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Original scientific paper

Proposal for Fuzzy based Adaptive Traffic Signal Control for Reducing Vehicle Emissions

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Abstract – **Traffic congestion and resulting pollution affect the quality of life in cities, notably in countries with dominant old diesel engines. One solution is Adaptive Traffic Signal Control using vehicle type and emission measurements. Therefore, a fuzzy controller using a magnetic sensor for classifying vehicles and a sensor for measuring emissions is proposed.**

Keywords – **Intelligent Transportation Systems, Fuzzy Logic, Adaptive Traffic Signal Control, Vehicle Emissions, Magnetic Sensor.**

I. Introduction

The problem of traffic congestion and the resulting environmental pollution is not new and affects the quality of life in urban areas. Such problems are undoubtedly more significant in developing countries where traditional transportation modes with many old diesel engines are still dominant. One way to tackle this problem is to apply Adaptive Traffic Signal Control (ATSC) that uses additional real-time measurement information as input for changing the signal program on intersections [1]. Such information can be related to vehicle type and current vehicle emissions levels and is applied in this work also. The envisaged approach is feasible, especially when modern optimization methods [2] are used in a connected vehicle environment [3]. An important fact is that an appropriate adaptation of the signal program can reduce vehicle stops and shorten queueing lines improving intersection throughput and reducing vehicle emissions [1, 8].

In this paper, a proposal for a fuzzy logic-based ATSC using a newly developed magnetic sensor capable of classifying vehicles and sensor/integrated air quality monitoring station for measuring vehicle emissions is described. The proposal is based on the authors' previous work given in [4, 5, 8] that is augmented with the extension of the inputs of the fuzzy logic traffic signal controller with information about truck and bus presence coming from a magnetic sensor. The concept of the ATSC's structure and simulation-based evaluation is described, and plans for real-world testing on a highly polluted isolated signalized intersection are outlined in continuation.

This paper is organized as follows. After the introduction, the ATSC based reduction of vehicle emissions is described in Section II. Section III elaborates on the newly developed sensor, and Section IV the proposed fuzzy logic-based ATSC. Simulation-based testing methodology is given in Section V and Section VI ends the paper with a conclusion and description of future work.

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II. Reduction of Vehicle Emission and ATSC

Traffic signal control systems with fixed signal programs are still being used today on many of the signalized intersections in urban environments. That leads to decreased comfort of traveling, traffic safety, and a general increase in queue lengths and waiting times. Since traffic flows change significantly during the day, there is a need for ATSC. Today there are a lot of contributions and methods that are used for ATSC. Many of them range from classic solutions to holistic approaches using services from the domain of Intelligent Transportation Systems (ITS) combining several popular tools for optimization [2, 9] or methods from the area of artificial intelligence such as fuzzy logic, genetic algorithm, neural networks, and computer vision for finding the optimal signal programs [2, 4, 7, 9]. ITS based approaches can adapt the signal program by changing a particular phase duration and their sequence. To alleviate the signal program's adaption and ensure all safety requirements, the NEMA (The National Electrical Manufacturers Association) ring structure of signal programs is used [8, 9]. Decision points for phase sequence adaptation can be implemented to respect safety requirements regarding the amber and red time needed for the proper transition between phases.

With increased concern about the environmental state in recent years, vehicle caused emissions have become a significant indicator of driving behavior in road traffic. Among other measured parameters like travel times and queue length, vehicle emissions have shown to be very important when traffic control criteria are being defined [11]. Both in terms of determining the rate by which they need to be reduced and for discovering other traffic-related problems like their correlation with stop times on signalized intersections. Especially when different vehicle types have different dynamics and pollution rates [1, 10], and when in such cases, preemptive traffic signal control can be applied. Usually, preemptive traffic signal control is applied to change the signal program to reduce the travel time of emergency or public transport vehicles [10]. The same principle can be applied for high polluting vehicles like vans, trucks, and buses [1]. Modern sensors can detect such vehicles proofing the feasibility of such an approach [1, 5]. Especially in an environment of connected vehicles that are more and more present in today's traffic flows [3]. The availability of new measurements triggered the research about the correlation between vehicle emissions and traffic control strategies [11].

Reducing the number of stops and acceleration and deceleration cycles of high polluting vehicles reduces their fuel consumption and emission. At the same time, there is a positive effect on all other vehicles (mainly cars) also. This positive effect results from the fact that high polluting vehicles like vans, trucks, and buses have slower dynamics then cars acting as a traveling bottleneck/congestion point on the road. This is most evident for the high-loaded trucks. Since still today most vans, trucks, and buses use diesel engines, they contribute significantly to traffic-related pollution. Defining better traffic control strategies for protected areas of a city (usually city center) can, thus, reduce the pollution resulting from road traffic [11].

III. Measurement of Vehicle Emissions and Vehicle Classification

Road transport is a significant contributor to emissions of greenhouse gases and air pollution. According to the European Environment Agency (EEA), the road transport sector is responsible for almost one-fifth of Europe's greenhouse gas emissions [12]. Measuring exhaust emission from vehicles is a complex issue; there is a significant difference between official emission measurements and vehicle performance on the road. For example, nitrogen oxides (NO_x), a major air pollutant that harms health and the environment, can be more than seven times higher under real-world driving conditions for new vehicles than in official tests. New vehicles can emit up to 40% more carbon dioxide (CO_2) than official measurements would indicate [13]. Thus, the on-road vehicles sensing/counting are not sufficient to determine the actual level of emissions based on laboratory emission data.

A significant advantage in this proposal is the four-leg isolated signalized intersection measurement of emission and air pollution with one integrated air quality monitoring station based on SAM3x (ARM Cortex M3, 32-bit MCU) with Inova PM10/2.5 sensor, Winsen CO, CO_2, NO_x, and SO_x gas sensors, Sensirion temp/hum sensor, with Real-Time Clock and Data Logging on SD card, followed with four sensor nodes (for each intersection approach lines one) for vehicle sensing/counting based on the triple-axis HMC class magnetometer from Honeywell and ESP32 Espressif ultra-low-power MCU (Fig. 1). Air quality monitoring station and magnetometer sensor nodes use an ESP32-NOW low power 2,4GHz Wi-Fi communication protocol to communicate with a master access point. All measured data will be stored on a server and available to the ATSC.

After successful on-road vehicle sensing/counting, the vehicle classification process is very important. The later addresses the process and methodology to classify a vehicle signature in a specific format into a pre-defined vehicle class (e.g., passenger vehicle, bus, or truck [5]). For the purpose of our proposal, the vehicle magnetic signature from each magnetic sensor node needs to be transformed into average-bar and hill-pattern recognition schemes [14]. Such recognition schemes depend on vehicle types enabling a high accuracy classification of vehicles. Vehicle sensing/counting and vehicle classification data followed with real-time data from an air quality monitoring station implemented on a four-leg signalized intersection are real input data for the proposed fuzzy-based ATSC.

Fig. 1. The procedure and communication protocol for data collection

IV. Proposed Fuzzy Logic Control Method

Apart from day-to-day use in reoccurring and predictable traffic scenarios, adaptive fuzzy traffic control systems serve well in non-recurring traffic situations and can be used to decrease the overall number of stops and travel times significantly [4,8]. Subsequently, this effect also decreases overall fuel consumption and, therefore, also vehicle emissions. Further use of fuzzy-based systems for ATSC, which rules were additionally optimized with the genetic algorithm, shows that Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen Oxides (NO_x), and Carbon Dioxide (CO_2) were all strongly correlated with fuel consumption except for NO_x [7]. The research paper [8] shows vehicle emission values simulated on an isolated intersection model along with the measured fuel consumption. All the scenarios in [8] show improvement in terms of decreasing the emission rate compared to the fixed traffic control scenario, especially the one with the highest traffic demand.

The proposed adaptive system is an augmentation of the fuzzy traffic controller described in earlier work [4]. It consists of two fuzzy controllers, one for controlling the adaptive phase duration, and the other one for controlling the adaptive phase sequence. Each one is using different sets of interference rules and membership functions while working simultaneously during operation. In this paper, trapezoidal membership functions and Mamdani based inference are used. Both systems are used to calculate the output "Urgency" of the current phase. It describes which phase is the most urgent one, and therefore, it should be the next one executed in the current signal cycle decision point. The cumulative urgency of a particular phase is calculated using Eq. 1:

$$U_p = \frac{\sum_{i=1}^{n} Ul}{n}, \quad (1)$$

where U_p is the urgency of a particular phase; n is the number of lanes in a certain phase; and Ul is the urgency of a certain lane obtained using the proposed fuzzy logic interference system. The urgency value is from the interval [-1,1] and enables phase shortening and prolongation. To obtain the final duration of a particular phase, the following equations are applied:

$$\Delta T = U_p \cdot \Delta T_{max}, \tag{2}$$

$$\Delta T_{max} = T_p \cdot CDC, \tag{3}$$

where ΔT is the final duration of a particular phase, ΔT_{max} is the maximum amount of time a phase can be shortened/prolonged, and CDC is the maximum duration change coefficient. The later is usually set to a value between 0.20 and 0.30, denoting a maximal relative duration change between 20 and 30% of a particular phase. Obtained phase duration and sequence adaptation are applied in the scope of a control loop given in Fig. 2.

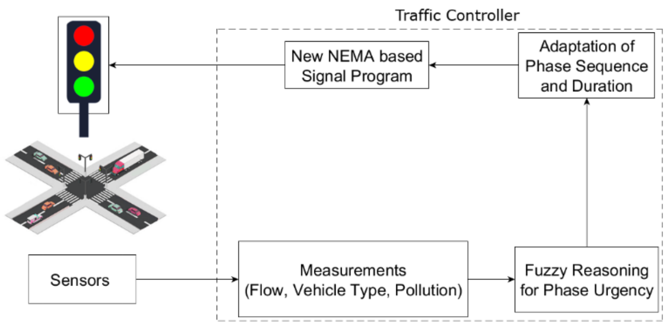

Fig. 2. Block scheme of the complete system

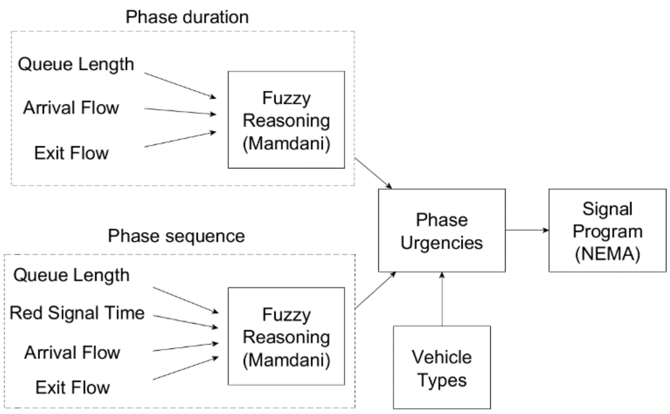

Fig. 3. Block scheme of the proposed fuzzy ATSC

The proposed adaptive system for phase sequence and duration further enables the processing of gathered vehicle type data as it is presented in Fig. 3. Its purpose is estimating the influence on the environmental aspect of the observed isolated intersection. The proposed enhancement of the existing system consists of added weight coefficients assigned to the vehicle classification types before the final signal program compatible with the NEMA ring structure is generated. For example, vehicle type "truck" has a weight coefficient of 1.2, while vehicle type "car" has a weight coefficient of 0.8. These values are then used to adjust the values of the already calculated output "Urgency," by multiplying them and therefore adding vehicle type into consideration. The addition of vehicle classification to the adaptive control system serves as a means of measuring the rate at which the air pollution on the isolated intersection is being increased, based on the number of vehicles in certain classes. The results of the pollution rate will be used to adjust the reasoning rules of the proposed fuzzy ATSC further.

V. Simulation Methodology for Testing

The urban intersections are a vital element of transport infrastructure and have a significant impact on traffic efficiency and environmental aspects. Before a real-world implementation of a solution in the form of ATSC, it is best practice to consider all the parameters and evaluate them using a microscopic traffic simulator with realistic traffic scenarios. Taking the purpose of the ATSC into account, it is crucial to test the newly constructed ATSC against the already existing fixed signal program across different traffic demand scenarios to accommodate for possible inconsistencies.

The testing and evaluation of the proposed adaptive system will be performed on a highly polluted, isolated urban intersection. The chosen intersection is located in the wider urban area of the city of Bitola, North Macedonia, as displayed in Fig. 4. To collect research data for the evaluation of the proposed ATSC, the following field data will be measured using the produced sensor from results described in [5]: a) geometric elements of the chosen intersection, and b) vehicle volume and data from the magnetic sensor capable of classifying vehicles and sensor/integrated air quality monitoring station for measuring vehicle emissions.

Fig. 4. Intersection design

The proposed traffic controller will be tested using microscopic simulator VISSIM, vehicle emission simulator EnViVer, and the programming platform Matlab. The procedure of communications and information processing data of the software mentioned above tools is as follows. The VISSIM COM interface provides a connection between micro simulator VISSIM and Matlab platform and enables them to exchange data and in real-time. Traffic flow parameters for the chosen isolated four-leg intersection created in VISSIM are collected, calculated, and executed using appropriate functions created in Matlab. Matlab function has access to detectors in VISSIM, which enables simulating the work of real traffic detectors and controllers. Additionally, VISSIM records all the required data for calculation of vehicle exhaust emissions into a detailed output data file after the simulation ends. These output data, after imported into the software EnViVer, will be used to calculate and obtain vehicle traffic emissions, observed during the simulation period. Using EnViVer, the results of traffic simulation software with emission models can be combined. This enables one to predict and to study the environmental impact of the proposed ATSC and to optimize its parameters accordingly [6].

The testing and evaluation of the newly proposed adaptive system in different traffic demand scenarios must be additionally obtained. For this, typical traffic demand scenarios related to morning and afternoon peak hours, transit periods between the peak hours, and free-flow traffic must be considered.

VI. Conclusion

ATSC systems can improve throughput on a signalized intersection and reduce the travel time of certain classes of vehicles when applied correctly. The later is called preemptive control and is usually applied for emergency and public transport vehicles. It can also be used for adding priority to high polluting vehicles like vans, trucks, and busses. By reducing the number of stops and acceleration and deceleration cycles of such vehicles, their emission levels can be reduced, and at the same time, traffic throughput increased. The resulting traffic controller can fulfill two criteria important today in urban traffic control: reduction of traffic congestion and reduction of vehicle emission. Such an approach is needed to achieve the EU goals of a smart, green, and integrated transport network.

This paper proposes a concept for a fuzzy logic-based ATSC that can utilize vehicle type measurements, and a framework for its simulation-based evaluation is described. The next step of this work will be the implementation of the proposed controller and its in-depth evaluation using calibrated realistic traffic scenarios in the chosen microscopic simulator. Optimization based on the genetic algorithm will also be considered to solve the complexity problem of creating fuzzy reasoning rules and needed membership functions.

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