Use of Fuzzy Logic Traffic Signal Control Approach as Dual Lane Ramp Metering Model for Freeways

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Abstract Metering of merging traffic flows from on-ramp section of freeways is an important research issue for traffic engineers. Although metering signal is one of the recent applications for the subject, assignment of signal timing is problematic. The problem is based on dynamic structure of traffic flows and uncertainties coming up from driver behaviors. Because of variations in car following behavior and perception-reaction times of drivers, uncertainties are occurred. To handle these uncertainties, fuzzy logic approach is preferred in this research. A **Fu**zzy **L**ogic**C**ontrol based Dual Lane **R**amp **Me**tering (FuLCRMe) Model is proposed. The model considers following parameters as inputs; arrival headways of mainline, queue length at ramp and red time of ramp. Decision about red signal timing is made using these parameters. Based on this decision the final red time is assigned. The FuLCRMe model is tested by a simulation developed in Microsoft Excel program considering different cases. Results of the comparisons show that the FuLCRMe model provides significant decrease in delays, queue length, cycle time, CO_2 emission, fuel consumption, travel time and total cost.

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1 Introduction

Ramp meters are used for controlling traffic at entrances to freeways by traffic signals. The main objective is to control the number of vehicles that are allowed to enter the freeway in ramp metering. On the other hand, reducing freeway demand is also aimed. The purpose of these objectives is to ensure that the total traffic entering a freeway section remains below the operational or bottleneck capacity of that section. A secondary objective of ramp metering is to introduce controlled delay (cost) to vehicles wishing to enter the freeway, and as a result, reduce the incentive to use the freeway for short trips during peak hour. If the ramp metering is applied properly, expected benefits can be achieved, such as increased speeds, decreased fuel consumption and emissions, safer operation and decreased travel times etc [1–3]. Otherwise, the results expected can not be satisfied. In conventional ramp metering approaches, determination of signal timing have uncertainties and it cannot meet fluctuations in traffic flow pattern. Signal timings are pre-determined considering limited time of observations. These observations can include traffic flows that are trying to merge freeway only within corresponding period. But it is not the same all the day and fluctuate in times of a day. Traffic signal timings are assigned discarding these variations. Therefore traffic flows can not be controlled efficiently. On the other hand, delays of vehicles that are arriving to ramp can be excessive, because of unbalanced assignment of traffic signal timings. This unbalanced and rigid control scheme yields problems related to capacity (i.e. overcapacity or under capacity cases). To remove these deficiencies, fuzzy logic (a flexible or soft) approach is preferred in this study (Fig. 1).

2 Fuzzy Logic Control Model for Ramp Metering

To handle the problem of excessive delay and unbalanced signal timing assignment for ramp flows, fuzzy logic approach is used and the FuLCRMe Model is developed. In FuLCRMe model, fuzzifications of the parameters are made using the membership functions that are determined with respect to previous field studies and experience [4–7]. Mamdani's inference mechanism and centroid method are used as inference and defuzzification procedure of the FuLCRMe model. The Fuzzy Logic Toolbox of MATLAB program is used in developed FuLCRMe model. In this model, red time of ramp is determined by the parameters and rule base. The parameters used in the FuLCRMe model are defined in the following:

- Arrival Headway of traffic flows at mainline (ARHE)
- Queue length at ramp (QULE)
- Rate of remaining red time for ramp (REMRED)
- Decision of red signal time for ramp (SIGDEC)

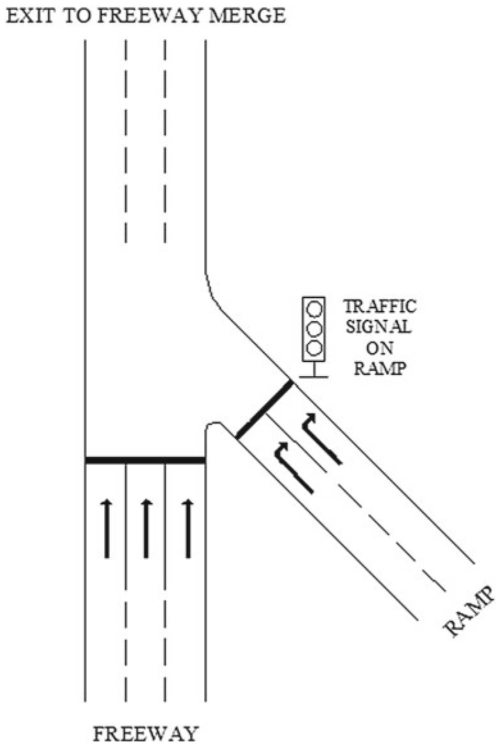

Fig. 1 Illustration of ramp metering signal

2.1 Arrival Headway of Traffic Flows at Mainline (ARHE)

Headways of traffic flows provide useful information about traffic conditions. Arrival Headway of traffic flows at mainline is considered as one of the input parameters in the FuLCRMe Model. It is used in signal timing decision (red time) of ramp. The boundaries of membership functions are determined considering results of previous researches and field studies [8, 9]. (Fig. 2)

2.2 Queue Length at Ramp (QULE)

Queue length at ramp is one of the key parameters in decision making. Traffic flows can be managed properly if signal timing is assigned considering queue length at ramp. Otherwise, excessive delays can be occurred for the vehicles on ramp. The red time of ramp is determined regarding queue length at ramp and arrival headways of mainline traffic flows. Membership functions of the parameter are defined in the Fig. 2.

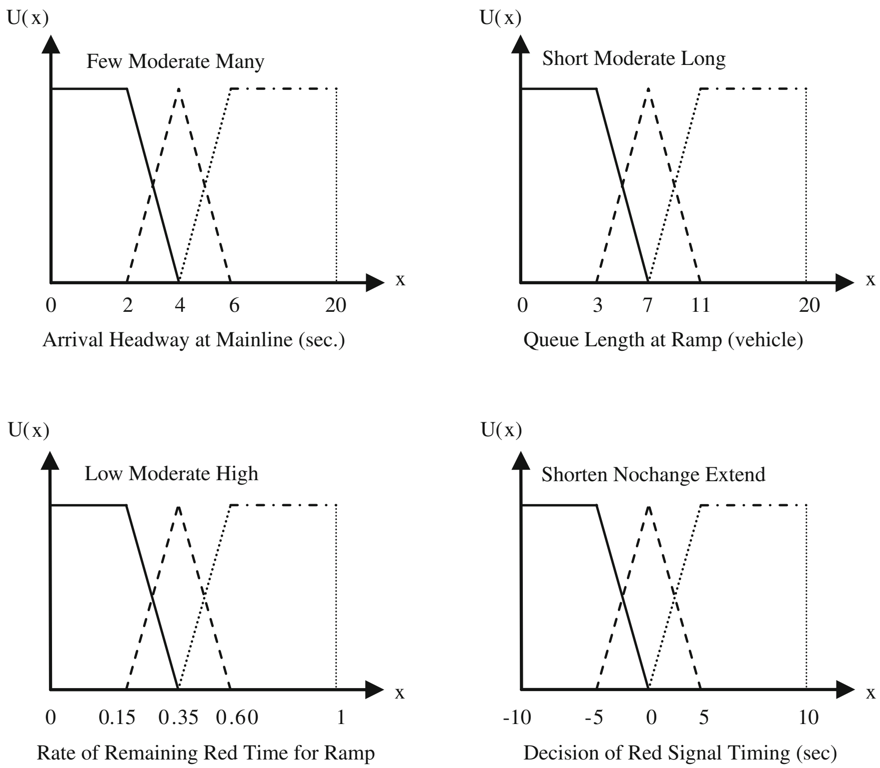

Fig. 2 Membership functions of the FuLCRMe model input and output parameters

2.3 Rate of Remaining Red Time for Ramp (REMRED)

Rate of remaining red time for ramp is a control parameter used in signal decision. Membership functions of this parameter are shown in Fig. 2. Rate of **Rem**aining **Red** Time parameter is obtained by following formula:

$$\mathbf{RemRed} = (\text{Remaining red time to switch into the green signal}) / (\text{Total red time in the cycle}) \quad (1)$$

2.4 Decision of Red Signal Time for Ramp (SIGDEC)

Decision of red signal time for ramp is critical in ramp metering. It can be determined based on trial-error approach or conventional signal timing methods.

Table 1 A few examples of FuLCRMe model rule base

Sample no.	IF	Arrival headway at mainline (sec.)	Queue length at ramp (veh.)	Rate of Remred for ramp	Signal decision
2		Many	Long	Moderate	Shorten
8		Many	Short	Moderate	Shorten
16		Moderate	Short	Low	Extend
23		Few	Moderate	Moderate	No change
25		Few	Short	Low	Extend

Based on this time, vehicles on ramp are controlled. Therefore it is considered as output parameter of the FuLCRMe Model. Decision about red signal timing for ramp is made considering the input parameters and the rule base. The FuLCRMe Model parameters and membership functions are given in the Fig. 2. In addition to this, a few examples of FuLCRMe Model Rule Base are given in the Table 1.

3 Analysis

3.1 Design of Experiments

The FuLCRMe model is tested regarding different cases. A total of 75 exercises were conducted. 15 sample cases which are provides best results are taken into consideration in the analysis. These sample cases are selected after analysis of numerous combinations. For each case, signal timing is computed both by fuzzy approach and by the conventional approach. Average delay, operational cost, 95 % back of queue, travel time, cycle time, degree of saturation value and capacity value are considered as parameters of performance index. In the analysis, two merging lanes for traffic flows on ramp and three through lanes for mainline flows are taken into account as the geometry for all cases. Illustration of geometry is shown in Fig. 1. In the analysis, it is assumed that traffic volumes given in the Table 2 are shared equally for lanes of each approach.

Table 2 Traffic volumes samples

Case no.	Traffic volumes (vph)		Case no.	Traffic volumes (vph)		Case no.	Traffic volumes (vph)	
	Mainline	Ramp		Mainline	Ramp		Mainline	Ramp
1	2400	1500	6	3000	700	11	3500	300
2	2550	1300	7	3000	1100	12	3500	600
3	2700	900	8	3100	700	13	3700	600
4	2850	700	9	3300	300	14	3800	300
5	2850	900	10	3300	600	15	3800	600

Table 3 Performance results comparisons for intersection

Cases no.	Traffic volumes	Performance results (FuLCRMe model/conventional model)-intersection						
		Average delay (s)	Operating cost (usd/h)	Travel time (s)	Travel speed (km/h))	95 (%) back of queue-vehicle	95 (%) back of queue-distance (m)	Cycle time (s)
1	2400–1500	8.9/14.3	1249.0/1426.0	34.1/39.5	44.3/38.2	24.7/37.2	173.0/206.6	96/114
2	2550–1300	7.7/11.6	1158.1/1285.0	32.0/35.9	45.6/40.7	18.4/26.9	128.9/188.0	79/94
3	2700–900	5.1/7.1	944.2/1005.1	27.9/29.9	49.1/45.8	8.6/12.3	60.2/86.3	49/60
4	2850–700	3.9/5.7	861.8/912.2	25.8/27.5	50.8/47.7	5.9/8.9	41.4/62.3	41/53
5	2850–900	5.3/7.6	982.8/1056.6	27.9/30.3	48.6/44.9	9.7/14.2	68.2/99.4	55/68
6	3000–700	3.5/5.8	880.6/949.1	25.3/27.6	51.6/47.3	5.7/9.9	39.6/69.2	42/60
7	3000–1100	9.8/13.1	1244.1/1365.2	33.0/36.3	42.1/38.3	23.6/30.3	165.5/211.8	102/114
8	3100–700	4.5/6.5	927.4/992.7	26.1/28.1	49.8/46.1	7.6/11.3	53.3/79.1	51/65
9	3300–300	2.0/2.6	735.3/753.0	21.9/22.5	54.4/52.9	2.7/3.7	18.8/26.0	37/48
10	3300–600	4.0/5.8	912.7/970.4	25.1/26.9	50.5/47.1	6.9/10.2	48.1/71.4	53/69
11	3500–300	2.2/2.9	778.9/799.9	22.0/22.7	53.9/52.3	3.2/4.4	22.7/30.9	43/55
12	3500–600	5.5/6.8	1003.8/1047.7	26.5/27.7	47.5/45.3	10.5/12.8	73.4/89.7	74/84
13	3700–600	6.6/8.0	1084.4/1134.6	27.5/28.8	45.5/43.4	13.7/16.3	96.0/114.4	96/107
14	3800–300	2.8/3.3	855.2/869.0	22.5/23.0	52.4/51.4	4.8/5.6	33.9/39.3	64/72
15	3800–600	7.1/9.2	1124.4/1203.6	27.9/30.0	44.7/41.5	15.3/19.3	107.1/135.3	107/123

Table 4 Comparisons of degree of saturation values and effective intersection capacity values

Cases no.	Traffic volumes (mainline–ramp) Samples	Comparisons of degree of saturation values (FuLCRMe Model/ Conventional approach) Intersection	Comparisons of effective intersection capacity values (vph) (FuLCRMe Model/ conventional approach) Intersection
1	2400–1500	0.694/0.824	5619/4732
2	2550–1300	0.664/0.790	5798/4873
3	2700–900	0.585/0.716	6159/5030
4	2850–700	0.543/ 0.703	6532/5053
5	2850–900	0.596/0.737	6287/5085
6	3000–700	0.547/0.696	6764/5317
7	3000–1100	0.744/0.831	5514/4933
8	3100–700	0.591/0.754	6424/5041
9	3300–300	0.602/0.636	5983/5658
10	3300–600	0.602/0.732	6481/5330
11	3500–300	0.638/0.729	5954/5213
12	3500–600	0.692/0.786	5922/5217
13	3700–600	0.727/0.810	5914/5306
14	3800–300	0.693/0.716	5917/5728
15	3800–600	0.740/0.851	5946/5173

3.2 System Architecture and Calculation Process

In the analysis, SIDRA Intersection program is used as a test environment for comparisons of the conventional and fuzzy logic based models. The FuLCRMe model is developed using Matlab program and it is worked interactively with the simulation program developed in Microsoft Excel environment. In first stage of calculation procedure, using the traffic volumes given in Table 2, cycle time, red time and green time are calculated by SIDRA for conventional ramp metering approach. In the second stage, the calculated cycle times for each case is used as starting cycle time in simulation of the FuLCRMe (fuzzy) model. In FuLCRMe model, each case is simulated using MS Excel regarding ARHE, QULE and REMRED parameters and decision about red signal time for ramp is made by cycle basis. Each case is simulated 15 min time periods and the results are reported.

3.3 SIDRA Intersection Program

The SIDRA Intersection is a mesoscopic simulation program that is used for both intersection design and research aid. Ramp metering is one of the useful tools of the SIDRA. In ramp metering tool, the cycle time can be used either calculating by

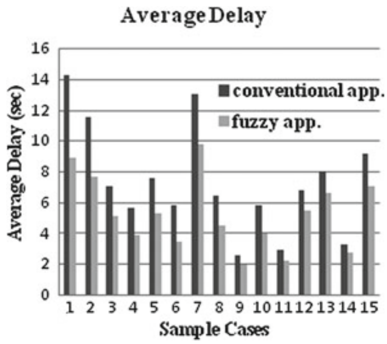

Fig. 3 Comparisons of average delay

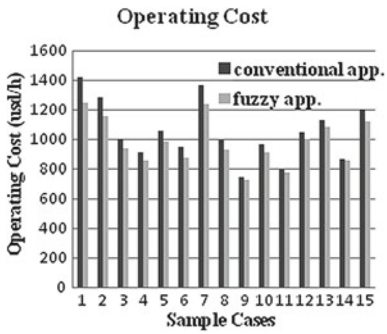

Fig. 4 Comparisons of operating cost

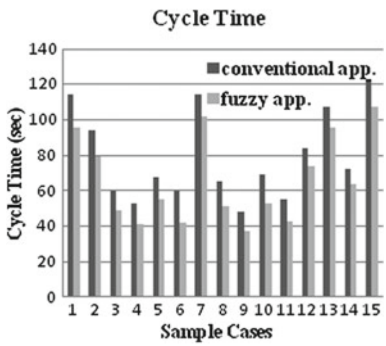

Fig. 5 Comparisons of cycle time length

the program or entering by user. Cycle time, red time and green time are calculated by the program for given traffic volumes. Cycle time calculation is based on conventional signal timing methods by Akcelik. Average delay, fuel consumption, queue length, operational cost, travel time, travel speed etc. are performance index parameters of the program that is developed by Akcelik.

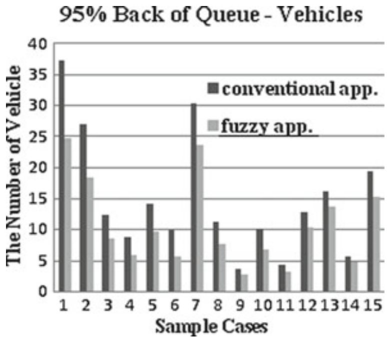

Fig. 6 Comparisons of 95 % back of queue—vehicles

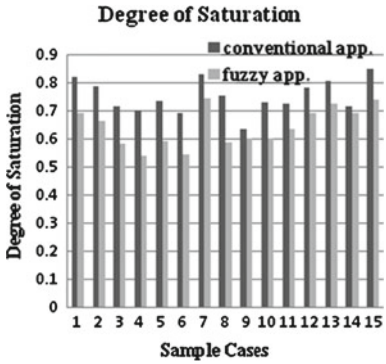

Fig. 7 Comparisons of degree of saturation value

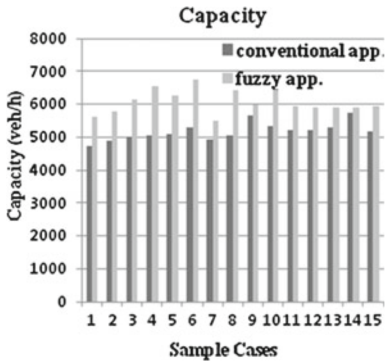

Fig. 8 Comparisons of capacity

Table 5 Paired-t test's results

Parameters	t stat	Critical t-value
Average delay	1.9226	1.7011
Operating cost	1.0431	1.7011
Cycle time	1.4508	1.7011
95% Back of queue	1.3347	1.7011
Degree of saturation	4.7021	1.7011
Capacity	7.8844	1.7011

3.4 Simulation Studies

Simulation study is conducted for testing the FuLCRMe model performance by Microsoft Excel program. In simulation, firstly random numbers are generated and then converted to headways of vehicles considering given traffic volumes. Based on these headways, vehicles are generated. Using these generated vehicles, simulation is carried out. Calculated cycle times of conventional ramp metering model are used as starting value of each case in simulation. FuLCRMe model produced decisions in three times of each cycle; half time of cycle, 75 % time of cycle and last 5 s of cycle respectively. Using these decisions, cycle time is changed and timing is assigned for each case. For each case, at the end of simulation period, average cycle time and red time is calculated and these balanced timings are used as input for SIDRA intersection program and performance values of FuLCRMe model are obtained.

4 Conclusions

In this section the results obtained from FuLCRMe model with these obtained from the conventional model are compared. Table 3 presents intersection based performance results comparisons while Table 4 presents comparisons of degree of saturation and capacity values. The results achieved from these analyses are remarkable. As seen on tables and figures, the FuLCRMe model performs better than conventional ramp metering approach for all performance criteria. Specifically, the FuLCRMe model provides about 30 % improvements in average vehicle delay comparing to conventional approach (Fig. 3). The improvements obtained for operating cost are about 10 % (Fig. 4) and improvements obtained for CO_2 emission and fuel consumption are about only around 5 % for the whole intersection. It is resulted that, the FuLCRMe model performs better if the traffic volumes on ramp is higher than 1000 vehicles per hour. This finding can easily be seen for the cases of 1, 2 and 7. For these cases, the FuLCRMe model met the fluctuations in traffic flows and regulates uncertainties by elastic control scheme (fuzzy membership functions and rule base). Comparisons of cycle times are shown in (Fig. 5). It is seen that, the cycle times obtained by FuLCRMe model are shorter than that of the conventional model yields for all cases. The FuLCRMe model provides about average 18 % decrease in cycle times with respect to all sample cases. Besides to improvements mentioned above, as seen on (Fig. 6) that FuLCRMe model decreases 95 % back of queue-vehicles values about 30 % (average), regarding conventional approach. To measure efficiency of the proposed model, in addition to the parameters given above, degree of saturation and capacity values are taken into account. Average benefit rate for degree of saturation is about 14 % (Fig. 7) and it is 15 % for capacity (Fig. 8). These values are meaningful for traffic engineering point of view and it is showed that, use of fuzzy logic approach for ramp metering removed deficiencies and balanced signal timing.

Paired-t test has been applied for the results provided from the Figs. (3–8). Different 6 parameters are investigated with the Paired-t test. These parameters are Average Delay, Operating Cost, Cycle Time, 95 % Back of Queue, Degree of Saturation and Capacity. Paired-t test's results are given in the Table 5.

In this study, α value is taken into account as 0.1 for the Paired-t test. As seen on the table, Average Delay, Degree of Saturation, Capacity values are statistically significant.

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