A New Approach for Modeling Vehicle Delay at Isolated Signalized Intersections

DETERMINING VEHICLE DELAY IS A COMPLEX TASK, ESPECIALLY FOR OVER-SATURATED TRAFFIC CONDITIONS. THIS STUDY CONSIDERS THE FUZZY LOGIC APPROACH FOR MODELING VEHICLE DELAY. THE FUZZY LOGIC DELAY ESTIMATION (FLDE) MODEL IS DEVELOPED TO ESTIMATE THE AVERAGE DELAYS OF VEHICLES AT SIGNALIZED INTERSECTIONS.

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INTRODUCTION

Traffic signal timing is designed considering the average delays of intersections. Average delay is the key parameter that determines the level of service at an intersection. To prevent congestion on road networks and to maintain accessibility, an accurate vehicle delay value should be known.

Manually collecting delay data from intersections through observation is difficult because vehicle delay includes many parameters, such as traffic volumes, car-following, queued vehicles, bus stops near intersections, road-side parking and pedestrians. Detectors that work based on magnetic induction or highly-sensitive cameras are used for measuring vehicle delay. Although usage of this equipment is the most convenient and accurate way of measuring vehicle delay, installation and maintenance costs are high. Therefore, an efficient and comprehensive model is required for engineers.

In general, vehicle delay consists of two parts: uniform and non-uniform. Uniform delay is determined based on signal timings and traffic volumes. It depends upon the signal control systems and phase sequencing. The red, inter-green and yellow signal times are the components of uniform delay.

Non-uniform delay is determined considering the vehicle queue and random arrivals. Determination of non-uniform delay has been a problem for researchers due to over-saturation, where the degree of saturation is greater than one. Conventional approaches or formulas cannot handle real situations or real values, especially for over-saturation.[1,2,3]

Although methods have considered similar parameters in the determination of vehicle delay, the results obtained are not comparable to each other. For example, field measurements show that vehicle delay is increased but cannot reach the values calculated by the Webster delay formula in the over-saturation case.[4] However, the *Highway Capacity Manual* (HCM) and Akçelik delay formulas give much more reasonable results compared with Webster.[5]

Neither method represents the observed values obtained from field studies because only measurable (crisp) parameters or factors are taken into account in these methods while calculating vehicle delays such as traffic volume, cycle time and green time. The following parameters are not considered in delay estimation: car-following behavior, psychology, age, sex and education of drivers, intersection geometry, traffic blockage factors and weather conditions.

Uncertainties in defining delay are due to human parameters, such as perception and reaction times while driving, maintaining a safe following distance and acceleration and deceleration maneuvers. These vary by driver and also bear on traffic flow conditions. For example, perception and reaction times of older drivers are longer than those of younger drivers. Older drivers cannot perceive a green signal in the shortest time and cause an increase in stopping delay. Therefore, composition of driver profile is as important as traffic composition.

Weather also is an important parameter that contributes to uncertainties. Because of poor visibility on a rainy or snowy day, drivers follow each other slowly. Thus, arriving and departing times of vehicles are increased compared to a sunny day. This vagueness cannot be modeled by conventional delay calculation approaches. Conventional methods are restricted by crisp values such as zero and one.

There also are interactions between these parameters. For example, on a rainy day, perception times of older drivers may be two or more times longer than on a sunny day. These interactions also contribute to the vagueness of the vehicle delay phenomenon.

The aforementioned factors and interactions have not been considered by conventional delay calculation methods. Thus, results of conventional methods may not match with observations in some cases, especially for over-saturated traffic conditions. This may be handled using the fuzzy logic approach and the membership function definition.

For example, stormy or windy days in addition to rainy and snowy days can be defined by fuzzy membership functions. Blockage factors also may be modeled by the fuzzy logic approach, which is based on graded concepts to handle uncertainties and imprecision in a particular domain of knowledge. The fuzzy logic approach was employed for modeling delays of vehicles in this study.

DELAY PHENOMENON

Vehicle delay at signalized intersections has been defined with some components; stopping, acceleration and deceleration delays are the components of total delay.[6] The deceleration delay consists of the vehicle deceleration time while approaching a signalized intersection. The stopping delay includes the vehicle stopping time during the red signal period at a signalized intersection. The acceleration delay may be defined as time of vehicle acceleration after the traffic signals turn green. Overall delay includes all of these components.

The Webster, HCM, or Akçelik delay calculation methods have been preferred by traffic engineers for many years. In this study, the HCM and Akçelik delay formulas are considered for comparison to the proposed new methods.[7,8]

Akçelik assumed that the total delay includes both acceleration and deceleration delays and stated that the effect of the queue length must be considered in delay calculation. The total delay for an isolated fixed-time signalized intersection is calculated as:

$$D = \frac{qc(1-u)^2}{2(1-y)} + N_0 x \tag{1}$$

where:
D = total delay
q = flow, in vehicles per second
c = cycle time, in seconds
u = green time ratio
y = flow ratio
N_o = average overflow queue in vehicles

The queue length can be determined as follows:

$$N_0 = \frac{QT_f}{4}\left((x-1) + \sqrt{(x-1)^2 + \frac{12(x+x_0)}{QT_f}}\right) \tag{2}$$

$$x_0 = 0.67 + sg \; / 600 \tag{3}$$

where:
N_o = average overflow queue
Q = capacity
T_f = flow period
QT_f = maximum number of vehicles that can be discharged during interval T_f
x = degree of saturation
x_o = degree of saturation below which the average overflow queue is approximately zero
s = saturation flow, in vehicles per second
g = effective green time, in seconds

The following formula is used in an updated form of the HCM method:

$$d = d_1(PF) + d_2 + d_3 \tag{4}$$

where:
d = control delay per vehicle
d_1 = uniform control delay assuming uniform arrivals
PF = uniform delay progression adjustment factor, which shows the effects of signal progression
d_2 = incremental delay to account for effect of random arrivals and over-saturation queues
d_3 = initial queue delay, which accounts for delay to all vehicles in analysis period due to initial queue at start of analysis period

The following equation gives the uniform control delay in HCM's approach:

$$d_1 = \frac{0.5c(1-\frac{g}{c})^2}{1-[\min(1,x)\frac{g}{c}]} \tag{5}$$

where:
d_1 = uniform control delay assuming uniform arrivals
c = cycle length
g = effective green time for lane group
x = volume-capacity ratio or degree of saturation for lane group

Non-uniform arrivals, cycle failures and over-saturation conditions cause an incremental delay in traffic flow. The incremental delay and initial queue delay are determined using Equations 6 and 7:

$$d_2 = 900T[(x-1) + \sqrt{(x-1)^2 + \frac{8klx}{CT}}] \tag{6}$$

$$d_3 = \frac{1800\, Q_b\,(1+u)t}{CT} \tag{7}$$

where:
d_2 = incremental delay to account for effect of random arrivals and over-saturation queues
d_3 = initial queue delay

T = duration of analysis period
K = incremental delay factor
L = upstream filtering/metering adjustment factor
C = lane group capacity
x = lane group degree of saturation
Q_b = initial queue at the start of period T
T = duration of unmet demand in T
U = delay parameter

It is apparent that these formulas consider similar parameters to describe the phenomenon. Because the formulas are empirically based, there are differences between them.

In addition to these formulas, many delay studies have been conducted by researchers.[9–14] Although valuable studies have been completed, the vagueness in vehicle delay has not been defined. Therefore, this study concentrates on delay estimation at signalized intersections using a fuzzy logic approach for both under-saturated and over-saturated conditions.

FUZZY LOGIC APPROACH

Fuzzy logic was first introduced by Zadeh.[15] It was proposed as an extended version of Aristotelian logic considering all values between zero and one. After Zadeh, many researchers carried out the fuzzy logic approach and developed models in different areas.[16,17] The common use of fuzzy logic comes from its attractive features.

One of the main attractions of fuzzy modeling is its simplicity and natural structure. In addition, the uncertainties encountered in life may be easily represented with fuzzy logic approaches. Inexact or intuitive knowledge that could not be modeled by most conventional mathematical modeling approaches may be modeled using fuzzy logic. Ross explores fuzzy logic and engineering applications in his text, and many other textbooks provide basic information on the phenomenon.[18]

The fuzzy logic system structure indicated in Figure 1 consists of three parts: fuzzification, inference and defuzzification.[19] Determination of parameters and membership functions is the first step in fuzzy modeling. Fuzzification is the conversion of crisp values to fuzzy using membership functions. The parameters associated with the subject are determined based on experience. Parameters are divided into subsets using membership functions. Membership functions of the parameters can be selected as triangular, trapezoidal, or bell type based on the problem considered.

The relationship of parameters can be defined using an "if-then" analysis. The rule base is constituted considering all the relations of input and output parameters. The inference can be obtained using rule base and some methods such as "max-min" or "max product." The Mamdani (max-min) is the most used method for fuzzy input and outputs.

In the max-min process, the minimum membership values of the used rules outputs are selected (the minimum membership value of each input subset) and the maximum of the minimums is determined (the maximum membership value of each output subset is selected). This process is applied to all valid rules and a geometric shape is obtained.

The last step of fuzzy modeling is called defuzzification. The fuzzy results are converted to crisp values in this step. The centroid, weighted average, mean of maximum and maximum membership defuzzification methods are used in fuzzy modeling. The method is determined based on the type of problem considered. The centroid is a widely used defuzzification method by researchers.[20]

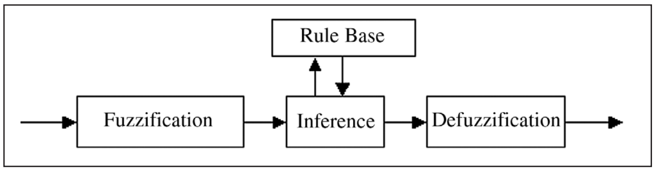

Figure 1. Structure of a fuzzy logic system.

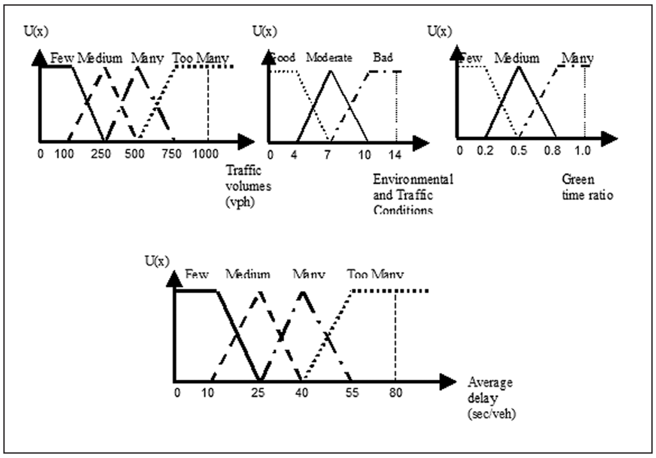

Figure 2. FLDE model parameters and membership functions.

FUZZY LOGIC VEHICLE DELAY MODEL

The fuzzy logic delay estimation (FLDE) model was developed to estimate average vehicle delays at signalized intersections for under-saturated and over-saturated conditions (see Figure 2). The traffic volumes (TV), ratio of green time to cycle time (RGC) and environmental and traffic conditions (ETC) were ascertained as input parameters of the FLDE model.

The required data for the model were obtained from 10 different signalized intersections located in Denizli and Izmir, Turkey, in 2002 and 2003.[21] The overall delay data including deceleration, stopping and acceleration delays were collected for 100 hours considering lane group basis at peak and off-peak periods during weekdays.

Vehicle delays are affected by traffic volumes. Increases in traffic volumes cause increases in delays. Vehicle queues occur if traffic volumes are very high, and vehicle delays increase if queues are not dissipated. Therefore, traffic volume is considered one of the effective parameters on vehicle delays. Green signal time and cycle time have been used in various previously developed delay formulas, and these are directly related vehicle delays. Both timings are effective on vehicle delay, and are considered a ratio in the models.

Environmental and traffic conditions also are effective on vehicle delay at signalized intersections. Factors considered in the scope of environmental and traffic conditions include: lane type (shared, exclusive), road-side parking, bus stops, weather conditions, car-following behaviors, pedestrians and queuing. Vehicle delay is negatively affected by all of these factors.

In field studies, the maximum value of each factor is scored as two points. Based on field conditions, some factor is scored

Table 1. Samples of FLDE model rule base.

1. IF TV is few and RGC is many and ETC is good THEN AD is few.
3. IF TV is few and RGC is many and ETC is moderate THEN AD is medium.

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8. IF TV is few and RGC is medium and ETC is moderate THEN AD is medium.

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16. IF TV is medium and RGC is few and ETC is moderate THEN AD is medium.

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36. IF TV is too many and RGC is few and ETC is bad THEN AD is too many.

as one point. The total value for each approach of intersection is obtained by calculating the sum of values of the factors. The maximum value for ETC is 14 points, the worst condition.

The membership functions for the FLDE model parameters are ascertained regarding statistical analysis of the data collected. The maximum, minimum, average and standard deviation of the data are computed and used in determining ranges of membership functions. The rule base of the model is formed considering membership functions of the parameters. The ule base consists of 36 rules. Inferences are obtained from the rule base using the Mamdani method of inference. Samples from rule base are given in Table 1. To obtain precise results, the centroid method is selected for defuzzification in the FLDE model.

COMPARISONS OF DELAY ESTIMATIONS

The FLDE model validation is searched comparing the model results with the HCM and Akçelik delay formulas and the delay data obtained from the observations. The data are collected from 10 different intersections of two cities with 100 hours of observation. The hourly data that were not used in the development stage of the models are taken into account in comparisons. These data were selected from 10 different intersections. The adjusted saturation flow rates are determined for each lane of the intersections considering the field conditions and measurements. Comparison of average delay estimations for different degree of saturation values is given in Figure 3.

The comparisons show that the general trends of the FLDE model are parallel to observations for both under-saturated and over-saturated traffic conditions (see Table 2). On the other hand, the HCM and Akçelik delay formulas show higher deviations for over-saturated conditions (x > 1). Figure 3 shows that the formula and model results are very similar when the degree of saturation values are less than 1. The formulas give exaggerated results for degree of saturation values higher than 1. The results of the FLDE model are much more reasonable than the formulas, especially for over-saturation cases.

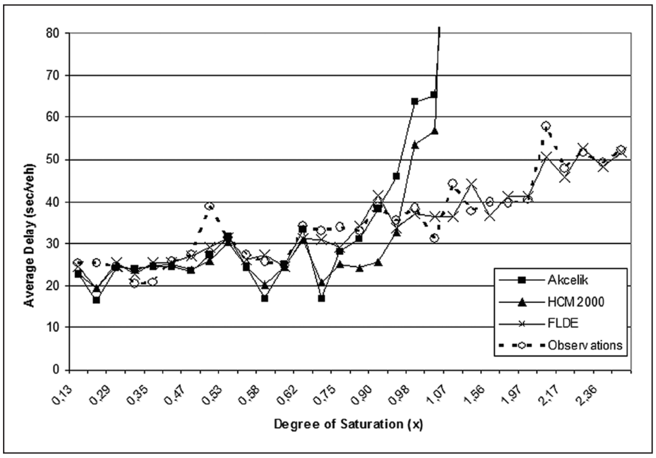

Figure 3. Comparisons of delay estimations.

Error rates of the models are determined to evaluate performance. The mean absolute error (MAE), mean squared error (MSE) and average relative error (ARE) rates are calculated for both under-saturated and over-saturated conditions and are given in Table 3. As shown in Table 3, the FLDE model has minimum error rates for both conditions under error criteria. MAE, MSE and ARE rates of the FLDE model are less than the compared conventional methods. The FLDE model gives the best results among the models in terms of all error rates. The ARE rates of the FLDE model are determined as 8 percent for under-saturated and over-saturated conditions. Error rates of the HCM and Akçelik delay formulas are acceptable for under-saturated conditions compared to over-saturated cases. High differences are reported for over-saturated conditions (x > 1).

The correlation coefficients also are determined for the compared methods. The correlation coefficient of the fuzzy logic model is the highest one (0.93) among the models. The HCM and Akçelik models follow the fuzzy model as the correlation coefficient values of 0.81 and 0.80, respectively. These values also prove the superiority of the FLDE model.

The success of the FLDE model is due to inclusion of uncertain parameters and definition of membership functions and rules. The FLDE model includes environmental and traffic conditions that have not been defined comprehensively by the HCM and Akçelik methods. Additionally, in conventional delay calculation methods, limits of parameters are crisp and strictly bounded. In the fuzzy logic approach, limits are gradual, transitive and flexible. The flexible membership functions and transitive boundaries provide much more accurate results in modeling.

RESULTS

One of the most significant findings of this study is evidence of the FLDE model is success in representing the uncertainties of the vehicle delay phenomenon. In the study, the environmental and traffic conditions are taken into account as uncertainties. Consideration of this parameter improves the success of estimation, especially for over-saturated conditions.

The FLDE model results are compared to the HCM and Akçelik methods and the real-world delay data. In conclusion,

Table 2. Data used and compared results.

Cycle time (seconds)	Red time (seconds)	Green time (seconds)	Traffic volumes (vehicles per hour)	Degree of saturation (x)	Environmental and traffic conditions	Average delay (seconds per vehicle)			
						HCM 2000	Akçelik	FLDE model	Observation
87	52	31	72	0.13	8	23.02	22.88	24.60	25.41
84	38	42	140	0.17	8	19.5	16.41	19.30	25.32
91	56	31	154	0.29	4	24.74	24.26	25.50	24.45
84	49	31	169	0.31	4	23.71	23.95	22.60	20.6
91	56	31	175	0.35	4	24.81	24.44	25.50	20.64
91	56	31	194	0.38	4	24.99	24.45	25.50	23.54
90	58	18	210	0.49	8	26.02	27.24	29.10	38.75
87	52	31	235	0.47	4	23.84	23.38	27.00	27.4
102	65	33	242	0.53	5	30.18	31.64	31.30	32.10
91	56	31	263	0.55	3	24.58	24.46	26.30	27.40
102	65	33	274	0.62	6	30.75	33.24	31.01	34.00
87	52	31	283	0.59	3	24.46	25.15	24.60	24.71
87	52	31	351	0.75	6	25.12	28.23	29.20	33.87
90	56	30	390	0.90	6	32.82	45.92	33.70	35.37
88	57	27	397	0.98	7	53.6	63.54	37.00	38.48
87	36	47	432	0.58	4	20.11	17.01	27.30	25.75
83	50	33	474	1.00	5	56.66	65.21	36.40	31.24
104	41	59	500	0.63	6	20.83	16.82	30.80	32.95
78	37	37	550	0.90	7	25.66	38.09	41.60	38.89
85	55	26	587	1.56	7	1041.16	613.15	36.50	39.78
87	36	47	620	0.84	5	24.19	31.01	34.00	33.16
90	51	35	656	1.36	6	673.64	398.01	44.20	37.64
85	55	26	698	1.80	6	1461.78	1143.13	41.10	39.67
88	60	24	738	1.97	7	1768.25	1614.25	41.10	40.45
88	42	42	742	1.07	7	166.97	123.13	36.40	44.20
88	60	24	814	2.17	7	2131.65	2357.25	45.90	47.69
90	60	36	825	2.18	7	2145.31	2389.35	52.70	51.66
88	60	24	841	2.36	8	2468.11	3069.22	48.20	49.03
78	50	24	944	2.45	7	2639.09	3802.59	51.70	52.20
90	50	36	1000	2.01	8	1841.3	2307.97	50.45	57.87

Table 3. Error rates and correlation coefficients.

Models	Errors						Correlation coefficients (R)
	Case of x < 1			Case of x > 1			
	MAE	MSE	ARE	MAE	MSE	ARE	
HCM 2000	5.60	53.02	0.17	1445.68	2807409	30.74	0.81
Akçelik	5.75	72.84	0.18	1581.08	3928114	32.69	0.80
FLDE model	2.32	11.09	0.08	3.31	18.55	0.08	0.93

the fuzzy logic model showed better performance than the HCM and Akçelik methods, especially for high traffic volumes and over-saturated traffic conditions.

The analysis showed that fuzzy logic, an extendable and flexible approach, may be used for vehicle delay estimation. The deficiencies about delay estimations for over-saturated conditions could be removed using the FLDE model without any precise measurements. Only using approximate values of the model parameters, an acceptable vehicle delay can be estimated by fuzzy logic. ■

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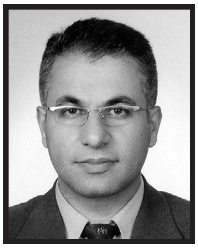

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