Abstract- A considerable amount of work has been done on the problem of modeling and controlling traffic junctions. Although the description of the events occurring in any individual intersection in the linked or disjoint system can be useful in modeling simple traffic networks the major problem in cities concerns sets of intersections (not individual ones). An adaptive traffic controller using fuzzy logic is presented which takes into consideration the situation of its neighbors. The controller gives preference to less fuel consuming vehicles, public transport vehicles and high priority vehicles. A traffic grid system is designed using Simevents Toolbox of Simulink with provisions for turning and random class of vehicles. The results obtained from the implementation of this fuzzy logic controller are tabulated against those corresponding to a conventional cyclic fixed time controller, vehicle actuated controller and a basic fuzzy logic controller (design for isolated junction). Simulations are done for varying traffic conditions namely heavy, medium, light and random. With the performance criterion being the average waiting time of vehicles, it is shown that the use of this fuzzy logic controller results in a better performance.

Keywords- Fuzzy logic, Adaptive, Traffic controller, Traffic grid, Simulink.

I. INTRODUCTION

A. The Traffic Management Problem
One of the main characteristics of modern cities is the increasing population in a relatively small area. The consequence of this fact is the increase in the number of vehicles and also the necessity of movement and transport of people and goods in urban city networks. Thus, monitoring and control of city traffic is becoming a major problem in many countries. Several measures have been taken to address the problem of road traffic congestion in large cities. Among these measures are:
- construction of flyovers and bypass roads,
- building of several ring roads such as the inner ring road, middle ring road and outer ring road,
- introduction of city trains such as the light rapid transit (LRT) and monorails,
- restricting of large vehicles in the city during peak hours.

These measures however, have largely been unsuccessful to meet the target of freeing major intersections resulting in waste of valuable man hour during the working days. Operating traffic signals is inherently a difficult task with many conflicting objectives. The traffic control should be effective by
- minimizing the waiting times of the vehicles,
- maximizing the capacity of the intersection,
- In addition to this,
- minimizing of the emissions,
- enhancement of public transportation,
- prioritization of intervention vehicles,
- mitigation of high levels of noise.

All these objectives should be realized without compromising the safety of the road users.

B. Methods For Managing Traffic

Manual Control – This involves deployment of traffic policemen at the intersections. The policemen use human logic and experience in regulating traffic based on current situation. Automatic systems don’t work well in many circumstances especially during oversaturated or unusual load conditions (e.g. accidents, jams etc.) which could be due to limitations of the algorithms or sensing devices. In this respect manual control seems to be better due to the intelligence of the traffic policemen in understanding the traffic conditions at the respective junctions. However automatic control systems relieve humans from manual control.

Fixed time Control – Control of traffic at intersection using traffic signals which change either in fixed cyclic pattern or other fixed pattern developed on the basis of statistics and corresponding algorithms.

Vehicle Actuated Control – Vehicle actuated (VA) or responsive control presents an improvement over fixed time control. The VA control principle aims to adjust the length of green time in response to the real traffic flow variations. VA control requires vehicle detectors to provide accurate information of traffic in real-time. This method has limited ability to respond to real-time traffic demand, where its performance generally deteriorates with heavy traffic conditions. This is owing to the fact that VA algorithms do not consider many inputs (based on real life scenarios) simultaneously. Hence, dependence on a single factor leads to deteriorated outcomes. To overcome such problems adaptive traffic signal controllers are designed to address these deficiencies.

Adaptive control – Adaptive traffic control systems are usually closed loop multiple input systems with
algorithms to manage the complex relationship between those inputs. Fuzzy logic is one such algorithm used in adaptive traffic control. These algorithms may take into consideration factors affecting a single junction or those corresponding to a network of junctions.

C. Suitability of fuzzy logic in traffic management
The optimization of signal timing is complex due to randomness, complexity and nonlinearity of the transportation system. So a lot of conventional methods for traffic signal control based precise models fail to deal efficiently with the complex and varying traffic situations. The aims described earlier in section 1A are hard to cope with by using traditional time-based or detector-based control methods since there is no intuitive way of seeing how individual parameter changes affect the overall performance. Fuzzy logic is suitable for controlling intersections, especially those with heavy traffic, because it is able to emulate the control logic of traffic police officers who sometimes replace traffic signal control when the intersection is congested. There are two kinds of research based on fuzzy logic. One is focused on simple traffic conditions and researches single intersection. These researches usually don’t scale to complex traffic systems with many intersections as a whole in a modern city. The others try to consider all these intersections as a whole and make the average delay time of vehicle lower.

Fuzzy logic has been used widely to develop an adaptive traffic signal controller, because it allows qualitative modeling of complex systems, where it is not easy to solve using mathematical models and is good for systems that have inherent uncertainties. Many researchers have proposed the prototype traffic signal control systems using fuzzy logic.

Pappis and Mamdani (1977)[2], Chakraborty and Sarkar (1997), and Niittymaki and Pursula (1996, 2000) developed a fuzzy logic signal controller (FLSC) for an isolated intersection of simple one-way east-west/north-south without turning movement. Kelsey and Bisset (1993), Kim (1994), Khiang et al. (1995), and Trabia and Kaseko (1996) proposed a FLSC for an isolated intersection of four-way east-west/north-south without turning movement. Askerzade (2011) implemented group traffic control system using fuzzy logic. All of the above research has reported generally a better performance of the FLSC when compared to fixed time and actuated controllers.

- Other parameters like priority vehicles, public transport, fuel consumption etc. are not taken into consideration.

This paper deals with the design of an adaptive traffic control strategy for a network of junctions using fuzzy logic so as to decrease the average waiting time of vehicles at an intersection in that grid. The controller designed also gives preference to low fuel consumer vehicles, public transport vehicles and high priority vehicles like ambulances.

The paper outline:
Design of a fuzzy controller – Selection of input and output variables, their membership functions and ranges. The input variables take into consideration not only the characteristics of an isolated system but also that of a grid. Construction of a proper rulebase based on the linguistic variables.

Design of traffic system – This includes heterogeneous, non-lane traffic (Indian conditions) with turn based movements. This system must be generic in order to be adaptable to different control algorithms.

Simulation and Comparison – Implementation of cyclic, responsive, fuzzy algorithm for isolated junctions and that developed in step 1 on the traffic system designed. Simulation of all these control systems for various traffic conditions and comparison. Extension - Simulation on a real map to test its suitability to real traffic networks.

II. SYSTEM STRUCTURE AND ALGORITHM
The major part of the system has been designed using simevents toolbox. The components of this system deal with three major terms Entities - Discrete items of interest which can pass through a network of queues, servers, gates, and switches during a simulation. For this case vehicles are the entities. Events - In a discrete-event simulation, an event is an instantaneous discrete incident that changes a state variable, an output, and/or the occurrence of other events. Vehicle passing through an intersection is an event. Attributes - Entities can carry data, known as attributes. Average vehicle speed, start inertia etc. are examples of attributes. To consider the different aspects of traffic simulation the isolated junction system is divided into five sub-systems namely the generator sub-system, the road subsystem, the processing subsystem, the intersection subsystem and the scope subsystem.

- Most of the research focuses on an isolated intersection. These researches can’t
- apply suitably to complex traffic systems with many intersections as a whole in a modern city.
- The turn movements are usually not included in simulations.
D. The Generator Subsystem
Generation of vehicles which are input to the road subsystem is the task of generator subsystem. It defines each vehicle based on its type and the turn it is going to take at next traffic intersection.

The various features of the vehicle are set as attributes in this subsystem. The entities which arrive at input node of generator subsystem (here A) is given attributes: Class of vehicles (COVs), Turn and Approach. Six different COVs are considered, along with 3 turns (numbered 1 -> Straight 2 -> Right and 3-> Left). Approaches (phases) are named /numbered clockwise from left most being A/1 then B/2 and so on. These are randomized using port based attribute set and random number generator. The other features which are based on COV are set in attribute function block using a simple switch-case statement.

The values taken are based on statistical averages and may be changed without affecting the algorithm of control. The input of vehicles into the ‘In’ node of this subsystem maybe at a constant rate or any random rate depending on which generator configuration is required. Also an entity counter is used to count the number of vehicles entering each junction from previous junction. This counter is reset at each phase change hence number of vehicles arriving from previous junction in each pass is calculated.

The entity output of this subsystem goes into road subsystem and signal output goes as inputs to processing system block.

E. The Road Subsystem
The road subsystem simulates the transit time taken by vehicles on the road and the stop line at which the vehicles wait for signal to become green.

The average speed attribute of incoming vehicle is used along with length of road to calculate transit time of that particular vehicle on road. This transit time is given as input to an infinite server which delays that vehicle by the transit time hence imitating the vehicle travelling on road. Each vehicle is also provided a timer tag which helps in calculating waiting time of vehicles at that particular intersection. An entity splitter splits vehicles based on attribute ‘Turn’ to get Left turn vehicles which do not wait at the stop line. The stop line is a FIFO queue where if output port is blocked then the vehicles stay in the queue. The inputs for processing subsystem are also generated in the road subsystem. The number of vehicles waiting in the queue (#n), average waiting time of vehicles at a particular a stop line (w), number of low fuel consumers (LFC) waiting, number of public transport vehicles waiting (PT), number of priority vehicles blocked (Pri) are calculated and concatenated as a single input to processing subsystem. These inputs in real life can be taken using image based detection from a camera at traffic intersection. The LFC PT Pri calculator consists of entity departure counter similar to that used in generator subsystem which gets reset at each phase change of that particular approach.

F. The Processing Subsystem
The processing subsystem is the most important block of the traffic junction system. It controls the traffic by deciding the phase which should get green light and the time for which the green light must be ON. This is the only subsystem where there are no vehicle input or output ports but only signal ports. This is because the subsystem does processing of data received to calculate and decide the mentioned results. This subsystem can be divided into two parts: the decision part and the implementation part.

The decision part consists of the Function-Call subsystem along with its inputs (which come from generator and road subsystems). It decides the phase which should be given green light and the time for which the green light must be given or Green Light Extension (GLE). This part changes for different control strategies. The implementation part enforces the calculated next phase and GLE and gives it as input to the intersection subsystem. The output of this part is a phase number which is suitable held for GLE seconds. Various different approaches could be taken to design this implementation part like c coding, simulink block etc. However, owing to its ease in usage and simple design Again Simevents toolbox is used for this purpose.
The entities used in this part should not be confused with vehicles. These entities are just carriers of information which are destroyed in entity sink in this subsystem itself. A combination of event based function calls and a signal latch performs the objective of the implementation part. An event based entity generator is used to generate carriers at the lapse of each GLE time upon a function call. However, at the start of simulation a function call could not be caused hence a time based entity generator with intergeneration time as infinity is used to generate a carrier (entity) at the start. GLE calculated by Function-call subsystem is given as attribute to this carrier.

An entity departure event to function call event block is used to generate 3 function call at the time of GLE lapse. 3rd function call is obtained using a function call splitter.

The first call is used to read the phase status in memory of signal latch to its output port. The remaining two calls are used to call two other function call generators: the write call generator and the read call generator. However, the timings of these calls are not the same and are decided by the read and write call delay functions. These function blocks are supplied the GLE as input after being read by a get attribute block. The delay for write call is GLE itself while that for read call is a constant time (here 4 seconds) less than GLE. This difference allows GLE being calculated and ready at output port of Function – call subsystem before a carrier comes to receive it. Also the next phase is written to the memory of latch 4 seconds before it is read out the output port. In real life scenario this delay provides for warning time to vehicles about the next phase. So if GLE is calculated as 30 second at the end of some phase then the next call to calculation port is generated at 26th second. At the same time a memory write function call is given to signal latch. At the 30th second a read call is generated to output the contents of latch memory to its output and a call to produce new carrier is generated. This effectively simulates the change of green lights at a traffic intersection. The decision part of the processing subsystem is different for different control methods. The method which is implemented here is a fuzzy algorithm for traffic network (grid) with provisions for low fuel consumers, public transport and priority vehicles. We will call this modified fuzzy algorithm. This control method is compared with a cyclic fixed time control which is predominantly in used in present in cities. It is also compared to a responsive or vehicle actuated method and a basic fuzzy logic control method developed for an isolated junction. Their implementation of decision part is discussed next.

The cyclic controller selects phases sequentially in a cyclic manner and thus has no feedback input from road subsystem. The GLE is a constant and taken as 30 seconds in this case.

The responsive controller selects the next phase on the basis of number of vehicles waiting in the queue. Hence the phase or approach which has the largest number of vehicles waiting is given green light for a fixed duration of 30 seconds. This controller has some kind of feedback from traffic however a single factor is not sufficient to model the complexities in traffic situations.

The fuzzy logic controller selects the next phase and awards GLE to it based on a value “priority” of a phase. The priority of each phase has range 0 to 4. The phase having highest priority is selected as next phase and GLE given to it is based on the formula

\[ \text{GLE} = \text{round}(10 \times (3 \times ( \text{priority of selected phase} ) - \text{sum of priorities of other phases})) \]

Thus relative difference between the priorities is considered for giving green light time. A constant time of 10 seconds is added to this GLE such that a phase gets at least 10 seconds of GLE. The relative difference is scaled to realistic time values. The priority of each phase is calculated using fuzzy logic controller from fuzzy logic toolbox.

The seven linguistic variables of this fuzzy controller are:

- Queue Length (QL) : Number of vehicles waiting in the queue of phase.
- Waiting Time (WT) : Average waiting time of vehicles waiting in the queue.
- Number of Low fuel consumers (LFC) : Number of low fuel consuming vehicles waiting in the queue of phase.
- Number of public transportation vehicles (PT) : Number of public transportation vehicles waiting in the queue of phase.
- Number of priority vehicles (Pri) : Number of priority vehicles waiting in the queue of phase.
- Number of arriving vehicles (NA) : Number of vehicles arriving from previous phase. This is the variable which takes care of network parameters.
- Priority : Output linguistic variable. Priority value of the phase under consideration for allotment of green light.

The membership functions for the QL and WT are Gaussian functions with a range of 0-60. The membership functions for the given LFC and PT are

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triangular functions with range 0 to 20 vehicles for LFC and 0 to 5 vehicles for PT. The triangular functions are computationally efficient. A suitable membership function for variable Pri is chosen such that there is a flat region near 1 value. This accounts for possibility of a single priority vehicle getting due preference. The range of Pri is 0-2. The membership function of NA is a Gaussian function with a range of 0-60 vehicles arriving at the intersection.

Queue Length has membership functions Short, Medium, Long. Waiting time too has membership functions Short, Medium, Long. Number of priority vehicles can be low, medium or high and similar mfs are used for number of arriving vehicles. Priority of phase (named GLE over here to avoid confusion with Pri linguistic variable) could be Low, Medium or High.

The rulebase for this controller has 38 rules with QL, WT and LFC set; QL, WT and PT set; QL and NA set and Pri set.

21. If (QL is Long) and (WT is Medium) and (LFC is Short) then (GLE is High) (1)
22. If (QL is Medium) and (WT is Medium) and (PT is Long) then (GLE is High) (1)
23. If (QL is Medium) and (WT is Medium) and (LFC is not Long) then (GLE is Medium) (1)
24. If (QL is Medium) and (WT is Medium) and (PT is not Long) then (GLE is Medium) (1)
25. If (QL is Medium) and (WT is Short) and (LFC is Short) then (GLE is Very Low) (1)
26. If (QL is Medium) and (WT is Short) and (PT is Short) then (GLE is Very Low) (1)
27. If (QL is Medium) and (WT is Short) and (LFC is not Short) then (GLE is Low) (1)
28. If (QL is Short) and (WT is Medium) and (PT is not Short) then (GLE is Low) (1)
29. If (QL is Short) and (WT is Medium) and (LFC is Short) then (GLE is Very Low) (1)
30. If (QL is Short) and (WT is Short) and (PT is Short) then (GLE is Very Low) (1)
31. If (QL is Short) and (WT is Medium) and (PT is not Short) then (GLE is Low) (1)
32. If (QL is Short) and (WT is Medium) and (PT is not Short) then (GLE is Low) (1)
33. If (QL is Short) and (WT is Medium) and (PT is not Short) then (GLE is Medium) (1)
34. If (QL is Short) and (NA is High) then (GLE is Medium) (1)
35. If (QL is Medium) and (NA is High) then (GLE is Medium) (1)
36. If (QL is Long) and (NA is High) then (GLE is High) (1)
37. If (QL is Medium) and (NA is Medium) then (GLE is Medium) (1)
38. If (QL is High) then (GLE is High) (1)

Fig. 7. Modified Fuzzy Rule base

G. The Intersection Subsystem
This subsystem is responsible for regulation of traffic flow at an intersection. Based on the phase status received as input from the processing subsystem, an input switch regulates the flow of vehicles from that particular phase. A N-server is used to imitate start inertia, sending a set of vehicles with service time based on the their inertia attribute. Once the vehicle is out of intersection an attribute function block allocates new approaches or phases to the vehicles based on their previous phases and turn attribute.

Fig. 8. Intersection subsystem

A vehicle has only three conditions in a network. Either it
- enters a network
- leaves a network
- is within the network

Different number and types of junctions can be combined together in different combinations to form a traffic grid. However, few points have to be kept in mind while doing so.

- The class of vehicle attribute (COV) is defined only for vehicles entering a network. Hence, while setting attribute of vehicles in generator subsystem setting COV should be avoided for vehicles which are within the network. The ‘turn’ attribute is however set as it is because a vehicle may take any random turn at any intersection irrespective of its status in the network.
- The road lengths mentioned as inputs to road subsystem should be consistent with the neighboring junctions i.e. same road can’t have two different length.
An entity (vehicle) source and sink must be specified for each entry/exit point of a network.

Fig. 9. Implementation of designed system on a map of Nagpur.

III. RESULTS

The intergeneration times of entity (vehicle) generators are random between 1s to 6s. Also the initial seed value is maintained in the different control strategies. The simulation is done for 3600s.

Fig. 10. Phase status of intersection 6 in different control strategies

Fig. 11. Average Waiting Time Comparison in Random traffic conditions

TABLE I. COMPARISON OF CYCLIC, RESPONSIVE, BASIC FUZZY CONTROLLERS WITH DESIGNED CONTROLLER IN RANDOM TRAFFIC CONDITIONS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control Strategy</th>
<th>% Improvement of Fuzzy Modified over</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cyclic</td>
<td>Responsive</td>
</tr>
<tr>
<td>Average Waiting Time (AWT) (s)</td>
<td>36.02</td>
<td>37.52</td>
</tr>
<tr>
<td>AWT of Low Fuel Consumers (s)</td>
<td>31.86</td>
<td>36.55</td>
</tr>
<tr>
<td>AWT of Public Transport Vehicles</td>
<td>28.12</td>
<td>39.06</td>
</tr>
<tr>
<td>AWT of Priority Vehicles (s)</td>
<td>32.26</td>
<td>36.86</td>
</tr>
</tbody>
</table>
The following conclusions are drawn from graphs and tables (only random traffic results are shown here)

- In heavy traffic conditions an improvement of 68.52%, 30.92% and 10.9% in average waiting time of vehicles is achieved by the designed controller over cyclic controller, vehicle actuated controller and basic fuzzy controller respectively.
- In medium traffic conditions an improvement of 38.98%, 41% and 13.83% in average waiting time of vehicles is achieved by the designed controller over cyclic controller, vehicle actuated controller and basic fuzzy controller respectively.
- In light traffic conditions an improvement of 37.4%, 39% and 20.72% in average waiting time of vehicles is achieved by the designed controller over cyclic controller, vehicle actuated controller and basic fuzzy controller respectively.
- In random traffic conditions an improvement of 50.36%, 52.34% and 28.99% in average waiting time of vehicles is achieved by the designed controller over cyclic controller, vehicle actuated controller and basic fuzzy controller respectively. Since random traffic conditions are most prevalent this improvement is significant.
- The response of vehicle actuated controller and basic fuzzy controller deteriorates for light traffic conditions with improvement shown by cyclic controller. However, no such limitations for the designed controller.
- For different traffic conditions the average waiting time of low fuel consumers is about 10% less than the average time of all the vehicles.
- For different traffic conditions the average waiting time of public transport is about 2.3% more than the average time of all the vehicles.

However, as compared to other heavy vehicles it is much less.
- For different traffic conditions the average waiting time of priority vehicles is about 21% less than the average time of all the vehicles.

**REFERENCES**


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**TABLE II. COMPARISON OF AWT OF LFC, PT, PRI AND OTHERS IN RANDOM TRAFFIC CONDITION.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control Strategy</th>
<th>% Improvement of Fuzzy Modified over</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of vehicles served (10^3)</td>
<td>Cyclic</td>
<td>Responsive</td>
</tr>
<tr>
<td>41.01</td>
<td>49.95</td>
<td>41.46</td>
</tr>
</tbody>
</table>

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