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Application of Logit Modeling to the Decision-Making Process of Drivers at the Onset of the Yellow Signal

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Drivers approaching an intersection at the onset of yellow change interval have two choices: to continue through the intersection or stop. Some of those who continue through the intersection succeed in reaching the other side, while others do not, causing gridlock and/or accidents. For drivers located in a "dilemma" zone, the decision to continue or stop is random in nature, and would be suitable for analysis by means of logit models.

This research is based on the statistics gathered at nine intersections in Tehran, Iran. The behavior of drivers at the onset of the yellow interval was studied and their decisions to stop or proceed were modeled using logit modeling. The results indicate that the duration of the yellow interval and volume of traffic at the other two approaches to the intersection influenced the decision-making of drivers who had decided to go through the intersection. However, factors such as time of day, number of vehicles in front, duration of the red phase, number of lanes in the traveled direction and traffic volume, also, influenced the drivers' decision choice.

INTRODUCTION

A road transportation system is composed of three parts: road, vehicle and driver. Of these three parts, understanding driver behavior and decision-making processes is the most difficult. Recognizing the physical and psychological characteristics of human beings and the extent of variation in adherence to traffic regulation is vital. If all other parts of the system are well-designed, but driver behavior is not properly considered, the system will not operate efficiently. Thus, driver behavior should be studied and compared with what has been deemed as an ideal behavior.

An important consideration at a signalized intersection is the behavior of drivers at the onset of the yellow interval. Much research has been carried out in developed countries on this issue, but little has been done in Iran [1,2].

The purpose of the yellow interval is to warn drivers of the impending onset of the red phase. They should prepare to stop or clear the intersection before the opposing traffic starts to move [3-7]. Drivers approaching the intersection at the onset of yellow interval have two choices: to continue through the intersection or stop. There is an area before the intersection, the location of which varies with the speed of the vehicle and its distance from the intersection, which is called the dilemma zone. In this zone, the driver must decide whether to continue into the intersection and be caught there when the signal changes to red or risk a rapid stop [8-11].

The decision to pass or stop in the dilemma zone is random, making use of logit models appropriate for the analysis of this type of decision-making process. In this study, data collected at nine intersections in Tehran are analyzed using logit models and the effect of factors such as speed, duration of the yellow warning light and vehicle distance from the intersection on behavior of drivers is studied.

LOGIT MODELS

Logit structures are one of the common models for the study of decision-making based on increasing utility considering constraint [12]. In logical models, people are assumed to behave logically and make the most desirable selection. The assumption of being logical is based on certain fixed functions, but, because individuals may not be aware of all parameters of utility function, a random factor is used to show and analyze desire. It is assumed that individuals, by assessing

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and selecting from competing choices, maximize their utility functions [12,13]. However, all aspects of the utility function cannot be observed or measured. In practice, the utility function U_i has two parts, the measurable part, V_i, and the random error part, E_i, such that:

$$U_i = V_i + E_i. \tag{1}$$

The definite part of the desirability function depends on the properties of the choice, economic and social characteristics of the person deciding and E_i, the error part is used for parameters that cannot be observed.

Using the random desirability function, the selection of one choice from a collection of choices follows this probability:

$$p_i = p[U_i > U_j, \forall j \neq i]. \tag{2}$$

In the above equation, p_i is the probability of choosing "i". By knowing the error distribution of i, the probability of choosing i can be defined. If part of i error has an independent distribution and is of the Gambel type, then it can be shown that:

$$p_i = \frac{\exp(V_i)}{\sum_j^A \exp(V_j)}, \tag{3}$$

where p_i is the probability of choosing i from the collection of choices (A) and V_i is the defined part of the function. V_i is usually shown as:

$$V_i = \alpha_i + \beta_{1i}\ X_{1i} + \beta_{2i}\ X_{2i} + \beta_{3i}\ X_{3i} + \cdots, \tag{4}$$

where:

V_i	=	utility that can be measured (for choice i),
α_i	=	constant part of function (for choice i),
X_{ji}	=	jth property of choice i,
β_{ji}	=	jth property weight of choice i.

It is always assumed that in logit models the choices are independent of each other, so that the probability of selecting one choice is independent of the existence of other choices. This creates some limitations in the use of logit models [14]. Although this property seems logical in numerous cases, it can create incorrect results in some situations.

DATA COLLECTION

Video camera data from nine pre-timed signalized intersections in Tehran were collected for 75 minutes, at 15 minutes intervals, resulting in 968 observations of driver behavior. The following information was analyzed:

1. Vehicle approach speed,
2. Vehicle distance from intersection stopline at the onset of yellow interval,
3. Number of vehicles ahead at the onset of yellow interval,
4. Traffic volume,
5. Intersection width and number of lanes.

The approach speed for each one of the observed vehicles was calculated from the equation of $x = vt$. In this equation, x is the distance between two fixed objects such as streetlight poles or other objects, identified and measured at each intersection. The travel time between the objects was measured from the video film using a chronometer. Similarly, vehicle distance from the intersection stopline and also the number of vehicles ahead were observed. Traffic volume was collected and classified by vehicle type at 15- minute intervals for a duration of approximately 75 minutes. Data for two of the nine intersections were collected at night. The remaining seven were observed during daytime. The intersection geometric information (i.e., width and number of lanes) was collected at the sites. In this research, the adequacy of intersections' signal timings was not checked because it would have required special authorization. Table 1 provides a summary of the data resulted from video films.

Drivers' behaviors at the onset of the yellow warning light at intersections with signals were modeled using logit modeling. The logit models estimate the probable selection of "complete stop", "not clearing the intersection" and "clearing the intersection". Figure 1 shows the structure of the nested logit model in this study and its comparison with a simple logit model. In Model 1, the structure is divided into two branches, "complete stop" and "continuing". "Continuing" is then divided into "clearing the intersection" and "not clearing the intersection". In this model, it is assumed that "clearing the intersection" and "not clearing the intersection" are dependent events and the decisions to stop or continue are independent. In Model 2, it is assumed that the choices "clearing the intersection" and "not clearing the intersection" are independent of each other and choices of "complete stop" and "not clearing the intersection" are dependent on each other and are examined in the lower branches of the model. Finally, if the results of Models 1 and 2 indicate that the assumption of dependence of choices is wrong, the choices "complete stop", "not clearing the intersection" and "clearing the intersection" are examined by use of simple logit structures. One common method to process the logit models is "maximum likelihood estimation", which is done by using the software known as "GAUSS". The results of this program execution contain maximum likelihood estimations, shown as $L^*(\beta)$.

Table 1. Summary of the data resulted from video films.

Inter-section Number	Intersection Name	Observation Period	Observation Date	g/c	Cycle Length (c)	No. of Obser-vation	No. of lanes per Direc-tion	Traffic		Speed	
								Other Direction (Veh/Hr)	Direction Under Study (Veh/Hr)	Avg. Speed (Km/hr)	85th Percentile Speed
1	Enghelab-Shariati	7:45-9:00	Aug. 1, 1996	0.54	80	120	3	1301	6960	19.1	25.7
2	Jomhori-Kargar	7:30-8:50	Jan. 1, 1995	0.39	135	158	3	5518	3690	19.4	24.1
3	Chamran-Valieasr	18:15-19:30	sep. 27, 1995	0.42	140	84	4	4471	6517	36.9	42
4	Sohrevardi-Andisheh	8:00-9:15	Dec. 26, 1995	0.27	60	74	2	4310	1023	27.9	32.4
5	Kordestan-Uosefabad	14:40-15:55	April 15, 1997	0.23	145	43	2	6856	1627	26.7	36.3
6	Taleghani-Vesal	17:25-19:00	Oct. 26, 1995	0.33	80	122	3	31.7	2708	21.3	30
7	Fatemi-Hejab	7:45-9:00	July 31, 1996	0.58	90	129	3	1551	6611	21.5	30
8	Kargar-Jomhori (North-bond)	11:30-12:45	April 14, 1997	0.52	80	156	3	3002	5719	19.5	27.2
9	Molavi-Valieasr	14:40-15:55	April 16,1997	0.59	105	82	3	2290	4980	28	35

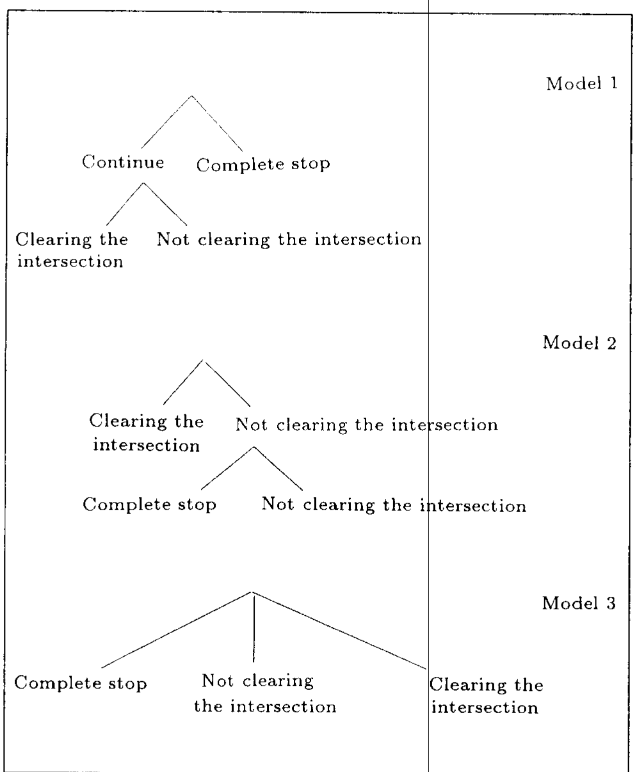

Figure 1. Logit model structure studied.

GENERAL RESULTS

Model 1

Model 1-A: Clearing the Intersection Versus Not Clearing the Intersection

In this model, all vehicles that have tried to pass the intersection at the onset of the yellow interval are studied. Of the 470 approaching vehicles, 94 succeeded in clearing the intersection, while 376 were still at the intersection when the yellow interval ended. Table 2 shows the results of Model 1-A, containing the coefficients of desirability function of "clearing the intersection", V_c. A positive sign before a variable coefficient means that the variable increase will result in an increase in the chance or conditional relative likelihood of clearing the intersection. A negative sign means that any increase in the amount of this variable causes a reduction in the conditional relative likelihood of clearing the intersection for drivers who have entered the intersection. The parameters in Model 1-A are:

- SPD: A continuous variable representing the velocity of the vehicle approaching the intersection (km/hr),

Table 2. Results of Model 1-A analysis.

t-Distribution	Coefficient	Variable Name
-5.285	-14.613	Constant
10.960	0.4884	SPD
-14.456	-0.3305	DST
5.9216	3.758	YELL
-1.649	-1.35×10^{-3}	VOL2

Number of Observations	470
Number of Coefficients	5
Number of Repetitions	20
$L^*(0)$	-325.78
$L^*(C)$	-235.19
$L^*(\beta)$	-78.404
$\rho^2 c$	0.667
ρ^2	0.759q

- DST: A continuous variable representing the vehicle distance from the intersection at the onset of the yellow warning light,
- YELL: A continuous variable representing the length of the yellow warning light (seconds),
- VOL2: Volume of traffic in opposing direction (number of cars),
- $L^*(0)$ = Log likelihood function when all the coefficients are zero, meaning that each alternative has an equal likelihood of being chosen,
- $L^*(C)$ = Log likelihood function for only the constant terms in the utility function which is equal to the market share of each alternative studied,
- $L^*(\beta)$ = Log likelihood function at convergence (estimated parameters),
- $\rho_c^2 = 1 - \frac{L^*(\beta)}{L^*(C)}$ = Explanatory power of the model when compared with the market share of each alternative. It is a measure of goodness of fit.
- ρ^2 = Explanatory power of the model compared with the case in which no information is available, meaning each alternative is equally likely to be chosen.

Among all the models calibrated, the results presented in Table 2 with $\rho^2 = 0.759$ are chosen as the best model. All the coefficients of this model have the expected signs. Moreover, observing the t-statistics, all the estimated coefficients are statistically significant at 95% confidence, except VOL 2, which is significant at 90% confidence.

As expected, the chance of clearing the intersection increases with an increase in approach speed at the onset of the yellow interval. The coefficient (DST) is negative in Model 1-A, indicating that as the vehicle distance from the intersection increases, the chance of clearing the intersection decreases. The last effective factor on complete clearance is the volume of opposing traffic, which has a negative effect. Thus, an increase in the volume of opposing traffic results in a decrease in the chance of clearing the intersection. This is most likely because of the increased probability of encountering vehicles coming from opposing directions.

Model 1-B: Continuing Versus Complete Stop

Of the 968 vehicles observed, 470 continued and cleared the intersection, while 498 stopped. Table 3 shows the processed structure of Model 1-B with the coefficient of utility functions of passing the intersection V_p. The variables are as follows:

- NFRN: Number of vehicles in front of the observed vehicle at the onset of the yellow warning light,
- RED: A continuous variable representing the duration of the red phase (seconds),

Table 3. Results of Model 1-B analysis.

t-Distribution	Coefficient	Variable Name
-7.76	-3.378	Constant
-9.052	-0.802	NFRN
2.625	0.01	RED
7.116	1.343	NL3
7.371	3.2897	NL4
4.26	0.6875	PEAK
6.449	2.0868	DAY
2.521	0.965	DUSK
5.359	0.6185	IK

Number of Observation	968
Number of Coefficients	9
Number of Repetitions	9
$L^*(0)$	670.97
$L^*(C)$	670.56
$L^*(\beta)$	547.00
$\rho^2 c$	0.184
ρ^2	0.185

- NL_i: The number of lanes on the street being studied ($i = 3, 4$),
- PEAK: Peak or off-peak periods of traffic flow, where 1 = peak,
- DAY: Observation of the vehicle during daylight,
- DUSK: Observation of the vehicle during dusk,
- IK: Maximum expectable utility from an inferior branch of Model 1-A reflecting its effect on Model 1-B.

The results from Model 1-B analysis indicate that all the coefficients have the expected signs and are statistically significant at 95% confidence. The value of the coefficient IK is 0.6185, which is between zero and 1 meaning that the nested structure is appropriate. The value of ρ^2 is equal to 0.185 having the highest value among the models calibrated at this level. It should be noted that the absolute value of ρ^2 does not show the absolute goodness of fit but provides a means of comparing different models calibrated using the same data.

As expected, the number of vehicles ahead of the observed vehicle is an important factor in deciding to continue or stop. This variable is negative in Model 1-B meaning that with an increase in the number of vehicles ahead of the observed vehicle, the tendency to stop increases. Also, an increase in the length of the red phase results in an increase in attempts to clear the intersection.

For streets with three or four lanes in each direction, analysis of Model 1-B demonstrates that the likelihood of clearing the intersection increases with an increase in the number of lanes. This might be due to the possibility for drivers to change lanes and proceed through the intersection. The DAY or DUSK in the logit function is positive, illustrating that drivers are more willing to attempt to clear the intersection in the daylight or dusk compared to night-time, when they are less aware of their surroundings. The peak hour variable is also positive. This may be explained by the individuals' desire to get to work or home as quickly as possible. Variable IK shows the effect of Model 1-A on Model 1-B. Its coefficient of 0.62 shows the similarity between the choices of "clearing the intersections" and "not clearing the intersection". Also, this coefficient emphasizes that the choice of the nested logit structure has been correct.

Model 2

Model 2-A: Complete Stop Versus Not Clearing the Intersection

Of the total number of vehicles observed, 498 stopped after observing yellow signal, while another 376 did not clear the intersection before the onset of the red phase. Table 4 shows the result of processing Model 2-A, which contains the utility function coefficient of "complete stop" V_s. A positive variable means that its increase raises the conditional likelihood of stopping completely. A negative variable has the opposite effect. The variables are as follows:

Table 4. Results of Model 2-A analysis.

t-Distribution	Coefficient	Variable Name
12.007	0.1183	DST
3.755	0.3504	FRN
2.721	1.56×10^{-3}	VOL2
-3.754	-0.0344	RED
-4.982	-0.941	NL3
-4.089	-1.595	NL4
-4.33	-0.7912	PEAK

Number of Observations	874
Number of Coefficients	7
Number of Repetitions	7
$L^*(0)$	-605.81
$L^*(C)$	-597.27
$L^*(\beta)$	-442.1
$\rho^2 c$	0.258
ρ^2	0.269

- DST: A continuous variable expressing the distance of vehicle from the end of intersection,
- FRN: The number of vehicles in front of the observed vehicle at the onset of the yellow warning light,
- VOL2: The volume of traffic in the other direction of the intersection, at 15 minutes intervals (number of cars),
- RED: A continuous variable expressing the length of the red phase (seconds),
- NL_i: Number of lanes in each direction ($i = 2, 3, 4$),
- PEAK: Variable indicating off-peak and peak traffic hours (1 = peak).

The results from analysis of Model 2-A indicate that all the coefficients are significant at 95% confidence. In this model, the variable DST is positive indicating an increased tendency to stop when DSN increases. FRN is also positive, showing an increased willingness to stop when FRN increases. A positive VOL2 demonstrates that, when this factor increases, the conditional likelihood of stopping completely also increases.

Model 2-B: Clearing the Intersection Versus Not Clearing the Intersection

This model is in the upper branch of the nested logit structure. All vehicles observed are studied here, from which 94 were able to clear the intersection, while 874 vehicles did not clear the intersection during yellow interval. This includes vehicles that have stopped completely as well as others that could not clear the intersection. Table 5 shows the analysis of Model 2-B, containing the desirability function coefficient of "not clearing completely" V_p. A positive variable means that an increase in that variable results in a decrease in the chance of clearing the intersection. The variables used are as follows:

- YEL: A continuous variable indicating the length of the yellow warning light (seconds),
- VOL2: The volume of traffic in the direction under study,
- NA_i: The number of intersection legs ($i = 3$ for T-intersection and $i = 4$ for four-way intersection),
- IK: The maximum expected utility from the interior branch of Model 2-A showing the effect of Model 2-A on Model 2-B or on the upper branch.

The results from analysis of Model 2-B indicate that the coefficient of IK with a value of 0.8995 is closer

Table 5. Results of Model 2-B analysis.

t-Distribution	Coefficient	Variable Name
-5.545	-0.6816	YEL
2.379	0.789×10^{-3}	VOL2
1.998	0.6229	NA4
5.998	0.8995	IK

Number of Observations	968
Number of Coefficients	4
Number of Repetitions	10
$L^*(0)$	-308.483
$L^*(C)$	-281.259
$L^*(\beta)$	-0.088
$\rho^2 c$	0.581

to 1 compared to Model 1-B. This indicates that Model 1-B has a nested structure which is better than Model 1-A.

Analysis of Model 2-A shows that an increase in the length of the yellow interval results in an increase in the likelihood of clearing the intersection. VOL2 is positive, illustrating that its increase results in an increase in the number of vehicles that stop or cannot clear the intersection. NA4 is also positive, indicating that the likelihood of stopping in a four-legged intersection is greater than in a three-legged intersection.

Model 3: Comparison of Clearing the Intersection, Not Clearing the Intersection and Complete Stop

As stated previously, in the logit model, it is always assumed that choices are independent of each other, meaning that the selection of one choice does not depend on the presence of other choices. In this section, it is assumed that the choices of "clearing the intersection", "not clearing the intersection" and "complete stop" are independent of each other and a simple logit model structure is processed to define the likelihood of occurrence of each choice.

Of 968 vehicles, 94 cleared the intersection before the end of the yellow interval, 376 did not clear the intersection and 498 vehicles stopped when seeing the yellow interval. Table 6 shows the results of Model 3 with the coefficients of utility functions for "clearing the intersection", V_c, "not clearing the intersection", V_n and "complete stop" V_s. The results from analysis of Model 3 indicate that all the coefficients are significant at 95% confidence.

Comparison of Models 1 and 2

An important factor in comparing the two nested logit models is the general fitness of each model, ρ_c^2. Table 7 shows this comparison and indicates that Model 1 is more suitable than Model 2. Another

Table 6. Results of Model 3 analysis.

		Variable Name									
		Constant	SPD	DST	YELL	VOL2	FRN	RED	NA4	DAY	DUSK
V_C	Coefficient		0.4154	-0.3901	2.605	-0.0063					
	t statistics		12.02	-17.32	6.48	-5.29					
V_N	Coefficient	9.945	0.0342	-0.1173		-0.0051					
	t statistics	5.49	3.10	-12.51		-5.11					
V_S	Coefficient	6.867					0.445	-0.104	0.845	-0.958	-0.919
	t statistics	3.63					4.77	-8.15	2.18	-2.77	-2.22

Number of Observations	968
Number of Repetitions	25
$L^*(0)$	-1062.36
$L^*(C)$	-905.75
$L^*(\beta)$	-527.32
$\rho^2 c$	0.418
ρ^2	0.504

Table 7. ρ_c^2 values for Models 1 and 2.

ρ_c^2	Model
0.667	Model 1-A
0.184	Model 1-B
0.310	Model 1
0.358	Model 2-A
0.088	Model 2-B
0.200	Model 2

Table 8. Values of IK coefficient for Models 1 and 2.

t	IK Coefficient	Model
5.359	0.6185	Model 1
5.998	0.8995	Model 2

factor for comparison is the coefficient of maximum expected utility, IK. As shown in Table 8, it can be concluded that these coefficients have a significant level of 0.05. Also, based on the nested logit models, an IK value close to zero indicates a higher correlation and an IK value approaching unity indicates a lower correlation between alternatives of the lower branch. The structure of Model 1, which compares "clearing the intersection" and "not clearing the intersections" in the lower branch, is more suitable for modeling driver behavior at the onset of the yellow interval.

Defining the Credibility of Superior Models

Results of the estimated model were compared with the actual observations to define the credibility of Model 1 and ascertain whether or not the constructed model demonstrates real behavior. In Table 9, the estimated probability of each alternative with its observed share for each intersection is compared. The estimated probability is the aggregate of the probability of each observation record for each alternative. As can be seen, all the coefficients of correlation are greater than 0.85 indicating the rather high correlation between real behavior and model predictions.

SUMMARY AND CONCLUSION

Model 1-A indicates that several factors increase the possibility of clearing the intersection. These factors are listed below in order of priority:

1. Distance from the intersection stop-line at the onset of the yellow warning light,
2. Velocity of vehicle approaching the intersection,
3. Duration of the yellow warning light,
4. Volume of traffic at opposing parts of the intersection.

Model 1-B shows the most important factors in the drivers' choice between "clear the intersection" or "complete stop" which are as follows:

1. The number of vehicles in front of the vehicle being studied, at the onset of the yellow interval,
2. Time of day,
3. Number of lanes in the direction being studied,
4. Peak traffic period,
5. Length of red phase.

As expected, when the length of the yellow interval and velocity of the vehicle increase, the number of drivers who clear the intersection increases. Also, as the distance from the stop-line increases, the chance of clearing the intersection decreases. In Model 1-B, the coefficient of the number of vehicles in front of the vehicle being studied is negative, indicating that as the number of vehicles increases, the utility to clear the intersection reduces and the tendency to stop increases.

The time of day is also positive, indicating that drivers are more willing to clear the intersection during daylight. Also, analysis of Model 1-B illustrates that in intersections with three or four lanes in each direction, the chance of deciding to continue and clear the intersection increases.

Table 9. Comparison of the predicted versus observed values for each intersection for Model 1.

Clearing the Intersection (%)		Not Clearing the Intersection		Complete Stop (%)		Intersection Name	Intersection Number
Estimated	Observed	Estimated	Observed	Estimated	Observed		
0	0	31.5	30	68.5	70	Enghelab-Shariati	1
5.1	5.7	57.2	54.4	37.7	39.9	Jomhoori-Kargar	2
13.5	13.1	50.8	51.2	35.7	35.7	Chamran-Valieasr	3
16	14.8	25.5	23	58.5	62.2	Sohrevardi-Andisheh	4
0.7	2.3	37.6	46.5	61.7	51.2	Kordestan-Yesefabad	5
17.7	15.6	27.5	22.1	54.8	62.3	Taleghani-Vesal	6
21.3	24	41	52	37.7	24	Fatemi-Hejab	7
2.5	3.8	35.2	35.3	62.3	60.9	Kargar-Jomhoori (North-bond)	8
7	7.3	39.5	30.5	53.5	62.2	Molavi-Valieasr	9
$r = 0.98$		$r = 0.87$		$r = 0.88$		Coefficient of correlation	

The peak hour variable is also positive in Model 1-A, perhaps because of the desire to get to work (morning peak) or home (afternoon peak) faster. An increase in the duration of red phase results in an increase in the tendency of trying to clear the intersection.

Other factors, such as the type of intersection (3 or 4-legged), the ratio of traffic volume in the major direction to the secondary direction, the length of the green light, the ratio of the length of the green light to overall cycle length and the ratio of the length of the red phase to overall cycle length, do not appear to have a significant effect on the decision to stop or clear the intersection.

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