An Empirical Analysis of Fixed and Fuzzy-Based Traffic Congestion Control System

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Abstract Traffic Management in an optimum way seems to be an effective way to reduce traffic congestion over various intersections. The core idea behind this optimality is to provide green time for dynamic traffic flow changes in urban areas. As the vehicles are waiting in the queue during red light time, an effective control system is required to reduce the waiting time. In a fixed time/conventional traffic system green light is turned on for a fixed time in each direction. Such systems are generally pre-programmed or the fixed delay in each direction can be controlled manually and hence requires a human operator to make the desired changes, as and when required. Also, a human operator will change this for a limited number of times in a day. However, this process can be automated by using fuzzy control systems. In the fuzzy controlled traffic systems, the on time of green light is adjusted (during each transition of traffic lights) depending on the different input parameters such as Queue length, Time of the day, Arrival Rate and Waiting Time, etc. Adjustment in number of transitions indicates the flexibility/adaptive nature of fuzzy controlled system. In this paper, the novelty in the field of traffic engineering is introduced by computing the relative significance of identified parameters. Various fuzzy models with three input parameters, i.e., Arrival rate, Queue length and Waiting Time are implemented and comparative performance analysis of the seven fuzzy models hence obtained, is presented. The performance of all the implemented fuzzy models is also compared with the conventional traffic system. A traffic simulator is implemented in MATLAB to generate the real-time traffic conditions, each system is simulated

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D. Gupta et al. (eds.), *International Conference on Innovative Computing and Communications*, Lecture Notes in Networks and Systems 471,
https://doi.org/10.1007/978-981-19-2535-1_45

and compared for all possible combinations of traffic density. Fuzzy model with two input parameters Queue length and Waiting Time outperforms the other systems and provides 23.69% average improvement in the delay observed by the vehicles waiting in the queue.

Keywords Fuzzy traffic control · Arrival rate · Queue length · Signal transitions · Waiting delay

1 Introduction

Well-planned infrastructure and effective road management always help the people of any country to move safely from one place to another. But the unexpected growth of population in almost every part of India especially in urban areas leads to an increase in number of vehicles. As per Road Transport Year Book 2011, a total of 0.3 million number of vehicles have been registered in year 1951, whereas in year 2012 it rose to 159.5 million and may rose to 206 million to 309 million by year 2040 in countries like India [1]. On the other hand, the road infrastructure developments and road capacity are unable to meet the demands of increasing traffic. Traffic handling in almost at every intersection of urban areas uses fixed time signal controls. These controls use fixed phase system of green, yellow and red lights and are not adequate enough to handle dynamics of real-time traffic.

Traffic congestion is generally observed due to two reasons, i.e. Recurring/Expected and Non-recurring/Unexpected. It is generally easy to deal with the recurring traffic as it is occurring at the same place every day at the same time. Whereas, any random/unplanned/temporary event causes non-recurring/unpredictable traffic condition on road. The congestion problem is unfortunately growing day by day in almost every city of India such as Delhi, Mumbai, Bengaluru and Kolkata which further leads to huge wastage in economy. In India, an economic loss of 1.47 lakh crore annually has been reported in these cities as reported by global consultancy firm [2]. Moreover, an economical loss of US$124 billion was borne by United States Government in 2014 [3]. Whereas European Union suffered a loss of 1% of their GDP due to traffic congestion [4]. Further, the traffic problem will become more dreadful, if not managed properly and may cause other adverse effects on traveling time, fuel consumption and threat to environment.

To address the problem of congestion in urban areas, a lot of research in terms of Intelligent Transportation Systems (ITS) has been conducted to make traffic management systems safer, efficient and eco-friendly and plenty of solutions have been presented in literature. The paper is organized into five Sections. Section 1 describes the introduction to the problem of traffic congestion; Sect. 2 describes the research carried out in this context by different researchers. Section 3 details the implemented systems and the methodology used for finding the significance of various input parameters. Section 4 discusses the results and the conclusion of the paper is given in Sect. 5.

2 State of the Art

From the last few years, a lot of proposals in terms of Intelligent Transportation System (ITS) toward traffic light optimization have been presented. Among these proposals, Artificial Intelligence (AI) and fuzzy logic-based proposals have gained much popularity as an effective way of controlling traffic at signalized intersections in urban areas. The green time requirement and delay on each phase with optimal cycle length are calculated by Webster [5]. Fuzzy logic theory proposed by Zadeh [6] has been widely applied over traffic problems for urban areas by Pappis and Mamdani [7], Nakatsuyama [8], Favilla et al. [9], Bisset and Kelsey [10], Chiu and Chand [11], Kelsey et al. [12] and Trabia et al. [13]. The isolated intersection traffic control systems such as SCOOT [14], SCATS [15], RHODES [16], FLMuSiC [17] have also been developed. Niittymaki [18, 19] has given framework for real-time traffic systems using Lukasiewicz's multiple/many valued logic and carried out simulations using HUTSIM. Optimisation of signal timing for isolated intersections has been carried out LHOVRA [20], MOVA [21] and SOS [22] algorithms. Distributed Geometric Fuzzy Multi agent and Type-2 fuzzy set based Multi agent Controller for urban traffic system has been designed by Balaji and Srinivasan [23, 24] and these implementations are compared to Green Link Determining (GLIDE) and Hierarchical Multi agent System (HMS). Traffic controllers based on fuzzy neural network, two-stage fuzzy controller and Type-2 fuzzy logic controller (Gravitational Search Algorithm based model) designed by Cheng et al. [25], Yan Ge [26] and Bi et al. [27] respectively. Another useful proposal by (Logi et al. [28]; Pranevičius et al. [29]; Olivera et al. [30]; Das et al. [31]) to address the traffic congestion at intersections has been developed.

Apart from the above proposals, recently some new innovative ideas have been presented to alleviate the congestion over roads. A straightforward traffic modeling over urban area intersections of various cities such as Manhattan, New York has been presented and controlled the large-scale signalized intersections in an optimum way in comparison to traditional approaches. Further, to address the congestion conditions and to control the duration of green lights, framework has been presented by Bianchin and Pasqualetti to achieve the goal of optimality toward mass departure of vehicles. Later on, the proposed model and framework have been evaluated by carrying out the macroscopic and microscopic simulations [32]. Based on Webster Delay Formula, a logarithmic delay modeling paradigm has been presented in order to compute the parameters such as cycle length, vehicle delay, fuel consumption and emission. Various simulations have been carried out to meet the demands of traffic using INTEGRATION simulation software. The model proposed by Calle-Laguna et al. effectively utilized cycle length in an optimum way [33]. A novel arithmetic mean theorem approach to address the problem of congestion in India's metropolitan cities has been proposed. The system considers both static/dynamic road network conditions along with network topology parameters and finds out the nodes responsible for congestion. In 2019, Jain et al. proposed an approach utilizing RFID detectors for finding the parameters such as vehicle count and velocity [34]. Kumar et al. proposed an intelligent traffic controller, based on dynamic traffic algorithm, considered queue length, waiting time and rate, assigns the time duration for the queue formed at each road. The system is utilized as three step procedure, i.e., collection of data, processing of data, and the decision-making system [35]. For determining the priority of road-based segment along with vehicles emergency management, a framework based on traffic information optimization is developed by Maya et al. The deployed sensor nodes observe the desired traffic information and then fuzzy logic is applied for the determination of priority assignment. The applicability of congestion aware routing algorithm and simulated results show reduction in waiting time experienced by vehicles in emergency [36].

Aleko and Djahel proposed an Adaptive Traffic Light Control System (ATLCS) which ensured synchronization between the consecutive traffic lights and allow the vehicles to get the green phase by minimizing the "stop and go" procedure. ATLCS results in considerable improvement in traveling time [37]. Celtek et al. designed a Social Learning Particle Swarm-based Optimization (SL-PSO) method for real-time traffic control and simulated it using Simulation of Urban MObility (SUMO). The method is analyzed with respect to real-time traffic data of intersection in Kilis (City in Turkey) and has shown considerable improvement in average travel time [38]. Ng and Kwok applied an evolutionary algorithm-based approach for both Fixed Cycle Traffic Light (FCTL) system traffic model and Intelligent Traffic Light System (ITLS) traffic model, simulated and evaluated those for peak and non-peak traffic hours [39]. Traffic flow analysis at a junction in Bangladesh is conducted by Roy et al. using MATLAB and Arena software with the idea to minimize the queue formed at intersection and finding out the waiting time range. The analysis is conducted with respect to Webster's equation and also results in an optimum way for traffic control [40]. Sukhadia et al. described a Smart Traffic Governance System based on Artificial Intelligence that monitors the traffic scenarios in urban cities and also analyzed a range of data inputs. It is suggested that a systematic approach that considers cost and delay provides an efficient mean of traffic handling during dense traffic conditions [41].

3 Implementation

Fuzzy logic can be used to improve the traffic state at the remote intersections of the cities. Also, these systems can be combined with other AI techniques to alleviate the traffic congestion problems. From the literature survey three important parameters, i.e., Queue length (QL), Arrival Rate (AR) and Waiting Time (WT), used by many researchers were identified and their performance comparison is conducted. Queue length represents the length of roads filled due to traffic and it is proportional to the traffic density. In the implemented system, the sum of current vehicle count on all the three waiting lanes is taken as the Queue length. The vehicle count is updated after every sampling interval. Arrival rate is the rate at which vehicles reach the other three lanes which are facing red signal. More the number of vehicles reaching at the junction more is the arrival rate. Waiting Time is the total waiting time observed by the vehicles waiting at other three sides of the intersection when traffic is allowed to pass from the fourth side.

The performance comparison of different models is conducted on the basis of delay in waiting time observed by vehicles waiting for their turn to pass the intersection and the number of transitions in traffic signal in both fixed time as well as fuzzy controlled systems. Experimental simulations were conducted with all the three parameters, i.e., Queue length, Arrival Rate and Waiting Time. To adjudge the order of significance of these parameters, three more experimental simulations were conducted by eliminating one parameter in each case and another three by considering only one parameter at a time. The simulation results of 3 existing models [42–44] and 4 models implemented in this research work are compared here. The input combination of all the implemented systems is shown in Table 1. The input and output parameters, their universe of discourse, type of membership functions of each parameter and their specifications were fixed for all the experiments. The membership functions of each input and output parameters are shown in Figs. 1, 2, 3 and 4.

Also, to maintain a uniformity in experiments, same method of implication and defuzzification are selected and the rulebase formed was also similar to the maximum extent. All the fuzzy models and the fixed delay traffic systems were designed, implemented and simulated in MATLAB. Each implemented fuzzy system is compared to the fixed time model and the reduction in waiting time observed by vehicles standing

Table 1 Input Parameters considered for implementation of each fuzzy model

Input	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Arrival rate	√	√		√	√		
Queue length	√		√	√		√	
Waiting time		√	√	√			√

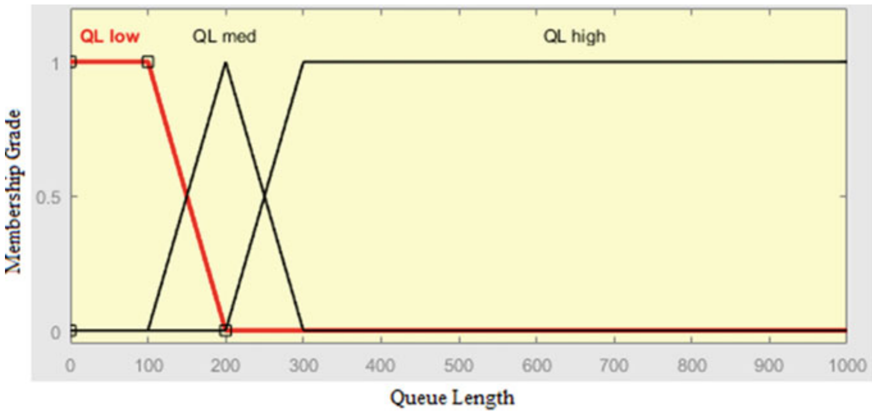

Fig. 1 Membership function specifications of input parameter: Queue Length

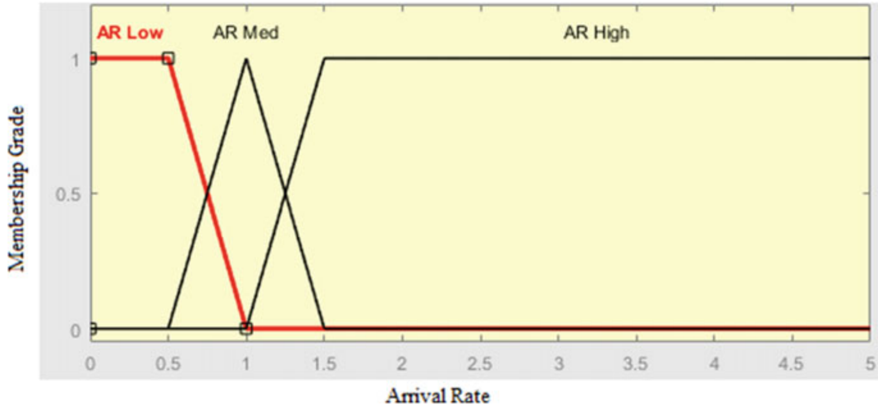

Fig. 2 Membership function specifications of input parameter: Arrival Rate

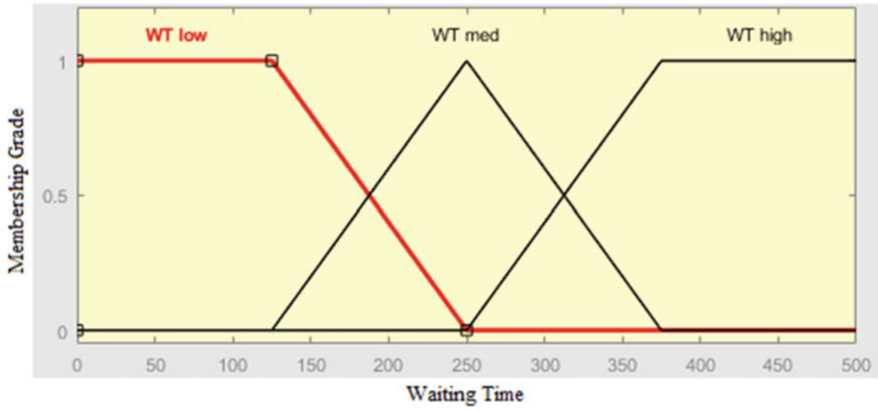

Fig. 3 Membership function specifications of input parameter: Waiting Time

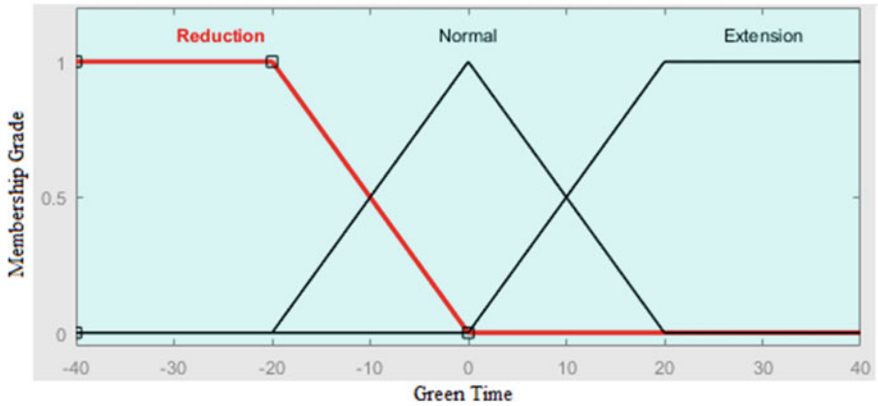

Fig. 4 Membership function specifications of output parameter: Green Time

in queue is noted and considered as improvement in system. Also, in the fixed time systems, the time allowed to pass the traffic in each direction is fixed and hence the number of traffic signal transitions in a fixed time remains same. However, when the timings of green light are controlled by the fuzzy models the number of signal transitions is varied depending upon the traffic at the intersections. This indicates the adaptability of fuzzy models and the average transitions of green lights is also compared for all the models in the next section.

4 Results and Discussion

The performance of the fixed time system and each fuzzy system is observed for varying traffic density to mimic the real-time traffic conditions. As the traffic density on each side of the road is independent of the other sides hence, 3 cases of traffic density, i.e., Low, Medium and High is considered in each direction of four-way intersection, independent of the each other and this led to total of $3^4 = 81$ cases of traffic density. Each system is simulated for 2 h with each of 81 cases of traffic density and to obtain a representative value of the entire set, this simulation was performed 20 times for each case and then an average of these readings is taken to observe the reduction in the waiting time observed by the vehicles waiting in the queue. This completed a single trial and the average improvement of 81 cases is then compared with the fixed time system to obtain the percentage improvement in the average delay observed by the vehicles standing in the queue. A total of 15 such trials were run and the average of the percentage improvement in delay observed by the vehicles waiting in queue is presented in Table 2. In this Table, results of each system are presented column wise. The reduction in delay is achieved due to flexible green time in fuzzy systems. In fixed time systems, number of transitions of traffic lights is fixed and when the transition of green light occurs at an interval of 60 s, then the total number of signal transitions occurring in 2 h is fixed and is equal to 120. However, in fuzzy systems, these signal transitions are adjusted according to the traffic density and is presented in Table 3. First column represents the case number of 81 cases of traffic density. The value listed in the table under each model is the average signal transitions for a particular case of traffic density obtained in 15 trials. Average signal transitions for every model are listed in the last row of Table 3.

Initially, four fuzzy models with two inputs and three inputs, i.e., Model 1 to 4 of were considered for experimentation. From the results of these models, it was observed that in all the runs, the performance of all the four systems is consistent and it also depicts that the fuzzy model based on just two inputs viz. Arrival Rate and Queue Length provided maximum improvement among first four fuzzy models with two and three input parameters. As the system with two parameters performed even better than Model 4 (with all the three parameters taken together), it motivates to include the comparative performance of the fuzzy systems with single input parameters. We ran three more experiments with single controlling parameters and the results obtained have unveiled another important observation about the fuzzy models. Fuzzy models

Table 2 Percentage improvement in 15 trials of each system with respect to Fixed time traffic control system

S. no	Model 1: QL and AR	Model 2: AR and WT	Model 3: QL and WT	Model 4: QL, AR and WT	Model 5: QL only
1	21.36	10.93	23.64	21.32	20.10
2	21.61	10.83	23.73	21.03	19.99
3	21.36	11.24	24.01	21.81	20.21
4	21.65	11.61	23.94	21.39	20.30
5	21.96	11.42	23.40	21.94	20.42
6	21.68	11.41	23.73	21.36	20.06
7	21.93	11.40	24.25	21.08	19.99
8	21.61	11.03	23.59	21.51	20.28
9	21.50	11.28	23.94	21.48	19.96
10	21.63	11.41	23.53	21.26	20.33
11	21.44	11.17	23.92	21.05	20.10
12	21.35	11.82	23.39	21.31	20.37
13	21.61	11.59	23.60	21.47	20.14
14	21.76	10.75	23.21	21.18	19.97
15	21.47	10.99	23.56	21.20	20.05
Average percentage improvement	21.60	11.26	23.69	21.36	20.15

with single input Arrival Rate or Waiting Time have shown negative performance but with only Queue Length (Model 5), system has provided an average percentage improvement of 20.15% over the fixed delay model. From the Table 2, it is apparent that Model 3 outperforms all other models, with average percentage improvement of 23.69%. Further, the models with Queue Length as one of its parameters perform well as compared to Model 2. Hence, it may be concluded from the current experimentations that the Queue Length is the most significant parameter among the three parameters considered for this research work. It is recommended to include this parameter for controlling traffic congestion at intersections.

5 Conclusion and Future Scope

In this paper, to compute the significance of various parameters an extensive comparative performance analysis of various fuzzy models for traffic congestion control is performed. Three existing fuzzy models with two input parameters and four other models possible with the same input parameters were designed, implemented and simulated. Five fuzzy models that perform better than conventional system, are

Table 3 Traffic signal transitions for each of 81 cases* of traffic density

Traffic Case	Model 1: QL and AR	Model 2: QL and WT	Model 3: AR and WT	Model 4: QL, AR and WT	Model 5: QL only	Fixed delay model
1	206	120	120	206	206	120
2	204	120	120	204	206	120
3	162	119	103	160	163	120
4	204	120	120	204	206	120
5	199	120	120	199	206	120
6	149	115	101	144	154	120
7	196	119	120	196	206	120
–	–	–	–	–	–	–
–	–	–	–	–	–	–
53	152	100	120	152	206	120
54	122	96	96	109	135	120
–	–	–	–	–	–	–
–	–	–	–	–	–	–
75	120	100	92	117	128	120
76	159	106	103	160	169	120
77	136	100	99	131	161	120
78	116	96	91	104	118	120
79	150	100	100	148	167	120
80	130	96	97	120	158	120
81	115	92	90	97	112	120
Average	161	110	108	159	175	120

* Only partial table is given here to reduce the space required

compared for their signal transitions at the intersection and the waiting delay observed by the vehicles waiting in queue. Model 3 with two inputs, i.e., Queue Length and Waiting Time outperforms all the compared models and the comparative performance is shown in Fig. 5.

In 15 trials, the average of percentage improvement obtained in this case is 23.69%. It is concluded that, the performance of fuzzy models largely depends of the choice of input parameters chosen to control the green light time. Out of the three parameters considered for comparison in this work, Queue Length is found to be the most significant parameters and shall not be ignored while designing a fuzzy-based traffic congestion control system. In this study, parametric specifications of all membership functions, implication operators and defuzzification method for all the models were kept same to make an authentic comparison. However, if they are changed and each system is tuned separately, the corresponding performance may improve.

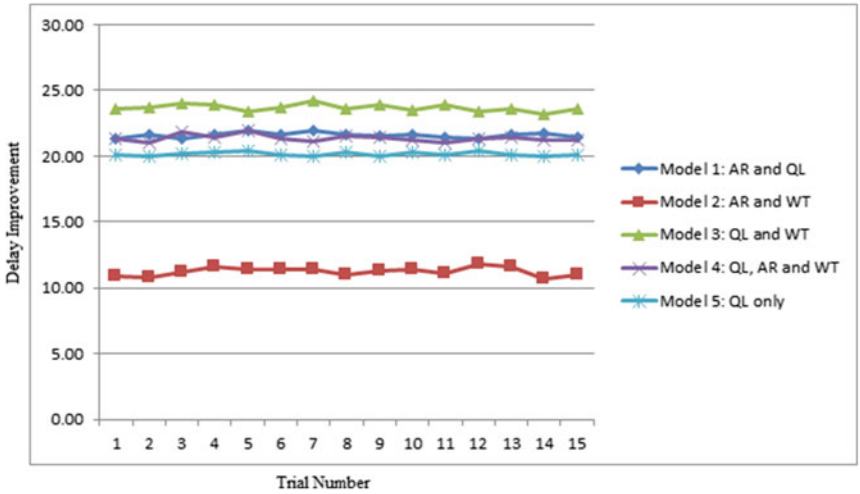

Fig. 5 Average of Percentage Improvement in Delay observed by vehicles for 81 cases of traffic density

Hence, there is a scope to implement these systems with tuned if–then fuzzy rules or parametric specifications and will be worked upon in future.

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