

ADAPTIVE TRAFFIC SYSTEM CONTROLLERS IN TRAFFIC ENGINEERING : A SURVEY

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Abstract

In today's era, traffic congestion is the widest spread problem observed all over the world, arising as consequence of exponential rise in vehicle count at the traffic intersections. This growth has largely affected the people as they are experiencing enhanced delay in travelling time and increased fuel consumption which led to wastage of billions of dollars. The current road infrastructure design and traffic signal controlling using a cycle of fixed time phase of green/red/yellow lights are not adequate to tackle the rising demands of traffic in an optimum way. These traditional traffic signal systems cannot handle the dynamics of road traffic at the intersections and hence results in exceeding delays. Also, the volume of traffic at any intersection at different times of the day is uncertain and hence it is hard to get an exact mathematical model for this problem. Many researchers have proposed some solution to this problem and their work is reviewed extensively in this paper. Due to its ability to deal with uncertainty, fuzzy logic is considered as the most appropriate technique to solve this problem and is highly recommended method for implementing automated traffic controllers. Due to its inherent advantages, most of the research in the field of traffic engineering is carried out using fuzzy logic techniques. Hence, this paper presents a systematic review of various techniques that are used for an effective management of traffic, especially focusing on different fuzzy based traffic controllers and their performance comparison to identify the best input output parameter.

Keywords: Fuzzy based traffic controller; Hydrocarbon (HC); Intelligent Transportation System (ITS), Intelligent Traffic Management System (ITMS),

Introduction

World population has increased by 25.3% (Worldometer, 2022) in last two decades resulting in increased demand of vehicles over the road. Further, it is observed that due to easy payable installments (EMIs) and finance facilities available on purchase of automobiles, the vehicle's number is rapidly increasing on the roads which lead to more

congestion. Since last 20 years, with the average increase by 9.82% (CEIC Data, 2022) in vehicle's number in countries like India the traffic congestion problem is taking a terrible form. A total of 0.3 million vehicles have been registered in 1951, it has exponentially grown to 210 million in 2013, 230 million in 2016 and has reached 295.8 million

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by 2019 in India (Ministry of Road Transport and Highways, Government of India, 2021). The traffic congestion is exponentially striking high population cities such as Delhi, Bengaluru, Kolkata and Mumbai which leads to massive wastage in economy. Apart from economy loss perspective, other undesirable effects such as elongated travelling time, fuel consumption wastage and severe threats to environment have been reported. In 2018, an annual 1.47 lakh crore loss in economy has been observed in countries like India (Financial Express Online, 2018). In Indian city; Bengaluru travelers suffered an average loss of 243 h travelling time wastage i.e., 10 days and 3 h in 2018 (Dipak, 2020).

Apart from India, a significant wastage of 5.5 billion hours of travelling time and 2.9 billion gallons of oil has been observed in United States of America during interval 2000 to 2010 as per the Urban Mobility Report prepared by Victoria Transport Policy Institute (Litman, 2023). A 160 billion dollars economic loss has been borne by United States Government in 2014 and these statistics have reached to 6.9 billion extra travelling hours. and purchase of 3.1 billion extra gallons of fuel (Schrank *et al.*, 2015). Despite the modernized road infrastructure and development, United States suffered a \$87 billion loss in 2018 (Fleming, 2019). Moreover, in 2019, UK suffered a £6.9 billion economic loss due to congestion (Press Releases, 2020).

Worldwide Congestion Levels

As per Traffic Index statistics report based on real time traffic data by TomTom (Netherlands based Vehicle Navigation Company), India has been found among worst congested country across 57 countries on 6 continents (TomTom, 2021). Report of year 2019 reveals Bengaluru ranked 1st in the worst traffic congestion conditions with 71% congestion level. Not only in India but this problem of traffic congestion is being faced by the whole world and the stats listed in Table 1 shows the 5 most congested cities of the world and their congestion level in the last three years.

Traffic Congestion Reasons

Traffic congestion in urban areas is occurring due to increased population that has caused substantial increase in vehicles on the road. Generally, the congestion is 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 (Federal Highway Administration, (2019). Whereas, any random/unplanned/ temporary event causes non-recurring/unpredictable traffic condition on road (Fonseca *et al.*, 2011; Falcocchio and Levinson, 2015; Ghosh *et al.*, 2016). Department of Transportation Federal Highway Administration of United States, reported 50% nonrecurring congestion and 40% recurring congestion took place in proportion to all traffic congestion (Systematics, 2005). In metropolitan cities, congestion is heavy during peak hours of the day and the commuters face delay while travelling from one place to another. As per Federal Highway Administration of United States, following are some specific reasons of congestion that have been reported.

Traffic Accidents/incidents: Breakdown of vehicles, trash in travelling lanes leads to disruption in smooth traffic flow which, later on reduces the capacity of roads.

Bottlenecks: *Bottleneck* being the very common cause for traffic congestion occurs, when number of vehicles exceeds per kilometer of available road or number of automobiles surpasses the number of road lanes during peak hours and is shown in Figure 1. Administrations are working to deal with many severe bottlenecks (Mahapatra, 2018).

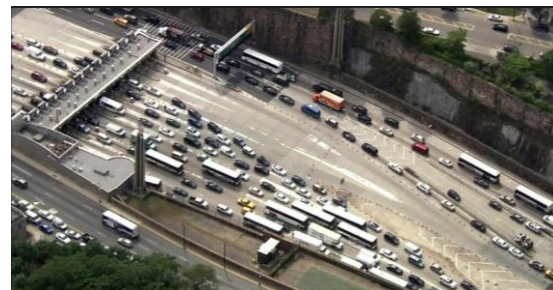


Figure 1. A typical traffic bottleneck

Table 1. Top congested cities of world (2019-2021)

Rank	2019 City (Congestion Level)	2020 City (Congestion Level)	2021 City (Congestion Level)
1.	Bengaluru (71%)	Moscow (54%)	Istanbul (62%)
2.	Manila (71%)	Mumbai (53%)	Moscow (61%)
3.	Bogota (68%)	Bogota (53%)	Kyiv (56%)
4.	Mumbai (65%)	Manila (53%)	Bogota (55%)
5.	Pune (59%)	Istanbul (51%)	Mumbai (53%)

Work Areas: New road constructions, road closure due to road repairing as well as maintenance of existing roads results to reduction in number of

travelling lanes and even reduces the effective road width for travelling.

Weather: Weather changes such as heavy rainfall, snowfall, dense fog, and smoke in the atmosphere may affect the state of the traffic mobility as well as the driver's safety very significantly. Poor weather conditions slow down the speed of the vehicles and even may result in crashes over the road. Based on NHTSA data (National Highway Traffic Safety Administration, United States), the reason and percentage of total crashes on roads is as follows: 70% on wet pavement, 46% during rainfall, 18% during snowfall, 13% in icy pavement and 3% during fog (FHWA, year).

Faulty Traffic Controllers: Faulty traffic light controllers results into poor or mismanaged traffic signaling of traffic light and may cause congestion.

Miscellaneous Events: Normal traffic flow gets disrupted due to events like public gatherings, sports day, strikes, functions, agitations, marathons, and concerts etc.

Lack of Infrastructure and Traffic Variation: Road Infrastructure is not sufficient enough to accommodate the number of vehicles due to increased population. Moreover, the arrival of automobiles towards the intersection is uncertain and varies during different timings of the day. Due to variation in traffic density, the delay may occur which results in traffic congestion.

Most of the above-mentioned reasons for traffic congestion are uncertain or unpredictable and does not follow any set pattern and hence it is difficult to obtain a mathematical model of the controller to deal with this issue. Furthermore, increase in number of automobiles is making it even worse in almost all high populated countries and hence for the effective management of traffic, an intelligent traffic management system is required. Such intelligent systems, once designed not only decrease the level of congestion in the city but may also be utilized to allow path to priority vehicles such as ambulances and fire brigade vehicles. Further, use of such systems reduces wait time at the intersections thereby reducing fuel consumption, CO₂ emission, travelling time and increase the safety of passenger in urban areas. Many methods of controlling this problem of traffic congestion have been proposed and implemented from time to time.

This research work presents a comprehensive review on various traffic controllers used in controlling the traffic at the intersections. As fuzzy systems are capable of handling uncertainty and can be easily modelled using Fuzzy If-Then rule to mimic the intelligence of human, they are the best choice to design controllers for traffic management. Many researchers have proposed fuzzy models to

handle this issue and one of the objectives of this review is to perform a comparative study among various fuzzy based adaptive traffic controllers implemented under real time scenarios.

The content in this paper is arranged as follows: The introduction to the problem of traffic congestion and the reasons for its occurrence are presented has been presented in this section. Following section discusses the various proposals to control this issue and also explains the need for some intelligent methods including artificial intelligence to handle it. Further, Fuzzy based traffic models proposed by different researchers and their comparative analysis to find the best is done. In the last section, the conclusion of this review is presented which also suggests the future scope of this work.

Various Traffic Controlling Proposals

For controlling the traffic flow various control mechanisms namely Pre-timed, Traffic Actuated, and Adaptive Controller (Bhatia and Aggarwal, 2020) are used to control timings of the signals at signalized traffic control.

Pre-timed control: Such systems use a predetermined time slot assignment for every lane and are not quite enough to handle the traffic flow under very light and very heavy volume of traffic.

Traffic actuated control: These traffic control systems have an upper edge on fixed timed systems and these respond to real time traffic flow with limited capabilities under heavy traffic conditions.

Adaptive Controllers: Adaptive controllers overcome the shortcomings of above-mentioned types by varying the timing of green signal, which indicates the time to allow vehicles cross, to deal the real time scenario of traffic variations. Basically, at the signalized traffic intersection, the timing for the green signal light is varied depending upon the traffic conditions, such as heavy and light traffic cases. Various traffic light controlling proposals are summarized in Table 2.

Artificial Intelligence in Traffic Controlling: Effective traffic management is an important issue to deal with, by every country especially in urban areas due to rising population densities in these areas. Since last decade, Artificial Intelligence (AI) and its successor technologies such as Probabilistic Reasoning, Machine Learning algorithms is significantly playing very crucial role in almost every problem domain. Among these problem domains, Traffic Engineering is the field which is utilizing AI for handling traffic congestion and traffic estimation utilizing parameters such as

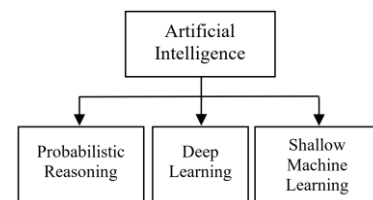
Table 2. Summary of Traffic Light Controlling Proposals (TLC)

Paper Reference #	Contribution
Zhao <i>et al.</i> , (2012)	Addressed the randomness and non-linearity of the traffic system and provided a comprehensive review over various traffic signal control systems for freeway networks and urban surface-way.
Sundar <i>et al.</i> (2015)	Suggested the hardware implementation of traffic control system by utilizing a special RFID tag on each vehicle with a PIC16F877A system on chip (SoC), NSK EDK-125-TTL and RFID reader for tracking number of vehicles passed that allows changing of green light duration.
Koukol <i>et al.</i> (2015)	Focused on the various fuzzy based modeling approaches used for traffic management along with genetic algorithms.
Olivera <i>et al.</i> (2015)	Proposed a traffic control system and analyzed it with respect to standard traffic emission model, i.e., HBEFA which provides improvement in the fuel reduction of CO by 23.3% and NO_x by 29.3%.
Silva <i>et al.</i> (2015)	The proposed design helps the drivers in ensuring non-stop crossing of intersections especially in early morning hours which helps in avoidance of accidents. The proposed intelligent system achieved this by keeping the traffic lights to blinking yellow light mode and turns all to red as soon as it detects risk of accident.
Younis and Moayeri (2017)	Proposed 2 protocols i.e. Road based Infrastructure Traffic Control (RITCO) and Vehicle based Infrastructure Traffic Control (VITCO) to control dynamic traffic at the intersections, analyzed and evaluated their performance based on different metrics.
Das <i>et al.</i> (2018)	- The proposed method, based on Radio Frequency Identification (RFID), utilizes a chip and antenna for addressing the traffic congestion issues efficiently in a lesser amount of time. - The system is capable of monitoring the vehicles, observing the movements which lead to controlling the vehicles.
Calle-Laguna <i>et al.</i> (2019)	- The simulation of two/four phase isolated intersections is carried out in INTEGRATION simulation software. - It helps in deriving the multi-objective cycle lengths (computed using weighted coefficients) to compute the optimum cycle length based on both vehicle delays and fuel consumption.
Kumar <i>et al.</i> (2019)	- It utilizes inputs queue length, waiting time, rate of in and out flow to assign the time duration as required by each road. - It is a three step procedure i.e., collection of data, processing of data and decision-making system which plays a significant role in identifying the particular traffic light to be utilized as per time allotted to it.
Aleko and Djahel (2020)	- It ensures synchronization between the successive traffic lights in a particular direction with respect to the delay calculated and thus by minimizing the “stop and go” procedure, the vehicles get the green phase. - It is coded in Simulation of Urban Mobility (SUMO) using TraCI (Traffic Control Packages).
Celtek <i>et al.</i> (2020)	- The methodology is a two-step procedure, i.e., optimization followed by simulation. - It is also simulated using SUMO and utilizes real time traffic data of intersection in Kilis (City in Turkey).
Jain <i>et al.</i> (2020)	- The proposed approach utilizes forward reasoning with six input variables including congestion level. - Based on calculation of the congestion level, the inference rules are framed up using If-then. Further, the period of green/red traffic light is updated by the traffic light control interface as per traffic situations
Ng and Kwok (2020)	- The proposed approach utilizes both Fixed Cycle Traffic Light (FCTL) system traffic model and Intelligent Traffic Light System (ITLS) traffic model for some intersections. - The traffic videos are captured using cameras at the intersection and then the recorded videos are analyzed with Tensorflow for counting the vehicles and pedestrians.

vehicle speed, traffic density, queue length, waiting time, congestion index (CI), etc.

These techniques are widely applicable to control the dynamics of traffic flow as well as focused on reducing the average delay, fuel consumption, CO₂ emission etc. The classification of AI techniques is shown in Figure 2.

Probabilistic Reasoning: Probabilistic Reasoning theory is applicable when the system is comprised with uncertainties. Based on the past situation, probabilistic reasoning seems to be effective way of predicting a conclusion. Probabilistic Reasoning based approaches are shown in Figure 3 and are widely used in predicting the traffic congestion.

**Figure 2. Classification of AI Techniques**

Fuzzy Logic: Fuzzy logic is a multi-valued logic and its membership degree varies from 0 to 1 in any of the fuzzy sets. As per classical theory of logic, a member either belongs to a set or not

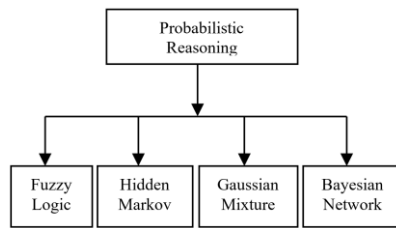


Figure 3. Probabilistic Reasoning based Approaches

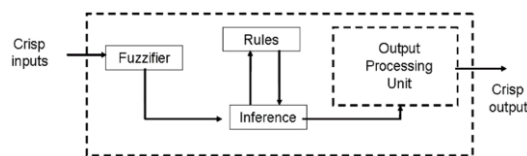


Figure 4. Fuzzy Logic Controller

however in theory of fuzzy logic any member may belong to more than one set with different degree of membership. The process of converting a crisp value into fuzzy membership function in different fuzzy sets is known as fuzzification and is performed by fuzzifier. Inference engine contains knowledge base and implements the fuzzy (if-then) rules. Further, it provides a fuzzy output. In the output processing block the fuzzy value is again converted to crisp value and this process is known as defuzzification and is performed by Defuzzifier. Hence, in Figure 4. output processing block contains Defuzzifier only. However, in type-2 fuzzy systems it contains a type reducer to convert type-2 fuzzy set into type-1 fuzzy set also.

Fuzzy Logic based Traffic Light Controllers

In order to handle the real traffic demands at signalized traffic intersection, all the above contributions were subjected to alleviate the problem of traffic congestion in urban areas. Apart from these, the fuzzy set theory has been broadly utilized by different researchers for traffic signal control. The fuzzy traffic light controller adjusts the green time by utilizing the traffic statistics data collected either by deploying sensors or camera at any intersection as shown in Figure 5.

Pappis and Mamdani (1997) designed a fuzzy controller using fuzzy logic confined to four directional (E-W/N-S) traffic controls. The model of the intersection for two one-way streets is designed with restrictions on turning movements. Nakatsuyama *et al.* (1984) designed a traffic (phase) controller

based on fuzzy logic-based statements for heavy traffic with two traffic junctions.

Bisset and Kelsey (1992) proposed graphical simulation of a traffic state including signal lights, vehicle traffic and intersection and controlled it by using fuzzy based controllers proving its effectiveness in reducing average waiting time of the vehicles waiting at intersections. Chiu and Chand (1993) tested a distributed fuzzy control scheme with street intersections and further suggested queue length to be used as another input parameter. Favilla *et al.* (1993) designed a traffic controller based on fuzzy logic i.e., an Adaptive Module and State Machine. The designed controller was evaluated by means of adaptive strategies, such as fuzzy adaptive and statistical-adaptive, for traffic control system in urban areas. Kelsey *et al.* (1993) has carried out the fuzzy control based simulation of a traffic flow over an intersection and evaluated its performance in comparison to the conventional systems.

Trabia *et al.* (1999) designed two stage fuzzy logic controllers to tackle the demands of traffic in real time scenario. This controller used vehicle loop detectors for the estimation of queue length and then decides whether to terminate or extend the signal phase of lights at cross roads. Niittymäki (2002) achieved the objective of designing a system (fuzzy logic based) in adaptive traffic signal control by using some input values. Niittymäki and Turunen (Niittymäki and Turunen, 2003) used Lukasiewicz's multi value logic and introduced an algorithm for real traffic control systems. The proposed system is simulated using HUTSIM and its results are contrasted against Mamdani type inference method. Murat and Gedizlioglu (2005) introduced a FLMuSiC i.e., Fuzzy Logic Multi-phased Signal Control model. This model is developed under dynamic signal control for isolated type signalized intersection. The modeling is done in two ways i.e., in terms of phase green times duration and with traffic volumes. Zhang *et al.* (2007) designed and simulated an anti-congestion fuzzy algorithm to

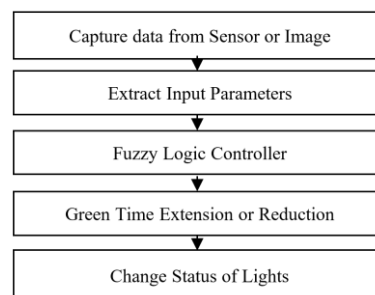


Figure 5. Fuzzy Logic based Traffic Controlling

reduce average delay experienced by vehicles and congestion avoidance for a category of traffic networks with intersections as middle area where chances of congestion are large. Li and Zhang (2008) drafted a control system based on two controllers for providing the extension to green time and optimization to phase change.

Gokulan and Srinivasan (2010) proposed a system i.e., Distributed GFMA (Geometric Fuzzy Multi Agent System) to control congestion due to heavy traffic in cities. This Type-2 based multi agent system is designed in micro-simulator (PARAMICS) to address the uncertainties in inputs and its testing is carried out in Singapore. Karakuzu and Demirci (2010) designed a general Smart traffic light simulator hardware which can be used for any random intersection in the real-world scenario. The proposed simulator used two microcontrollers for handling traffic flows in all the four directions. Askerzade and Mahmud (2011) proposed and simulated fuzzy-logic-based controller to decide extension time for both single and group intersections. The performance of both Mamdani and Sugeno models is analyzed. Balaji and Srinivasan (2011) proposed T-2 (type-2) fuzzy sets based fuzzy multi-agent system for traffic signal control decision. The proposed system is simulated in PARAMICS in order to test its optimality in terms of green time against number of vehicles observing traffic delay. Mehan (2011) designed a fuzzy traffic light controller for an intersection facing dynamic traffic flow of two wheelers i.e., motorcycles. Cheng *et al.* (2014) recommended a traffic controller using fuzzy neural network which calculates the termination/extension required at a junction with reference to adjacent junctions. The neural network-based model is designed for public transports and two/four wheelers. Eze *et al.* (2014) introduced a multipurpose fuzzy based traffic model to make optimal predictions about the traffic, which can also be used to suggest the timing plans of the traffic lights.

Ge (2014) designed a fuzzy controller in two stages for controlling congestion over an isolated intersection. Initially, the proposed model considers traffic urgency degree which is further utilized to compute the green delay of the current phase. Bi *et al.* (2017) presented a type-2 fuzzy sets based fuzzy logic controller (FLC) using GSA i.e., Gravitational Search Algorithm which is addressed to the arterial traffic for the reduction of the pressure of traffic. Further, to reduce the pressure of traffic, the controller comprises of two-layer model, i.e., control layer and coordination layer. Khooban *et al.* (2017) ensured flow of traffic with least waiting time and average queue length using type-2 fuzzy logic set theory and Modified Backtracking Search

Algorithm (MBSA). The proposed Optimal General Type-2 Fuzzy Controller (OGT2FC) utilizes input variables such as waiting time (W_i), queue length (Q_i) and 2 pairs of output variable (S_i) i.e. S1-S3 and S2-S4 for traffic light times of legs 1 and 3 and legs 2 and 4 respectively. Atta *et al.* (2020) designed an intelligent system that reduces the congestion by using sensor based Internet of Things (IoT). The sensors used in the system calculate the no. of vehicles crossing the light and the automobiles approaching to the junction. Depending upon various parameters used along with number of membership functions, the fuzzy logic-based traffic controllers are reviewed in Table 3.

In the above literature survey, various adaptive fuzzy based models for the signalized traffic intersection have been observed and is compiled in Table 3. It is found that there are few common parameters like waiting time, queue/queue length, no. of automobiles on the arrival/queue side with respect to green and red-light phase which have been widely used in most of the research articles. Further, it is observed that these models are compared with Conventional/ Fixed/ Pre-timed, Traffic Actuated, Type-1, Type-2 fuzzy based and various other systems such as Hierarchical Multi-agent System (HMS), Green Link Determining (GLIDE). Fuzzy controller proposed by Trabia *et al.* (1999) is contrasted against the traffic actuated controller on the basis of vehicle delays and percentage of stopped vehicles. It is observed that the fuzzy controller experienced better average delay for heavy and medium periods of traffic flow. The fuzzy controller resulted in reduction of vehicle delays in comparison to traffic actuated controller. The presented simulation results claimed an overall improvement of 9.5% and 1.3% over average delay, percentage of waiting vehicles respectively.

The Fuzzy Logic Multi-Phased Signal Control models (FLMuSiC) proposed by Murat and Gedizlioglu (2005) are contrasted to traffic-actuated models on the basis of vehicle delays. For an isolated four-armed intersection, the performance of FLMuSiC model matched the performance of traffic actuated simulation model but outperformed aaSIDRA. Depending on the average delays of vehicles, for a three phased control situation, the FLMuSiC performs almost equal to traffic actuated model under volume of traffic ≤ 500 veh/h. The FLMuSiC model has shown a considerable enhancement of 15.6% over traffic actuated signal control under (traffic volume > 500 veh/h) conditions. Also, under high variation in the traffic volumes, the FLMuSiC model decreases the vehicle delays by almost 23% for a three phased control situation when compared to traffic actuated control model. The FLMuSiC performs almost equal to the traffic

Table 3. Review of Fuzzy Logic Based Traffic Controllers (FLBTC)

Paper Reference#	Input: Number of Membership Functions	Output	Comparison and Improvement observed with respect to various models
Pappis and Mamdani (1997)	Time: 5, No. of Vehicles Arriving:6 Queue: 6	Extension	----
Nakatsuyama <i>et al.</i> (1984)	Time, No. of Vehicles Arriving, Queue	Extension	----
Bisset and Kelsey (1992)	Number of Cars (Green & Red Sides): 4 Cycle Time: 3	Change in State	----
Chiu and Chand (1993)	Degree of Saturation(E-W/N-S): 5	Adjustment in Time	----
Favilla <i>et al.</i> (1993)	Arrival of Vehicles (Green Phase): 4 Queue of Vehicles (Red Phase): 4	Extension Time	----
Kelsey <i>et al.</i> (1993)	Average Density of Traffic (Both at Green & Red Light): 4 Current Cycle Time: 3	Change in State	----
Trabia <i>et al.</i> (1999)	Traffic flow (vehicles/second/lane): 4 Queue: 4	Traffic Intensity (Green & Red), Change in State	Traffic Actuated Delay Improvement- 9.54 %
Niittymäki and Turunen (2003)	Pedestrian waiting time: 3, Number of vehicles approaching/lane: 3 Gap between the vehicles: 2	Decision (Terminate/Extend)	----
Murat and Gedizlioglu (2005)	First Model Longest queue during red light: 4 Arriving vehicles in green signal: 4 Green time indicator: 4 Second Model Next Phase Longest Vehicle Queue: 3, Longest Queue Red Time: 3	Signal Timing, Phase Order	Traffic Actuated Delay Improvement - 15.6% (Traffic Volume >500 veh/h) Delay Improvement - 23% (Three phased control) Delay Improvement - 20% (Four phased control)
Zeng <i>et al.</i> (2007)	Queue (Current Phase-Green Signal/Next Phase-Red Signal):7	Green Signal Time	Traditional Method
Li and Zhang (2008)	(Fuzzy Green Time Extension Controller) Queueing length (current phase):7 Queueing length (next phase):7 (Fuzzy Phase Change Controller) Queueing length (feasible traffic flow): 5 Current phase Remainder time:5 Traffic Phase: 4	Green Time Extension, Phase Change	Pappis Delay Improvement – 15%
Zarandi <i>et al.</i> (2009)	Queue Length:4 Arrival Rate:3	Green Time Extension	Pretimed Control System
Balaji and Srinivasan (2010)	Flow: 3 Queue:3 Communicated Data: 3	Green Time	Hierarchical Multiagent System (HMS), Green Link Determining (GLIDE)
Karakuzu and Demirci (2010)	Queue Length (North/South): 3 Queue Length (East/West): 3	Extension Time (Red & Green Lights)	Conventional Light Controller Waiting Time Improvement- 66% Passing Vehicle Improvement- 48%
Askerzade and Mahmud (2011)	Number of cars (Arrival Side): 5 Number of cars (Queue Side): 5 Synchronization Time: 5 Number of cars (Next Intersection): 5 Waiting Time: 5	Extension Time	----
Balaji and Srinivasan (2011)	Flow: 3 Neighbor Status: 4 Queue: 3	Weight for flow, Traffic State	Hierarchical Multiagent System (HMS) During first peak period Delay Improvement-39% End of 24 hr. simulation Delay Improvement-66%
Mehan (2011)	Quantity of traffic (Arriving Side): 5 Quantity of traffic (Queue Side): 5	Allocated Green Time	----
Cheng <i>et al.</i> (2014)	(Traffic Monitoring Module) Green Light Ratio (Cycle): 5 Ratio of Vehicles (Downstream /Upstream): 5 Vehicle Density: 5 (Message Module) Urgency: 5 Current cycle green time remaining: 5 Intersection Remaining time: 5	Probability to change, Pass Demand	Fixed Time, Fuzzy-1, Fuzzy- N, Random for normal cars Waiting Time Improvement- 68% to 88% for public transports Waiting Time Improvement- 14% to 60% for public Motorcycles Waiting Time Improvement- 25% to 31%
Eze <i>et al.</i> (2014)	Quantity of traffic (Arrival Side): 4 Quantity of traffic (Queue Side): 4	Extension	----
Ge (2014)	(Traffic Urgency Degree Module) Number of Vehicles: 5 Red Light Duration: 5 (Decision Module) Number of Vehicles (both green/red light phase): 5	Traffic Urgency, Delay Time	Pretimed, Common Fuzzy Control (without traffic urgency degree) Under low Traffic Flow: a) Delay Improvement- 45.6% b) Delay Improvement- 5.4% Under middle Traffic Flow: a) Delay Improvement- 48.8% b) Delay Improvement- 8.2% Under high Traffic Flow: a) Delay Improvement- 30.6% b) Delay Improvement- 2.36%

Table 3. (Continue)

Paper Reference#	Input: Number of Membership Functions	Output	Comparison and Improvement observed with respect to various models
Adewoye <i>et al.</i> (2015)	Arrival (No. of cars):4 Queue (No. of cars):4	Extension	----
Alam and Pandey (2015)	Traffic urgency decision module (TUDM): Queue (No. of vehicles):5 Time:5 Extension time decision module (ETDM): Queue-Lane:5	Decision Module: Traffic Urgency Urgency Decision Module: Extension Time Extension-Time	Pre-timed
Homaei <i>et al.</i> (2015)	Fuzzy Phase Selector Function Queue Length:4 Fuzzy Green Extender Function Queue Length:4 Traffic Volume:3	Next Phase Extension or Reduction	Pre-timed
Lai <i>et al.</i> (2015)	Waiting Time:5 Queue Length:5	Extension Time	Fixed, Fuzzy and Actuated
Cao and Wang (2016)	Traffic Flow: Phase of Red light, Phase of Green light	Green Light Time Delay	----
Yusupbekov <i>et al.</i> (2019)	No. of Vehicles difference (Entering, Leaving the control zone)	Green light Control	----
Jovanović and Kukić (2017)	Vehicle Queued (During Green Phase):3 Vehicle Queued (Waiting for the next phase of green time):3	Extension or Termination (Green Phase)	Fixed Time
Cheng <i>et al.</i> (2017)	Module: Vehicle grouping Group Size:3 Waiting Time (Avg.):3 Difference from concurrent groups:3 Module: Group scheduling Group Size:3 Waiting Time (Avg.):3	Inclusion benefit of Current vehicle in ending group Degree of Urgency	Adaptive Light No Group Fuzzy Group Fuzzy Group Learning
Zaid <i>et al.</i> (2017)	No. of Cars:5	Green Light Period	----
Bi <i>et al.</i> (2017)	(Basic Controller) Queue Length: 3 (Arterial Controller) Number of Vehicles: 5	Green Time Time (correction of extending)	Green Wave Band Control (GWC) Delay Improvement-24% to 49%
Khooban <i>et al.</i> (2017)	Waiting Time: 3, Queue: 3	Signal State	----
Zachariah <i>et al.</i> (2017)	Queue Length:7 Waiting Time: 7	Phase Extension	Static Phase Scheduling Traffic Light System (SPSTLS) Waiting Time Improvement- 65.35%
Atta <i>et al.</i> (2020)	Queue (Red Signal): 5 Arrival of Vehicles (Green Signal):5	Time	----
Dereli <i>et al.</i> (2018)	Length of Queue (for the duration of Red Light):3 Vehicles Left over (following Green Light):3	Phase Selection Extension (Green Light)	Delay Improvement Bisector Method- 8.97% Regression Equation-7.27% General Algebraic Modeling-2.098% Webster-(-12.37%)
Castá <i>et al.</i> (2018)	Number of arriving cars (within every Lane):4 Green light time:4 Day time:5 Type of road:2 Traffic condition:3	Decision about Green time change (Yes/No)	Performance Improvement- 18%
Zuraime <i>et al.</i> (2019)	Queuing of car:5 Departure of car:5	Optimal Green Time	----
Hartanti <i>et al.</i> (2019)	No. of vehicles:3 Queue Length:4 Width of Road:2	Green Light Duration	----
Singh <i>et al.</i> (2021)	Queue Length:3 Arrival Rate:3	Green Time Extension	Fixed Delay Improvement-18.8%
Singh <i>et al.</i> (2022)	Arrival Rate:3 Queue Length:3 Waiting Time:3	Green Time Extension	Fixed Delay Improvement-21.1`%
Tunc <i>et al.</i> (2023)	Green Phase:7 Red Phase:7	Green light duration	----
Yao <i>et al.</i> (2023)	Queue Length:5 Duration of Red:5	Priority of overflow movement	Traditional Queue Length reduced by 27.7% to 33.8%
Singh <i>et al.</i> (2023)	Arrival Rate:3 Queue Length:3 Waiting Time:3	Green Time Extension	Fixed with varying road width Delay Improvement-26.1%

actuated control under low traffic volumes condition and but increases the system's performance by 17.6% than traffic actuated model under high volume conditions i.e., greater than 400 veh/h. The model proposed by Li and Zhang (2008) is contrasted with traditional control algorithm, i.e., simple Pappis and fixed time models. A considerable improvement is observed in terms of imbalanced traffic flow and average delay of vehicles. The model exhibited 15% reduction in average vehicle delay.

The proposed Geometric Fuzzy Multi Agent System (GFMAS) in Gokulan and Srinivasan (2010) is contrasted with Green Link Determining (GLIDE) and Hierarchical Multi agent System (HMS). The performance of GFMAS is observed close to other controllers such as GLIDE and HMS under the low traffic conditions whereas GFMAS outperformed other techniques under heavy traffic conditions comprising uncertainties. Also, considering a hypothetical scenario of multiple peak traffic incidents GFMAS performs better than fixed time and GLIDE. The proposed fuzzy controller Karakuzu and Demirci (2010) is assessed with respect to vehicle's waiting time and is compared with conventional controller. It is observed that in it does not perform equally well in all times of the day, during morning it lacks by 19% whereas it outperformed in reducing the timing for other time intervals. The model shows almost 48% improvement in terms of number of passing vehicles and even better i.e., 66% improvement over conventional methods under dense traffic conditions. 66% appears to be the highest observed performance improvement, however it is for a particular case of dense traffic only and cannot be considered as the maximum improvement as the improvement degrades when averaged for mixed real time traffic conditions. The fuzzy Type-2 controller proposed by Balaji and Srinivasan (2011) has been contrasted to Green Link Determining (GLIDE) and Hierarchical Multi agent System (HMS) under six hours simulation with two peaks and long-term simulation with multiple traffic peaks scenarios. The proposed model experienced a mean time delay per vehicle of 224 sec (during 1st peak) and 222 sec (during 2nd peak period) in comparison to GLIDE, HMS benchmarks and Type-1 fuzzy system. Also, during eight-peak scenario (multi peak), the fuzzy type-2 system has exhibited a significant improvement in total mean delay in comparison to fuzzy type-1, type-2, GLIDE, and HMS. The results of simulation have shown a significant drop in total mean delay by 39% using the fuzzy based system for the duration of the 1st peak period in comparison to HMS and 66% delay reduction after simulation period of 24-hours.

The Fuzzy Neural Network (FNN) proposed by Cheng *et al.* (2014) is compared with Fuzzy-1, Fuzzy-N, fixed time and Random models on the basis of queue length average trip waiting time, average junction waiting time, and arrived road users. It is observed that the FNN suffers less average junction waiting time in comparison to other four methods with respect to different vehicle types such as normal cars, public transports and motorcycles. Also, the FNN has shown considerable improvement in comparison to four methods in terms of trip waiting time. It is also observed that all the other methods, except FNN, has reached the queue length of 768 road users. The performance of Fuzzy Signal Controller proposed by Ge (2014) is evaluated on the basis of average vehicles delay. The fuzzy control (without traffic urgency) fuzzy control with traffic urgency degree and pre-timed control are compared under low, middle and high traffic flow. It is observed that under low traffic conditions, the traffic urgency degree based fuzzy controller experienced 46% reduction in average vehicle delay in comparison to pre-timed control and even 5.4% improvement when compared to fuzzy control. Further, it is observed that the traffic urgency degree based fuzzy control experienced 48.8% reduction in average vehicle delay when contrasted to pre-timed control and even 8.2% improvement in contrast to fuzzy control under middle traffic conditions. Whereas under the high traffic flow, the traffic urgency degree based fuzzy controller experienced 30.6% reduction in average vehicle delay in contrast to pre-timed control and 2.36% improvement when compared to fuzzy control.

A Fuzzy Type-2 Logic Control (FLC) and Gravitational Search Algorithm (GSA) based model proposed by Bi *et al.* (2017) has been compared with type-1/type-2 fuzzy coordination control, optimized version of type-1 fuzzy coordination control (GSAT1) and Fixed-cycle Green Wave band Control (GWC). The parameters such as vehicle queue length, average delay, traffic passing rate and stop rate have been considered for comparison. The proposed model has provided an improvement of 24%-49% compared to conventional GWC when the distance between the adjoining intersections is 500 m. Also, it is observed that under different arrival rates the GSAT2 handled the arrival of vehicles (Queue Length) efficiently in contrast to other methods. Under the different dynamic arrival rates, the GSAT2 have shown a significant dropdown in queue length less than 18 vehicles and 13 vehicles. The results of simulation under dynamic arrival rates gave GSAT2 an upper edge in reducing the vehicle average delay.

In this section, we found that the fuzzy-logic has been proposed by most of the researchers to deal with the growing problem of traffic congestion due to its obvious advantages. However, the limitation of fuzzy is in the processing speed as it requires few extra steps to make the decision about the green time based on sensor provided input parameters and hence requires fast processors. This usually need to the change in the existing infrastructure. Also, the effectiveness of Fuzzy logic systems depends on its rulebase and hence it requires an experts knowledge to frame the rules or fine-tuned machine learning algorithms may be required to extract the rules automatically.

Conclusions

Traffic congestion is a prevalent problem which is being faced by the whole world and many researchers are working on this issue to get the world free from its effects that include, exceeding delays at intersections and CO₂ emission. Since the traffic volumes and the events effecting it i.e., bottleneck, accidents, traffic variation etc. are highly uncertain, intelligent control models based on artificial intelligence techniques such as genetic algorithm, machine learning, reinforcement learning algorithms is required. Fuzzy based traffic controllers due to their inherent capacity to deal with uncertainty are a good choice for modeling traffic management systems.

In this review paper, a survey is conducted over various adaptive traffic models along with commonly used input-output parameters in the field of traffic engineering. Moreover, a comparison of these models in terms of extension or reduction in green time with various models is conducted. It is observed that Fuzzy based Adaptive traffic models are much effective in handling the real time traffic loads by varying the timing of green signal to satisfy the real time traffic conditions. These proposals not only model the expert's knowledge in adaptive ways of signal controlling but, also proved better in performance when contrasted to traditional signal control methodologies. Also, the most influential input/controlling parameters, that affects that decision of green time extension have been identified as number of vehicles/length of queue of vehicles waiting for their turn to cross (commonly called Queue length), rate at which the vehicles are reaching the junction (referred as Arrival rate) and the delay occurred due to waiting in queue.

Although lot of work has already been done in the field of Traffic engineering, there is a huge scope for novelty to be introduced in adaptive signal controlling such as, inclusion of vehicle priority

requirements or other important parameters like road width. Also, as the rules explosion will occur due to inclusion of many additional parameters, future work may involve incorporating all important parameters and reducing the required rules to keep the system manageable.

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