle control and highway guidance. The operation of each layer is briefly discussed and described in the operation of the overall automated system. While their successes came after years of research, it should still be noted that full automation requires major infrastructure revision to ensure that the goals of higher efficiency and safety are obtained.

Platooning autonomous vehicles can significantly improve the performance of highways and urban networks. Fernandes and Nunez (2015) developed algorithms for the control and stability in traffic of communicant autonomous vehicles traveling in platoons. Each vehicle was labeled as a “Leader” or a “Follower”. Acceleration, deceleration, and maneuverability were controlled through algorithms to ensure safety and stability among members of the platoon. These algorithms were placed in MATLAB/Simulink and SUMO simulation software to test the soundness of the system. The simulation results supported that communicant autonomous vehicles travelling in platoons increase traffic capacity and avoid congestion.

Thus far, only research on the implementation of autonomous systems in highway settings has been discussed. Amirgholy, Shahabi, and Gao (2020) introduced the idea of an automated system that also accounts for mixed traffic. The idea proposes new lane management strategies in corridors, in which human-driven vehicles (HVs), autonomous vehicles (AVs), and communicant autonomous vehicles (CAVs) are considered. The research states that to optimize the network inflow, the CAV platoon size in the corridors must be controlled. Three different lanes are proposed: a conventional lane where all types of vehicles are allowed to transit, a high-performance lane dedicated to AVs and CAVs, and an automated highway system for CAVs only.

Following the same track and analyzing traffic within urban networks, the implementation of smart intersections is presented by Amirgholy, Nourinejad, and Gao (2020). The idea is introduced with a stochastic analytical model that aims to reduce congestion at intersections. The model assumes a fully automated system in which the automated vehicles transport in a platoon-based organization while following a single direction with no turns. The idea proposes signal-free intersections where the outmoded traffic lights are replaced by a cooperative control system that remotely coordinates the movements of the CAVs through intersections. The model works with speed sensors, vehicle-to-vehicle communication, vehicle-to-infrastructure technology, and an actuation system that ensures synchronization and resynchronization of the system.

This research investigates the challenges and potentials of using autonomous driving technology on automated roads in the smart cities of the future. This research proposes different progressive traffic control and management strategies for improving the mobility and reducing the congestion in cities. At urban intersections, this research proposes substituting conventional signs and signals with a decentralized control system. The system dynamically adjusts the speeds of AVs to coordinate their safe passages through intersections in first-in first-out (FIFO) settings. In urban networks, this research proposes optimizing routing of AVs to minimize the total travel time of the conventional vehicle and AV users in the network. To maximize the performance of urban networks, this research proposes dynamically controlling the inflow of urban networks by optimizing the speed of AVs on the network perimeter. This will keep the density of vehicles optimized in the urban network. The proposed traffic control and management strategies are further discussed in the following section.

Traffic Control and Management Strategies

These papers present different problems and solutions that span the course of many years. Interestingly, some of the same problems outlined in earlier papers are still being discussed today. Issues of control and implementation, which continue to be studied, still exist. As well as these persistent issues, new areas of interest also arise – lateral maneuvers, multi-lane planning, and the inclusion of pedestrian activity. These new areas offer an opportunity to do research which will help move this field forward. The following sections will present new research ideas, with the previous papers serving as background and reference material.

First-In-First-Out Control Strategy for Smart Intersections

The idea of a fully automated highway system has been widely studied in literature, while the concept of cooperative traffic control at signal-free urban intersections is relatively new. Cooperative control of traffic at signal-free intersections improves the performance of urban networks. Following the idea of smart intersections presented in Amirgholy, Nourinejad, and Gao (2020), a decentralized control system that analyzes speed, distance, and time parameters to coordinate the safe passage of vehicles in FIFO order was discussed. It is illustrated in Figure 1. Coordinating the passage of AVs at signal-free intersections can significantly improve the performance of urban networks. However, implementing a call-ahead reservation-based approach does not necessarily minimize the experienced delay at the intersection. This may be considered the primary drawback of the proposed strategy.

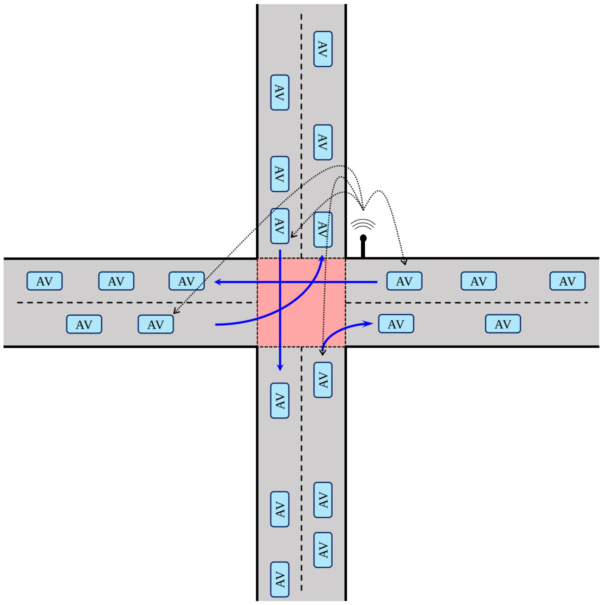

Figure 1. First-In-First-Out Control Strategy at Smart Intersections

In this system, each vehicle is considered an individual agent that is identified by the actuator when it approaches the intersection. The vehicles are then labeled according to their predicted arrival times at intersections. The vehicles' arrival times are predicted using their instantaneous speeds. The intersection will be reserved for the uninterrupted passage of vehicles at their optimal arrival times. To ensure and improve the intersection's performance, the actuator communicates with vehicles to authorize or deny their passage into the intersections. Additionally, the infrastructure of each road that connects the intersection can implement additional sensors. These sensors receive information from the actuator and communicate it to vehicles on each road. That way, there is only one activated or authorized road at a time. The system must have a time gap to ensure safety, but it should be minimized to achieve optimum capacity.

Optimal Routing of Autonomous Vehicles

Automated highway and network systems aim to increase efficiency and safety of roadways through multi-layer control architecture and communicant autonomous vehicles. Previous research provided solutions at the lower levels of the architecture; however, many of the system's capabilities will be determined by the higher levels. It has been theorized that these higher levels will be responsible for maintaining location and speed data for all individuals in the system, which presents the opportunity for these levels to be optimized.

One factor in increasing efficiency is travel time. This applies to highways but is especially important in urban networks. The ability to reduce travel time may potentially increase human productivity and decrease the number of vehicles in the network at any given time. This can be achieved through route optimization based on real-time network data and the use of communicant autonomous vehicles.

Expanding on the systems used in smart intersections, if all this data is aggregated at the network level, this layer will know where every vehicle is in the network and at what speed it is travelling. To reduce the complexity in the network layer, an urban network can be broken down into sectors. As a vehicle moves through these sectors, communication and control can be handed off to the sensors and equipment of the receiving sector. This would be similar to how a cellular network operates with a moving cell phone. To further reduce the complexity in the overall network layer, a sub-layer can be used. The sub-layer can store origins and destinations of each vehicle, which can then be fed into the network layer. The network layer can then determine an optimal route based on the variables in both layers. It should be noted that reduced total travel time does not equal shortest distance through the network.

In addition to being able to provide optimized routing for individual vehicles, as depicted in Figure 2, the network layer can also begin to assign platoons based on the determined route. This platoon formation can be based on a certain error percentage between vehicle end destinations. Based on this predetermined route, the network layer can determine an optimal platoon size as it is able to anticipate any intersections and obstacles along the route. This information can be fed down to the infrastructure sensors for more immediate decisions as the platoon travels. However, effectiveness of the proposed optimal routing approach largely relies on the users' cooperation. This is because the optimal paths may be different from the shortest paths in some cases. This can be considered the main limitation of the proposed approach.

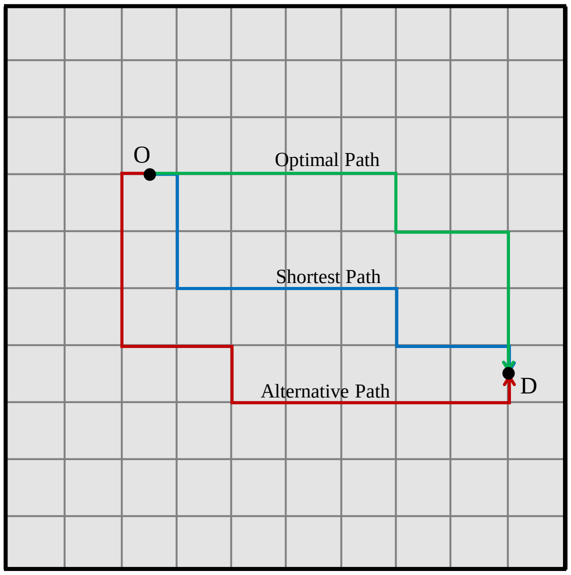

Figure 2. Routing In Grid Urban Networks

Dynamic Speed Control at the Perimeter of Urban Networks

To reduce congestion in urban networks, it is necessary to regulate and restrict the inflow of vehicles to keep a controlled density within the city. Currently there are different methods to target this purpose, such as speed reduction through signalization and traffic lights at highway entrance ramps that control vehicle passage. However, it is a difficult task to precisely control the speed at which people drive. Moreover, the implementation of communicant autonomous vehicles can ensure this speed reduction through infrastructure-to-vehicle communication technology.

The overall purpose is to reduce or slow down inflow into the city, where congestion is the biggest problem. This problem mainly occurs in heterogenous traffic systems where autonomous and conventional vehicles have access to all lanes. Therefore, the focus should be on the corridors that precede the network. This research proposes the estimation of a perimeter around the urban network, delimited by infrastructure items that create a closed loop around the city. These items' main purpose is to communicate with autonomous vehicles and order them to decrease their speed a specific percentage. This will allow the dynamic control of AVs' speed based on the instantaneous traffic condition of the integrated system. This will also allow the optimization of the urban network's inflow over time (Kouvelas et al., 2017). The delimitating points will be located at the main highways that surround the network in the form of a light post. This loop will act as an invisible border that the car will identify in its trajectory and will decrease its speed the specified percentage.

However, because the system consists of a mixed traffic condition, the primary question is how to reduce the overall inflow of urban networks. The scope of the system goes beyond autonomous vehicles. Having random autonomous vehicles in each lane creates a big impact along the lane in which it is located. One AV in a lane can even control the speed of the cars behind it, as shown in Figure 3. In the moment that the AV crosses the delimited perimeter and decreases its speed, the cars behind it are forced to slow down as well. The percentage of reduction in speed must be precisely calculated, so that the other cars do not feel the shock waves phenomenon of a sudden stop. Instead, this will ensure that the shock waves can be minimized and are almost imperceptible.

Implementing the proposed perimeter control strategy can significantly reduce congestion in urban regions. However, it can also cause traffic to worsen in suburban areas by transferring congestion from inside the region to its perimeter. Moreover, optimizing the inflow of the network in real-time requires an accurate estimation of the instantaneous traffic state of the network over time. This can limit the applications of the proposed approach in practice.

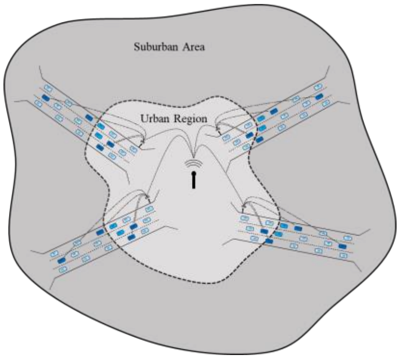

Figure 3. Perimeter Traffic Control Via Autonomous Vehicles in Urban Network

Conclusion

The implementation of a fully automated traffic system is an idea that has been discussed and researched for many years. It is only currently that modern technology allows us to model and simulate automated traffic systems to demonstrate their benefits to society. The discussion has opened the space to people of all fields to give opinions and possible solutions to the problems that the proposed system implies. Recent research in the field of driving automation has produced many theories and papers regarding the planning and implementation of automated highway systems. This proposes a set of traffic control and management strategies for improving the performance of urban networks in connected environments. The objective of the proposed first-in-first-out control strategy is to improve the performance of smart intersections. Implementing optimal routing and perimeter control strategies can significantly reduce the congestion in urban networks. These ideas can be transformed into detailed plans for implementation and cover different aspects of how to increase the efficiency of smart transportation systems.

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