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Fuzzy Traffic Light Control Based on Phase Urgency

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***Abstract*—Due to dynamical traffic flow changes in urban areas, traffic congestion occurs on many intersections over a certain period of time. Today there are still many traffic light controllers with fixed signal programs used on signalized intersections, which causes aggravation of the overall state of traffic. To solve this problem, some solutions have been presented within the field of Intelligent Transport Systems. This paper presents an adaptive traffic light controller based on fuzzy logic used for improving the traffic flow on an isolated intersection. Three methods of adaptive traffic light control have been designed in order to determine the urgency of a particular phase for adaptation of phase duration, phase sequence and simultaneously phase duration and sequence. The proposed adaptive methods are compared to a fixed controller in three scenarios with different traffic demands to prove their effectiveness. For this purpose, a model of an isolated intersection in the microscopic simulator PTV VISSIM, and a fuzzy based traffic light control system in the MATLAB programming environment have been implemented.**

***Keywords*— Intelligent transport systems; Traffic light control; Microscopic simulation; Urban intersections; Fuzzy logic**

I. Introduction

In the present time as traffic infrastructure in urban areas has little or no space for expansion, different methods of dealing with the increase in traffic demand must be employed. Only building new road infrastructure is not feasible. In urban areas, it is often impossible to expand the road capacity by adding new traffic lanes due to facilities located in nearby areas. Because of such problems, the domain of Intelligent Transport Systems (ITS) provides a wide range of services which are used to solve many traffic problems in urban areas. These ITS based services include adaptive traffic light control (the focus of this paper), route optimization, informing users, etc.

On many of the signalized intersections, traffic light control systems with fixed signal programs are still being used today. That leads to decreased comfort of traveling, traffic safety, and a general increase in queue lengths and waiting times. Since traffic flows change over periods of time, there is a need for adaptive traffic light control. In this paper, three methods of adaptive control based on fuzzy logic are designed in order to determine the urgency of a particular phase and adapt the signal program. The first method is designed to change the duration of a particular signal phase, while the second method is designed to change the phase sequence. Both methods are combined into the third method that implies a simultaneous change of the phase duration and sequence during execution.

Three simulated traffic demand scenarios for the isolated signalized intersection of Zvonimirova-Heinzelova streets in the city of Zagreb, Republic of Croatia were used to evaluate the effectiveness of the designed methods. The simulated traffic demand consists of the original traffic demand data (scenario 1, obtained from [1]), decreased and increased traffic demand data, which varied by 40% (scenarios 2 and 3 respectively). The original fixed signal program of the mentioned simulated intersection consists of three phases and is converted into a NEMA (The National Electrical Manufacturers Association) structure based adaptive signal program using the above-mentioned fuzzy based methods for adaptive traffic light control. All the work reported in this paper presents a continuation of the research described in the author's previous papers [2], [3] and augmented with results from [4].

This paper contains five sections. After the introduction, in the second section, similar approaches to the adaptive traffic control system as solutions to many traffic-related problems are described. The third section describes the three proposed fuzzy logic control methods made during this research. The fourth section presents the simulation model, traffic scenarios and obtained simulation results, including their evaluation and discussion. The last section contains the conclusion and possibilities for further work on this topic.

II. State of the Art

Today there are a lot of contributions and methods that are used in solving control problems of a signalized intersection. Many of them range from ITS solutions to combinations of several popular tools of artificial intelligence such as fuzzy logic, genetic algorithm, neural networks, and computer vision used for finding the optimal solutions in traffic problems. As technology grows, it provides numerous options for improving the performance of a traffic network such as the newest approach related to using the Connected Vehicle (CV) technology. Since the low CV penetration in the current vehicle market, authors of [5] developed a new method to estimate the speeds and positions of Non-Connected Vehicles (NCV) along a signalized intersection. The algorithm uses CV information, and initial speeds and positions of the NCVs from loop detectors and estimates the forward movements of the NCVs using the Gipps' car-following model.

According to [6] (first known application of fuzzy logic for traffic light control), using fuzzy logic as a traffic light

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controller for an isolated intersection enables a response to real-time changes of traffic demand in order to improve traffic light control. There are also other similar methods and solutions of fuzzy logic control approaches for signalized intersections in the literature. In [7–13], the full potential of fuzzy logic in solving various problems related to signalized intersections in cities is shown.

In [7], a two-stage fuzzy logic controller for an isolated signalized intersection has been proposed. It takes traffic efficiency and fairness into account. The performance of the proposed controller was further improved after its rules and membership functions were optimized by using the genetic algorithm. In [8], a similar controller with the use of fuzzy logic for a phase sequencer, which decides the next phase among the possible ones, was proposed. It uses queue lengths as decision input variables as it is also done in [12]. A similar approach can be found in [9] and [11] in which fuzzy logic is used for extension of the duration of green light and to decrease average vehicle delay. Both tackle the problem of improving traffic actuated control approaches. In [10], a traffic light control system that uses a combination of fuzzy logic and Q-learning as a solution for decreasing the total waiting time and queue length was proposed. It enables online learning during operation. In [13], fuzzy logic is used for cooperative control of a group of intersections enabling control of a small network of signalized intersections. All these proposed methods showed superiority to the fixed traffic light control.

To alleviate the creation of the needed fuzzy logic decision rules, in this paper the urgency of a particular phase is used similar to the idea described in [14]. The main difference to [14] is that more detailed traffic data from every driveway lane are used to compute the urgency more precise using fewer input variables for the fuzzy decision process. This results with fewer fuzzy decision rules making the proposed method easier to implement and optimize.

III. Proposed fuzzy logic control methods

The three below described methods of adaptive traffic light control are based on fuzzy logic. Fuzzy logic is used to grade the current traffic conditions at the intersection. Based on this idea, the fuzzy controller has the following inputs:

- Queue length;
- Arrival traffic flow;
- Exit traffic flow;
- Red signal time (not used in the first method).

The queue length, and arrival and exit traffic flows are registered by detectors positioned on their associated lanes. Using the listed inputs, associated fuzzy rules and membership functions a parameter called urgency is calculated. An excerpt of these fuzzy rules for the second method is shown in Table I and the activation of the associated membership functions with arbitrary inputs is shown in Fig. 1. This urgency is calculated for every lane and then averaged to determine phase urgency as shown here:

$$U_{phase} = \frac{\sum_{i=1}^{n} U_{lane_i}}{n}, \tag{1}$$

where U_{phase} is the urgency of a particular phase, n is the number of currently active lanes, and U_{lane_i} is the urgency of the ith active lane. Using this principle, two fuzzy sub-controllers were created for all proposed methods, one for primary and one for secondary driveways. The difference between the two is in their traffic demand, which is taken into account when designing the needed fuzzy rules and membership functions.

A. Adaptation of phase duration

The first method of signal program adaptation in this paper changes the phase duration. Traditionally used fixed phase duration proved throughout the years as an ineffective control method for signalized intersections [15], [16]. One way of adapting the phase duration is by varying the duration of the green signal as proposed in [2] and [3]. To determine the optimal green signal duration, three traffic flow parameters were evaluated using a fuzzy logic controller. Those were the average queue lengths, and arrival and exit traffic flow. Based on these inputs, fuzzy rules and membership functions were created in order to grade the urgency for shortening or extending the duration of the current phase. This urgency parameter is the output of the fuzzy controller and its value is in the interval from -1 to 1. The value of urgency is then used to calculate the phase duration. In order to determine the final phase duration using the obtained urgency, the maximum amount by which a phase can be shortened or prolonged, ΔT_{max}, must be known and can be obtained as:

$$\Delta T_{max} = T_{phase} \cdot CDC, \tag{2}$$

where CDC is the maximum change of duration coefficient and T_{phase} is the green signal duration in the original fixed signal program. Final change of the original green signal duration ΔT is obtained by taking the respective phase urgency into account:

$$\Delta T = U_{phase} \cdot \Delta T_{max}. \tag{3}$$

With the calculated value of ΔT, the final value of the green signal duration is calculated by adding the ΔT to the original duration in the fixed signal program. With this step, the phase duration calculation is over. To produce the best value, the phase duration is calculated right before the start of the current phase.

B. Adaptation of phase sequence

The second method used is the adaptation of the phase sequence. This method changes the sequence of signal phases in the order that corresponds best to the current traffic demand. A detailed description of the method is available in [4] and in continuation, only the most important parts are described.

TABLE I. EXCEPT FROM THE FUZZY CONTROLLER RULES

	Queue Length		RedSignal Duration		Arrival Flow		Exit Flow		Urgency
IF	$QL = low$	AND	$RD = long$	AND	$AF = medium$	AND	$EF = medium$	$THEN$	low
IF	$QL = low$	AND	$RD = long$	AND	$AF = medium$	AND	$EF = high$	$THEN$	low
IF	$QL = low$	AND	$RD = long$	AND	$AF = high$	AND	$EF = low$	$THEN$	$medium$
IF	$QL = low$	AND	$RD = long$	AND	$AF = high$	AND	$EF = medium$	$THEN$	$medium$
IF	$QL = low$	AND	$RD = long$	AND	$AF = high$	AND	$EF = high$	$THEN$	$high$

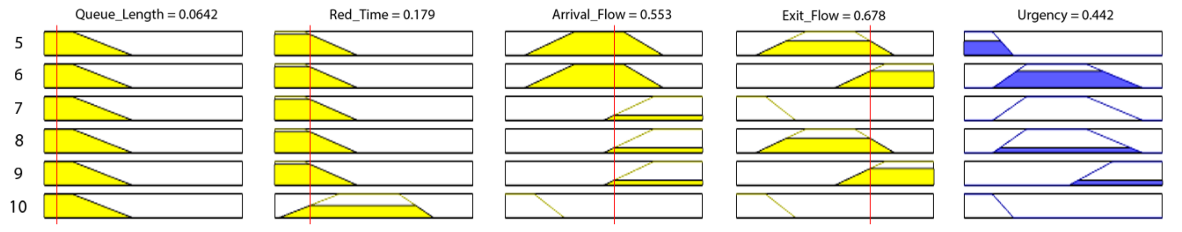

Figure 1. Activation of the chosen representative set of rules in MATLAB's Fuzzy Inference System

After the urgencies of all phases are calculated, phases are sorted from the highest to the lowest urgency value. The phase with the highest urgency gets the priority in being selected as the next phase in the cycle. In order for this approach to be properly executed, a customized NEMA structure has been constructed from the original signal program (Fig. 2). It ensures that all safety measures regarding phase sequence are taken into account. Therefore, the adaptive system used for changing the phase sequence has all the signal phases predetermined and ready for use in case their urgency turns out to be the highest. The fuzzy controller used for evaluation of the urgency consists of all four previously stated inputs.

The adaptive signal program produced for the isolated intersection is used for evaluation of all methods for adaptive traffic light control. It has to be mentioned that the adaptive signal program uses 2 types of signal phases: necessary and optional. The necessary signal phases are used in every cycle, regardless of the traffic demand. The optional phases are meant only for prolonging the use of certain directions if needed by adding another phase in the cycle, and they are used only in cases of higher phase urgency. In this case (Fig. 2), the phases labeled "1", "2" and "3" are necessary, while phases "4", "5", "6" and "7" are optional to be chosen during every cycle according to the current traffic demand.

C. Adaptation of phase duration and sequence

The third method produced in this research combines the previously mentioned adaptations of phase duration and phase sequence. In this instance of adaptation, both phase duration and sequence are subject to change during the execution of the signal program. Both parts of this third method function the same way as previously described. The only difference is in their simultaneous contribution to the adaptation of the signal program. Using this unification of the first two adaptive methods grasping for a larger scope of traffic parameters, which can then be measured and used during the operation of the controller, is possible. This also enables for much finer tuning of the adaptive control system and as such, this method contributed the most to the positive changes of the adapted signal program in the final results.

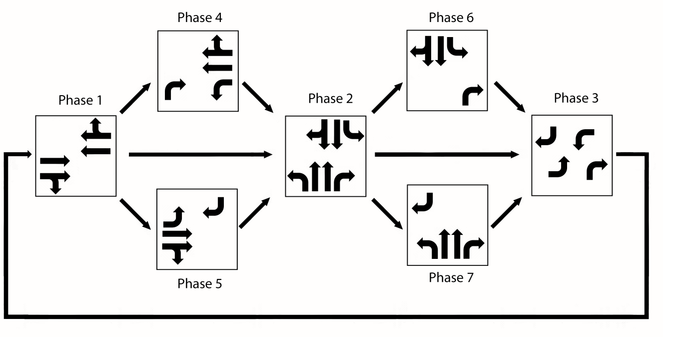

Figure 2. Customized NEMA structure used for adaptation of the signal program

IV. SIMULATION RESULTS AND EVALUATION

The proposed methods of adaptive traffic light control were analyzed in three traffic demand scenarios. Scenarios vary in the amount of traffic demand in order to examine to what extent the control methods are adaptive and can improve the traffic situation. The fuzzy control methods and original signal program were implemented using the MATLAB software environment and connected to the PTV VISSIM microscopic traffic simulator. Data exchange between the two tools was utilized using the Component Object Model (COM) interface [2].

A. Simulation model and scenarios

As mentioned, a traffic model of the chosen isolated intersection used to evaluate the proposed methods has been made

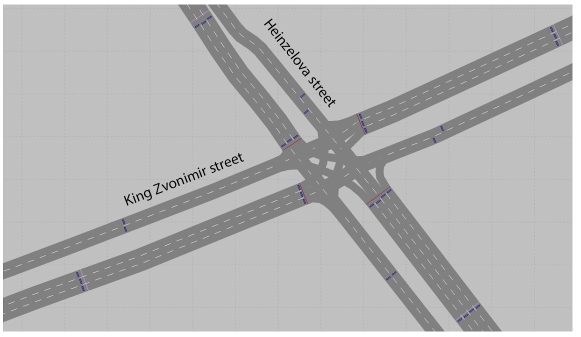

Figure 3. Model of the isolated intersection simulated in VISSIM

TABLE II. TRAFFIC DEMAND FOR EACH SCENARIO

Scenario	Traffic demand [veh/h]			
	Driveway			
	East	North	West	South
1	1136	291	660	372
2	1892	485	1100	620
3	2649	679	1540	868

in PTV VISSIM. It is shown in Fig. 3 and is compromised out of four driveways. The selected intersection is located in the city of Zagreb and is the crossing of King Zvonimir street (east-west movement) and Heinzelova street (north-south movement). The original fixed signal program of the intersection is compromised of three phases and a cycle time of 90 seconds. Its results are used as the base value for comparison. As mentioned, a custom NEMA structure based signal program was created from this signal program as presented in Fig 2.

Previously mentioned value of CDC was set to 0.30. Traffic demand for the three different scenarios is given in Table II. The first scenario is related to the original demand data obtained from [1], the second scenario uses traffic demand reduced by 40% and the demand in the third scenario is increased by 40%.

For the sake of the realistic evaluation, ten simulations were run per control method per scenario. Each simulation lasted for 4500 seconds. It was constituted out of 900 seconds warm-up of the simulation model and 3600 seconds that were taken into account when obtaining the final results for evaluation.

B. Obtained traffic parameters

To evaluate the implemented control methods, needed traffic parameters were collected during the simulation using the COM interface. From them, the following Measures of Effectiveness (MoE) were obtained for every scenario: QL as average queue length, MQL as maximum queue length, and VS as the average number of vehicle stops. As the intersection is constituted out of four driveways, QL presents the average of queue lengths on all driveways, MQL presents the maximum queue length on all driveways and VS is the sum of vehicle stop on all driveways. Obtained traffic parameters from the three different scenarios are shown in Tables III, IV and V. A side by side comparison is shown between the four traffic light control methods applied for each of the described traffic scenarios.

C. Discussion

As a result of the constructed adaptive systems and their use, signal phase duration and sequence have been successfully altered and therefore have affected the traffic flow in the desired way. Results of these methods' functions are presented in the following figures: variable phase duration in Fig. 4, variable phase sequence in Fig. 5, and system for variable phase duration and sequence in Fig. 6.

Obtained results show that the unification of both systems for simultaneous adaptation of phase duration and sequence described earlier gives the best performance. As such, the unified system gives much more balanced results than both methods used separately. The results of the used adaptive methods include three scenarios of simulated traffic demand, which are then compared to the fixed signal program.

During the first simulated scenario, a peak hour vehicle input data has been used and as such shows the highest traffic demand that usually occurs on the simulated intersection. The first tested method (adaptive phase duration) showed reduction in QL by $18,3\%$ and VS by $27,4\%$ and no change in MQL. The adaptation of phase sequence shows better results with a significant reduction in QL by $70,2\%$ and MQL by $15,5\%$ and VS by 53%. Using the third control method of adapting both phase duration and sequence resulted in the reduction of QL by $66,7\%$, MQL by $21,6\%$ and VS by $52,2\%$. All the tested control methods resulted in reductions in comparison to fixed time control, with the second and third methods ranking significantly better.

The results obtained by using the second simulated traffic demand scenario showed an improvement over the fixed signal program. This scenario has lower traffic demand and such results were expected. Adaptive change of phase duration showed little reduction in considered MoEs out of which the most notable is the reduction of MQL by $7,3\%$ that equals to $8,6$ meters shorter MQL. The method of adaptive phase sequence scored better results by reducing QL by $26,7\%$, MQL by $15,3\%$ and VS by 16%. The third method improved the results of the former two methods most significantly with a 36% reduction in QL.

The third scenario of significantly increased traffic demand showed mixed results. By using adaptive phase duration method the considered MoEs were not significantly improved with the exception of VS reduction by $8,8\%$ which is equal to 1082 fewer vehicle stops. With the method of adaptive phase sequence control, the QL was increased by 2%, MQL stayed mostly the same, but the number of vehicle stops was reduced by 12%. The third method gave the best results in the considered scenario with QL reduction of $5,5\%$, no change in MQL and reduction of VS by $19,5\%$ which is equal to 2410 less vehicle stops. It is important to state that this scenario of high traffic demand serves as a way of testing the capability of the system to endure further increase in traffic demand.

TABLE III. MoE values obtained for Scenario 1 - normal traffic demand

MoE	Fixed time control	Adaptive phase duration		Adaptive phase sequence		Adaptive phase duration and sequence	
		Value	Reduction [%]	Value	Reduction [%]	Value	Reduction [%]
QL	130.325	106.5	18.3	38.85	70.2	43.35	66.7
MQL	376	375.7	0	317.8	15.5	294.6	21.6
VS	7921	5747	27.4	3722	53	3790	52.2

TABLE IV. MoE values obtained for Scenario 2 - 40 percent lower traffic demand

MoE	Fixed time control	Adaptive phase duration		Adaptive phase sequence		Adaptive phase duration and sequence	
		Value	Reduction [%]	Value	Reduction [%]	Value	Reduction [%]
QL	19.825	19.25	2.9	14.525	26.7	12.675	36
MQL	117.4	108.8	7.3	99.4	15.3	93.8	20.1
VS	1961	1942	1	1646	16	1618	17.5

TABLE V. MoE values obtained for Scenario 3 - 40 percent higher traffic demand

MoE	Fixed time control	Adaptive phase duration		Adaptive phase sequence		Adaptive phase duration and sequence	
		Value	Reduction [%]	Value	Reduction [%]	Value	Reduction [%]
QL	182.225	179.1	1.7	185.9	-2	172.25	5.5
MQL	375.3	375.4	0	375.6	0	374.4	0
VS	12326	11244	8.7	10849	12	9916	19.5

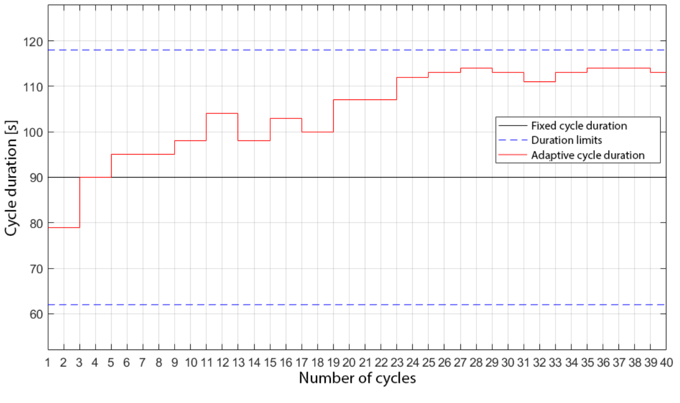

Figure 4. Variable phase duration obtained for the second scenario and first method

All the methods used for adaptive phase duration and sequence can be identified as a great substitute for the fixed signal program regarding the results of the simulated isolated intersection. The adaptive methods constructed for the purpose of this research showed satisfactory results in both scenarios of lower traffic demand as well as peak hour traffic demand. Although the results of the third scenario did not show much improvement, the adaptive methods have to extent yielded good enough results to show their endurance during a much higher traffic demand than the intersection was designed for.

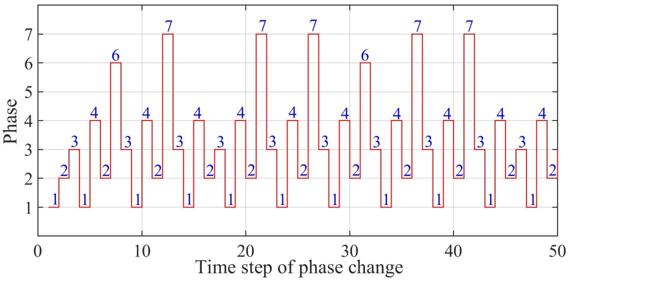

Figure 5. Variable phase sequence obtained for the first scenario and second method

V. Conclusion and future work

Three methods of adaptive traffic light control were created and tested in this paper. The first method was used to determine the optimal phase duration considering the current traffic situation. The second method was used to determine the optimal phase sequence, and the third method was used for the simultaneous adaptation of phase sequence and duration. The base of these adaptive methods is a fuzzy logic controller used to assess the current traffic situation and rate each driveway with a grade called urgency. The inputs to the controller were queue lengths, arrival flows, exit flows and red signal time. The performance of these methods was evaluated using the following MoEs: average queue length, maximum queue

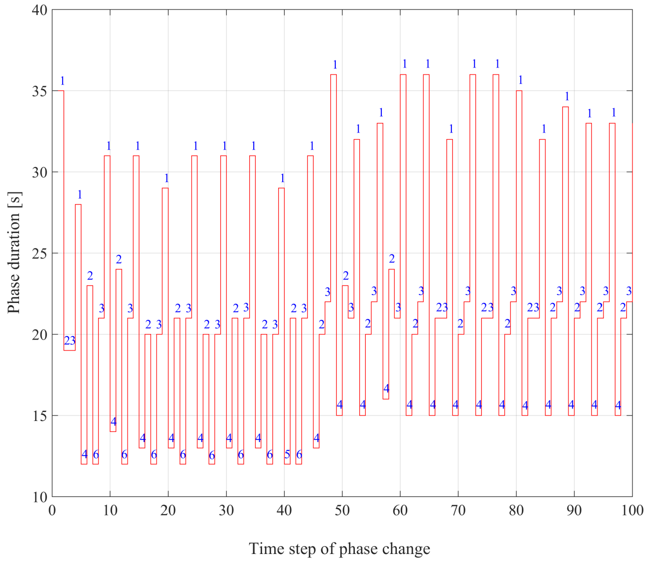

Figure 6. Variable phase sequence and duration obtained for the second scenario and third method

length and the number of vehicle stops. The evaluation was done using a model of a single isolated intersection with three different scenarios of traffic demand.

The results obtained from the scenario of lower traffic demand show reduction of all MoE using almost all of the methods (except for MQL while using the first method). The third method, of adapting both duration and sequence of phases, scored the best and most significant results. In the scenario of normal traffic demand, again all the methods provided a reduction of MoEs in comparison to the fixed signal program. The first method scored the lowest reductions while the second and the third method reduced the MoEs significantly. Also, it has to be noted that the third method performed better in this scenario. In the scenario of higher traffic demand, the adaptive methods performed pretty weaker but still better than the fixed signal program in almost all MoEs. Consequently, the main idea behind connecting the two proposed methods of adaptive control proved valid. Obtained results show significant improvement to observed MoEs indicating less stressful and more comfortable rides in the case of fuzzy based traffic light control.

While the use of fuzzy logic to capture the knowledge of a traffic engineer is a worthy approach, it also presents a challenge of designing a combined system such as the one presented in this paper. Designing fuzzy rules and adjusting membership functions for two separate systems and then joining them together proved to be a difficult task. The further improvement of this system includes using artificial intelligence techniques to optimize the fuzzy decision rules and membership functions like the genetic algorithm combined with an appropriate criteria function in order to alleviate the controller design process. Also in the sense of expanding the managed network, future work will also tackle cooperative control over a group of nearby intersections.

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