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VALIDATION AND PRACTICAL
APPLICATION OF THE UTCS-1s
NETWORK SIMULATION MODEL
ON AN URBAN ARTERIAL STREET

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Interim Report

APPLICATION OF THE UTCS-1 NETWORK SIMULATION MODEL TO SELECT
OPTIMAL SIGNAL TIMING IN A MULTI-LINEAR STREET SYSTEM

TO: H. L. Michael, Director
Joint Highway Research Project

December 17, 1979

FROM: G. T. Satterly, Jr. Research Engineer
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Project: C-36-66G

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The attached Interim Report "Validation and Practical Application of the UTCS-1s Network Simulation Model on an Urban Arterial Street" is submitted in partial fulfillment of the objectives of the research. It has been authored by Mr. Bruce A. Hillson, Graduate Instructor in Research on our staff under the direction of Professor G. T. Satterly.

The report details research accomplished to evaluate the ability of the UTCS-1s network simulation model to reproduce actual observed measures of effectiveness (MOE's) on an urban arterial linear signalized system in Indianapolis, Indiana and to develop a methodology to determine the optimal signal timings for a linear signal system using the UTCS-1s model.

Attempts at reproducing observed MOE's on the linear network by simulation using the UTCS-1s model were not successful. A study was then done to determine the ability of the UTCS-1s model to estimate changes in MOE's between two signal-timing schemes. It was demonstrated that the model could not adequately simulate the changes that were observed in field studies.

It was concluded by Mr. Hillson that he was unable to, through his research efforts, validate the UTCS-1s model for use as a computer program for improving signal timing in a linear system of signals.

It is proposed that the next phase of this study involve the examination of other computer programs that may be used to select optimal signal timing in a linear signal system.

The Report is submitted as partial fulfillment of the objectives of this study.

Respectfully submitted,

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Interim Report

VALIDATION AND PRACTICAL APPLICATION OF THE UTCS-1s NETWORK
SIMULATION MODEL ON AN URBAN ARTERIAL STREET

by

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ABSTRACT

Hillson, Bruce Allen. M.S.C.E., Purdue University, May 1979.
Validation and Practical Application of the UTCS-1s Network Simulation
Model on an Urban Arterial Street. Major Professor: Gilbert T. Satterly.

The primary objective of the study was to evaluate the ability of the UTCS-1s network simulation model to reproduce actual observed measures of effectiveness (MOE's) on an urban arterial linear signalized system. The simulated and observed MOE's that were compared include volumes of vehicle trips, stops per vehicle, total stop delay, and stop delay per vehicle.

A secondary objective was to develop a methodology to determine the optimal signal timings for a linear signal system using the UTCS-1s model.

The UTCS-1s model was found to be inadequate of reproducing observed MOE's on the linear network that was studied. A study was done to determine the ability of the model to estimate changes in MOE's between two signal-timing schemes. It was observed that the model could not provide the expected changes.

CHAPTER 1: INTRODUCTION

When the first traffic signals were installed many years ago, their purpose was to reduce or eliminate severe collisions in an intersection by dictating which approach(es) was to have the right-of-way. At the time that these signals were installed, there was no concern with energy conservation, air pollution, or severe rush-hour traffic congestion.

Today, traffic signals must do much more than assign right-of-way through an intersection. Signals are incorporated into systems which control traffic through a large number of intersections. The signals must have proper cycle lengths, offsets, and splits to minimize delay, fuel consumption, and air pollution.

The traffic engineer is confronted with developing the best possible signal-timing schemes by using the accepted engineering practices. It is never known whether the timing scheme that is implemented is actually the best choice. There are three problems associated with using the accepted traffic engineering practices (1). First, signal-timing schemes can be implemented only one at a time. Any problems with a timing scheme would be costly to revise. Second, experimenting with different timing schemes may be politically unsatisfactory. Excessive changes in the signal timings would lead to motorist confusion, and ultimately to complaints to the public

officials. And third, the effects of a timing scheme on various measures of effectiveness (MOE's) cannot be easily determined, since collecting field data is such a lengthy task. A network simulation model such as UTCS-1s would allow the traffic engineer to evaluate several timing schemes in the office, thus eliminating excessive field costs and reducing the disruptive effects to vehicular flow.

Several years ago the Indiana State Highway Commission requested that research be done at Purdue University to determine the availability of a computer program to help retime traffic signals. The original work in that area was conducted by Carini (2). He found that no programs were available at that time to optimize signal timings on a network. However, he found that the UTCS-1s simulation model was available to help determine the improvements in MOE's on a network for various signal timings. Carini attempted to validate the UTCS-1s model for a single intersection. The conclusions of the single intersection validation project stated that the UTCS-1s model probably could be applied to a network to determine the improvements in MOE's for various timing schemes. The present project has attempted to validate the UTCS-1s model's ability to simulate actual MOE's.

The two main objectives of this study were:

- 1) To determine the capability of the UTCS-1s network simulation model to reproduce observed MOE's for a linear signal system.
- 2) To use the UTCS-1s simulation model as a tool to determine the optimum signal-timing scheme for linear arterial systems.

A description of the UTCS-1s simulation model is presented in Appendix A. Also included are summaries of the required input data for the model and the output data that is generated.

During the research done for this project, three reports discussing previous research projects to validate the UTCS-1s simulation model were found (see Chapter 2). Two of the reports conclusively stated that the model could reproduce actual MOE's and the third report concluded the same, but with reservations.

The model has been applied to several networks around the country. In each case, the agency performing the work compared the simulated traffic volume with the actual traffic volume, and concluded that they were the same. The model was subsequently used to help improve the signal-timing scheme with reportedly good results.

As this project progressed, indications were that the UTCS-1s simulation model could not adequately reproduce field measured MOE's. The previous validation reports, as well as this research, were extensively analyzed to determine possible deficiencies. A description of the previous validation projects and a critique of each comprise Chapter 2. The research performed for this project is discussed in-depth during subsequent chapters. Lastly, conclusions and recommended additional research are presented in the final chapter.

CHAPTER 2: PREVIOUS VALIDATION PROJECTS

Washington, D.C. Project

The original validation project of the UTCS-1 computer simulation program was performed on a Washington, D.C. grid network by Peat, Marwick, Mitchell & Company. The final report which included the validation procedures and results was presented to the Federal Highway Administration in June of 1971 (3). The validation procedures compared observed and simulated data for the following MOE's:

- 1) Output - the total number of vehicles discharged past the stopline on a given link for a period of three consecutive cycles.
- 2) Flow rate - average flow rate across each link for three cycles.
- 3) Content - the average number of vehicles on each link during three cycles.
- 4) Vehicle Minutes - the total number of vehicle minutes accumulated for each link over three cycles.
- 5) Vehicle miles - the total vehicle miles of travel on each link for three cycles.
- 6) Total delay - the difference between the total travel time for all vehicles on a link and the time it would take the same number of vehicles to traverse the link at the target

speed (desired free flow speed) - for three cycles.

- 7) Average travel time - total travel time divided by the number of vehicles traversing a link for three cycles.
- 8) Average delay - total delay divided by the total number of vehicles for three cycles.
- 9) Average speed - link length divided by the average travel time on the link for three cycles.

The field data was collected using a combination of aerial and ground-based time-lapse photography.

Estimates of OUTPUT and CONTENT were made directly from both field and model data. The remaining seven measures were computed using input/output analysis for each link within the system and for the network as a whole (4).

Total stop delay, stop delay per vehicle, and stops per vehicle were not analyzed because it was believed that these MOE's could not be readily obtained from the data that was collected.

The following definitions are needed to understand the equations used for the input/output analysis (5). Figure 1 should be referred to for clarification of the terms.

C_0 = Initial CONTENT of the link at time t_0 , expressed in "vehicles"

C_1 = Final CONTENT of the link at time t_1 , expressed in "vehicles"

C_i = Intermediate CONTENT of the link, measured at instant i between times t_0 and t_1 , expressed in "vehicles"

C = Average CONTENT of the link over time t_0 to t_1 , expressed in "vehicles"

Q = Flow rate

O = Total number of vehicles discharged from the link past the stopline over period t_0 to t_1

Figure 1. Terms for Input/Output Analysis

(Source: Reference 6)

I = Total number of vehicles entering the link from the upstream intersection over time period t_0 to t_1

M = Total number of vehicles entering the link from an intra-link source node over time t_0 to t_1

N = Total number of vehicles discharged from the link at the intra-link sink node over the time period t_0 to t_1

L = Total length of the link

L' = Distance from the upstream end of the link to the intra-link source/sink node

The input/output analysis is based on the premise that each link has continuity.

$$0 = I + (M-N) + (C_0 - C_1) \quad (1)$$

If the observation period is broken into n point estimates of the link content, the average link content is found by:

$$c = \left[C_0 + \sum_{i=1}^{i=n-1} (2 \cdot C_i) + C_1 \right] / 2 \cdot (n - 1) \quad (2)$$

The remaining seven MOE's were found as follows:

Total Vehicle-Minutes

$$VM = C \cdot (t_1 - t_0) \quad (3)$$

Flow Rate

$$Q = (I \cdot \frac{L'}{L} + O(\frac{LL'}{L})) \quad (4)$$

Substituting equation 1 into equation 4 yields:

$$Q = 0 - \frac{L'}{L} \cdot (M-N + C_0 - C_1) \quad (5)$$

Total Vehicle-Miles of Travel

$$\begin{aligned} VMT &= (I \cdot L') + O(L - L') \\ &= (0 \cdot L) - L' (M-N + C_0 - C_1) \end{aligned}$$

$$= Q \cdot L \quad (6)$$

Ideal Total Vehicle-Minutes

$$VM^* = 0 \frac{L}{S^*} - (M-N) \cdot \frac{L'}{S^*} \quad (7)$$

where S^* equals the desired target speed

Total Delay

$$\begin{aligned} D &= VM - VM^* \\ &= C \cdot (t_1 - t_0) - \frac{0 \cdot (L - L')}{S} \end{aligned} \quad (8)$$

The Average Travel Time

$$\overline{TT} = \frac{VM}{Q} = \frac{C \cdot (t_1 - t_0)}{Q} \quad (9)$$

The Average Delay

$$\overline{D} = \frac{D}{Q} \quad (10)$$

The Average Speed

$$\overline{S} = \frac{VM}{VM} = \frac{Q \cdot L}{C \cdot t} = \frac{L}{TT} \quad (11)$$

The field and simulated data were obtained for eight consecutive three-cycle periods. All MOE's were determined either directly or by calculations for each three-cycle period. The means and standard deviations were calculated for the nine observed and simulated MOE's. Several statistical analyses were conducted to compare the simulated and observed MOE's. It was concluded that the UTCS-1 simulation model could reproduce field conditions for the a.m. peak period for the overall network. The a.m. off-peak testing resulted in greater discrepancies between the simulated and observed data than was found for the peak-hour testing.

In an effort to improve the model's capabilities for the off-peak conditions, several of the routines were rewritten. The model was again applied to the original validation network with similar peak period results. The off-peak results were better for the improved model than for the original model, but still were not as good as the peak period results. An analysis of the individual links indicated a number of differences between field and simulated data for each MOE. This finding was particularly prevalent on links which had discrepancies between the simulated and observed CONTENT values. The content value is the critical measure since it is directly or indirectly included in the seven calculated MOE's (7).

Critique

Peak, Marwick, Mitchel & Company performed statistical analyses on the observed and simulated data which they had obtained. However, two areas of question arise when analyzing their work. First, the report makes no reference to the probability of making a statistical Type II error (accepting a hypothesis when it is not true). When trying to show that two means are conclusively the same, the test for the Type II error becomes the critical analysis. Without having calculated the Type II error, all the results and conclusions that were made in the report are open to question. Secondly, the procedure of collecting field and simulated data for only the CONTENT and OUTPUT, and calculating the other seven MOE's by equations is a questionable practice when performing research. Since all the calculations were based on the two MOE's CONTENT and OUTPUT, any statistical analyses that were performed on the

other MOE's would only reflect the model's ability to reproduce the two measured factors. When attempting to validate a computer model, simulated data should be compared with observed data for all the MOE's being analyzed in order to reach a meaningful conclusion. The report produced by Peat, Marwick, Mitchell & Company recognized the critical effects that differences in the simulated and observed CONTENT values would have on the other MOE's.

The above discussion raises doubts about conclusively stating that the UTCS-1 model is capable of reproducing field measured MOE's.

FHWA Validation Project

The Traffic Systems Division Office of Research, an organization of the Federal Highway Administration, performed a validation procedure on the UTCS-1s simulation model (8). The original UTCS-1 model was modified by reducing the size of several of the input and embedded parameters. The model routines were left unaltered. The modified version of the UTCS-1 model would act in the same manner as the unaltered version, but could only be applied to small networks or single intersections.

The validation procedure incorporated field data that was collected at the intersection of Shattuck and Alcatraz Streets in Oakland, California and at an intersection in Arlington, Virginia. Only the Oakland validation project was described in detail in the report. The field data was collected for only one MOE, stop delay per vehicle. The field data was collected by using the Berry-Van Til sampling method. This sampling method is ostensibly the same as the Intersection Delay Method

described in Chapter 8 of the "Manual on Traffic Engineering Studies" (9). Data was collected for eleven fifteen-minute periods between 2:30 p.m. and 6:00 p.m. Only one field observation was obtained for each fifteen-minute period. Ten replicates for each fifteen-minute period were obtained from the UTCS-1s model. The field and simulated data were statistically compared by using the Student t-test with a two-sided α level of 0.05. The Student t-test is conducted as follows:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{(N_1-1)S_1^2 + (N_2-1)S_2^2}} \cdot \sqrt{\frac{N_1 N_2 (N_1 + N_2 - 2)}{N_1 + N_2}} \quad (12)$$

where t is the value compared with the critical t value for 9 degrees of freedom and $\alpha = 0.05$ (two-sided); $\bar{X}_1$ and $\bar{X}_2$ are the means of the observed and simulated data; N_1 and N_2 are the number of observed and simulated replications of the data; S_1^2 and S_2^2 are the variances about the observed and simulated means.

The field and simulated data are summarized in Table 1; an asterisk appears beside the simulated data where the Student t-test was rejected. The observed data is shown after it had been adjusted by $(26 \pm 8)\%$. An earlier study comparing methods of measuring stop delay per vehicle showed that data using the Berry-Van Til method was $(26 \pm 8)\%$ higher than data obtained from time-lapse photography (10). This adjustment factor accounts for the apparent mean with standard deviation format shown in Table 1 for the observed data.

The conclusions of the report were stated as follows:

It can be concluded that the UTCS-1s single intersection simulation model has been successfully validated against field data from two intersections differing widely in geometry and location (11).

Table 1. Data for the FHWA Project

TIME INTERVAL LINK	OBSERVED STOP DELAY (SEC/VEH)	SIMULATED STOP DELAY (SEC/VEH)	VOLUME	% LEFT TURNS	BETA **
2:30 - 2:45					
SHATTUCK N.B.	7.4 + 0.8	10.8 + 1.7	368	16	.08
SHATTUCK S.B.	11.8 + 1.3	9.5 + 1.7	356	19	.60
ALCATRAZ E.B.	8.1 + 0.9	9.4 + 1.8	308	12	.73
ALCATRAZ W.B.	9.6 + 1.0	5.4 + 0.9 *	292	7	
2:45 - 3:00					
SHATTUCK N.B.	11.1 + 1.1	9.6 + 1.8	376	13	.75
SHATTUCK S.B.	8.9 + 1.0	9.6 + 1.2	348	22	.30
ALCATRAZ E.B.	11.8 + 1.3	9.2 + 2.8	348	14	.63
ALCATRAZ W.B.	9.6 + 1.0	6.6 + 0.9 *	416	6	
3:00 - 3:15					
SHATTUCK N.B.	14.8 + 1.6	11.2 + 2.6	428	13	.50
SHATTUCK S.B.	6.7 + 0.6	9.5 + 1.3	396	14	.05
ALCATRAZ E.B.	13.3 + 1.4	10.8 + 3.6	412	14	.68
ALCATRAZ W.B.	9.6 + 1.0	7.1 + 1.1	396	4	.33
3:30 - 3:45					
SHATTUCK N.B.	11.1 + 1.1	10.7 + 1.7	368	15	.95
SHATTUCK S.B.	8.1 + 0.8	10.5 + 0.9	492	21	.20
ALCATRAZ E.B.	9.6 + 1.0	14.4 + 5.3	456	12	.25
ALCATRAZ W.B.	11.1 + 1.1	7.8 + 1.0	508	5	.20
3:45 - 4:00					
SHATTUCK N.B.	13.3 + 1.4	9.3 + 0.9	492	9	.25
SHATTUCK S.B.	7.4 + 0.8	8.9 + 1.2	324	12	.60
ALCATRAZ E.B.	17.0 + 1.8	9.7 + 2.3	344	12	.05
ALCATRAZ W.B.	8.9 + 0.9	7.0 + 1.6	332	6	.45

Table 1, cont.

TIME INTERVAL LINK	OBSERVED STOP DELAY (SEC/VEH)	SIMULATED STOP DELAY (SEC/VEH)	VOLUME	% LEFT TURNS	BETA **
4:00 - 4:15					
SHATTUCK N.B.	13.3 + 1.4	10.5 + 3.3	376	12	.65
SHATTUCK S.B.	11.8 + 1.3	10.0 + 1.1	388	27	.75
ALCATRAZ E.B.	11.8 + 1.2	11.0 + 3.1	448	8	.90
ALCATRAZ W.B.	11.1 + 1.1	6.8 + 1.0	348	2	.08
4:30 - 4:45					
SHATTUCK N.B.	15.5 + 1.7	10.2 + 1.7 *	464	16	
SHATTUCK S.B.	19.2 + 2.1	12.2 + 2.9	496	24	.15
ALCATRAZ E.B.	20.7 + 2.2	75.2 + 38.4	700	7	.03
ALCATRAZ W.B.	11.8 + 1.2	6.5 + 1.4 *	336	5	
4:45 - 5:00					
SHATTUCK N.B.	17.0 + 1.8	11.2 + 1.9 *	472	8	
SHATTUCK S.B.	13.3 + 1.4	12.8 + 2.3	592	20	.90
ALCATRAZ E.B.	31.8 + 3.4	34.1 + 18.0	684	12	.90
ALCATRAZ W.B.	11.1 + 1.2	6.0 + 1.1 *	312	1	
5:00 - 5:15					
SHATTUCK N.B.	28.1 + 3.0	10.1 + 1.6 *	536	15	
SHATTUCK S.B.	9.6 + 1.0	12.1 + 2.4	488	26	.45
ALCATRAZ E.B.	20.7 + 2.2	23.9 + 10.4	612	9	.85
ALCATRAZ W.B.	9.6 + 1.0	6.7 + 1.1	348	3	.25
5:30 - 5:45					
SHATTUCK N.B.	16.3 + 1.8	10.9 + 1.1 *	408	14	
SHATTUCK S.B.	10.4 + 1.1	9.7 + 1.1	440	18	.85
ALCATRAZ E.B.	16.3 + 1.8	12.5 + 3.8	452	9	.55
ALCATRAZ W.B.	6.7 + 0.8	6.4 + 0.8	308	4	.95

Table 1, cont.

TIME INTERVAL LINK	STOP DELAY (SEC/VEH)	STOP DELAY (SEC/VEH)	VOLUME	% LEFT TURNS	BETA**
5:45 - 6:00					
SHATTUCK N.B.	15.5 + 1.7	9.7 + 1.6*	416	17	
SHATTUCK S.B.	6.7 + 0.8	8.1 + 1.8	381	21	.65
ALCATRAZ E.B.	19.2 + 2.1	8.3 + 1.3*	312	5	
ALCATRAZ W.B.	5.9 + 0.6	6.0 + 1.4	248	5	.95

*Reject t-test.

**Beta values have been calculated as part of the present research.

Source: reference (12).

Critique

Besides analyzing the capability of the UTCS-1s model to reproduce only one MOE, the Traffic Systems Division research seemingly has two weaknesses. First, it is inappropriate to conduct a statistical analysis comparing two means when one of the means is a single observation. However, assuming that the single observation equals the mean of several observations (a highly unlikely probability), and that the variance of the field observations is statistically the same as the variance of the simulated observations, then this analysis is appropriate. The second apparent weakness is that no analysis of the probability of making a Type II error was conducted. The Type II errors were calculated as part of the present research based on accepting the possibility that the single observation represented the actual mean of several observations, and that the variances of the observed and simulated data were homogeneous. The number of observations for the observed data was taken to be one, and the standard deviation was assumed to be the $\pm 8\%$ as shown in Table 1. The assumed standard deviation was very close to the simulated standard deviation in most cases.

The Type II errors were determined by using the chart in Figure 2. The values of d and N were found as follows:

$$d = \frac{|\hat{\delta} - \delta'|}{\sqrt{\sigma_1^2 + \sigma_2^2}} \quad (13)$$

$$N = \frac{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}} \quad (14)$$

where $\hat{\delta} = 0$ and $\delta' = X_1 - X_2$.

Figure 2. Operating Characteristics Curve for Tests About Means
Source: reference (13).

The Type II errors are indicated in Table 1 under the column entitled "Beta". Only six of the thirty-four comparisons had a probability of making a Type II error of less than 20%. Nineteen of the comparisons had a greater than 50% probability of being accepted as being the same when they are actually different. It would appear that the conclusions reached in the report may not be conclusive, and the UTCS-1s model may not be capable of reproducing field occurrences in many cases.

Carini Validation Project

A validation project of the UTCS-1s model was performed at Purdue University by Carini (14). Observed and simulated data for four MOE's, volume of vehicle trips, stops per vehicle, total stop delay, and stop delay per vehicle were statistically compared. Field data was collected for five, five-minute periods on each approach to the validation intersection. Simulated data was obtained for five replicates of five minutes duration each. The Student t-test was used to compare the simulated and observed MOE's. Carini also considered the Type II error. The results of the statistical analysis conducted by Carini are shown in Table 2. It was concluded that the UTCS-1s model was reasonably adequate to reproduce field measured MOE's.

Critique

An analysis of Table 2 shows that four of the Student t-test results were rejected. Further, four of the remaining eight comparisons had probabilities of Type II errors that were greater than 25%. Since it appears that only four of the comparisons have positive indications that

Table 2. Summary of t-Tests for Observed and Simulated Data

$$H_0: \bar{X}_{\text{sim}} = \bar{X}_{\text{obs}} \quad \alpha = 0.40 \quad t_{8, \alpha/2} = 0.889$$

Approach	Stops Per Vehicle	Stopped Delay	Stopped Delay Per Vehicle
A	$t = 0.204$	$t = 3.0^*$	$t = 2.76^*$
	$\beta = 0.12$	$\beta = 0.39$	$\beta = 0.20$
B	$t = 0.40$	$t = 0.48$	$t = 0.63$
	$\beta = 0.35$	$\beta = 0.29$	$\beta = 0.42$
C	$t = 0.80$	$t = 0.26$	$t = 0.52$
	$\beta = 0.27$	$\beta < 0.001$	$\beta = 0.10$
D	$t = 2.63^*$	$t = 1.22^*$	$t = 0.675$
	$\beta = 0.05$	$\beta = 0.01$	$\beta = 0.003$

*Reject H_0 .

Source: Reference (15).

the observed and simulated data are the same, it would be difficult to conclusively state that the simulator can reproduce field MOE's.

Utah State Department of Highways

The Utah State Department of Highways (USDH) was the first state agency to use the UTCS-1 model. They validated the program before using it by comparing simulated and observed traffic volumes. A speed validation was attempted but discarded due to the high variance in the observed data. A delay study was considered but was not done because it was felt that delay data could not be accurately obtained. The USDH applied the UTCS-1 model to a signalized network based on the assumption that if the model could reproduce the actual volumes, then it could reproduce all other MOE's that the model calculates. This assumption was based on the conclusions of the original validation project done by Peak, Marwick, Mitchel & Company. The research done for the present validation project will show that even when the model reproduces the actual volumes, it does not necessarily reproduce the other MOE's.

CHAPTER 3: VALIDATION PROCEDURE AND ANALYSIS

The validation procedure that was performed for this project was designed to be the most rigorous and statistically complete test conducted on the UTCS-1s simulation model to date. It must be remembered that the UTCS-1 and UTCS-1s models differ only in the size of the network that can be simulated. The internal workings of each model are the same. The following seven step procedure was developed for the validation attempt of the UTCS-1s model as applied to a linear network.

1. Choice of the validation network (linear).
2. Determination of the MOE's to be analyzed.
3. Formulation of the statistical evaluation method to compare the observed and simulated MOE's.
4. Determination of the required number of observation and the duration of each.
5. Collection of the field data.
6. Generation of the simulated data.
7. Comparison of the field and simulated MOE's.

Choosing the Validation Network

The validation network that was chosen had to satisfy several criteria. First, it had to be a network on which the Indiana State Highway Commission was interested in improving the signal timings.

Second, the traffic flows should remain unchanging throughout the duration of this study. Third, the network had to be within easy traveling distance of Purdue University. U.S. 31 (East and Madison Streets) south of the Indianapolis CBD was chosen as the validation network (see Figures 3, 4 and 5 for location and description of the validation network). U.S. 31 is a major arterial that carries p.m. peak-period traffic from the CBD to points south of the city. Since the validation study dealt with the peak period only, it was assumed that the traffic patterns would not vary during the length of this project. The network was approximately two and a quarter miles long and included eight signalized intersections.

Determination of the MOE's

When undertaking a project of this nature, it is desirous to analyze and evaluate all of the MOE's generated by the simulation model. However, there are certain constraints such as time, money, and personnel capabilities which dictate the elimination of certain evaluations. UTCS-1s is capable of generating data for seventeen MOE's. With the resources available, only four of the simulated MOE's could be readily obtained in the field. Simulated and field-observed data were collected for volumes of vehicle trips, stops per vehicle, total stop delay, and stop delay per vehicle.

Statistical Analysis

It was decided to compare the observed and simulated MOE's for each link by use of a statistical Student t-test. The null hypothesis

Figure 3. Location of the Validation Network

Figure 4. Diagram of the Validation Network

Figure 5. Coding for the Validation Network

(H_0) would state that the observed and simulated MOE's are the same. Since accepting the null hypothesis when it was not true would be contrary to the goal to validate the UTCS-1s program, the probability of making a Type II error (accepting H_0 when it is not true) had to be kept small. The significance levels are directly related to the sample size and will be discussed in the next section.

Number of Observations

The required number of observations was determined by use of "Graphs for Determining the Power of Student's t-Test" (16). The graphs were developed to show the relationship of four variables: α , the probability of rejecting the null hypothesis when it is true; β , the probability of accepting the null hypothesis when it is false; δ , the acceptable difference between two means divided by their pooled standard deviation; and N , the number of observations.

When using the graphs, it was decided to set the acceptable differences between the means equal to one standard deviation (hence $\delta = 1$), and to set β equal to 0.05. A trade-off situation involving α and N was established and solved based on the time, money, and personnel constraints. The required number of observations was determined to be 10 with α (two-sided) equal to 0.20, and β and δ as stated above.

The duration of each observation was found to be the result of N divided by the traffic volume per hour where

$$N = \frac{(1-P) \chi^2}{P d^2} \quad (1)$$

N is the minimum acceptable number of vehicles passing through the

intersection, P is the probability that a vehicle will have to stop, χ^2 is the chi-squared statistic, and d is the acceptable error. Since UTCS-1s could only simulate one time period for all links, and the cost of running several time periods was prohibitive, one duration for all links had to be determined. An eight minute duration period was found to be acceptable for all links when a 90% confidence interval and a maximum error of ± 0.15 were employed.

Data Collection and Simulation

The field data was collected in accordance to the intersection delay procedure described in Chapter 8 of the "Manual of Traffic Engineering Studies" (17). Field data was collected during the p.m. peak period on Monday through Thursday for four consecutive weeks. Data was collected on each link for ten consecutive eight-minute periods. The traffic was assumed to be from the same population for the p.m. peak period of each day throughout the study.

Input data (i.e. link lengths, number of lanes, speed, signal splits and offsets, and turning movements) for UTCS-1s was collected and coded, and ten simulated replicates of eight minutes duration each were generated.

All simulated and observed data was coded onto computer cards for easier analysis. Tables 3, 4, 5 and 6 summarize the mean values of the observed and simulated results for the four MOE's.

Analysis

The statistical package for social sciences (SPSS) was used to find the means and variances of each observed and simulated MOE on

Table 3. Volume of Vehicle Trips - Original
Signal Timings

APPROACH LINK	OBSERVED	SIMULATED
9 - 1	247.80	215.90
2 - 1	88.20	100.90
10 - 1	27.20	26.00
11 - 1	45.50	42.50
1 - 2	246.30	211.80
3 - 2	110.10	114.80
12 - 2	19.80	17.70
13 - 2	35.10	28.80
2 - 3	233.90	226.40
4 - 3	129.60	129.10
14 - 3	61.90	49.70
15 - 3	74.10	64.10
4 - 5	190.30	179.70
6 - 5	94.40	84.70
17 - 5	29.40	26.60
18 - 5	17.90	18.90
5 - 6	192.50	183.40
7 - 6	93.40	90.20
19 - 6	19.50	16.60
20 - 6	29.10	22.60
6 - 7	215.70	191.70
8 - 7	112.40	107.20
21 - 7	56.70	49.50
22 - 7	65.60	65.20

Table 4. Stops per Vehicle - Original Signal Timings

APPROACH LINK	OBSERVED $\pm$ s.d.	SIMULATED $\pm$ s.d.
9 - 1	.702 $\pm$.096	.686 $\pm$.032
2 - 1	.731 $\pm$.066	.665 $\pm$.099
10 - 1	.770 $\pm$.076	.795 $\pm$.108
11 - 1	.804 $\pm$.072	.852 $\pm$.119
1 - 2	.381 $\pm$.042	.242 $\pm$.052
3 - 2	.319 $\pm$.068	.256 $\pm$.047
12 - 2	.903 $\pm$.109	.899 $\pm$.233
13 - 2	.875 $\pm$.146	.889 $\pm$.199
2 - 3	.561 $\pm$.064	.409 $\pm$.050
4 - 3	.675 $\pm$.081	.441 $\pm$.050
14 - 3	.882 $\pm$.072	.858 $\pm$.091
15 - 3	.821 $\pm$.202	.738 $\pm$.054
4 - 5	.172 $\pm$.053	.181 $\pm$.026
6 - 5	.400 $\pm$.049	.361 $\pm$.159
17 - 5	.874 $\pm$.064	.753 $\pm$.073
18 - 5	.846 $\pm$.096	.750 $\pm$.129
5 - 6	.140 $\pm$.038	.238 $\pm$.066
7 - 6	.510 $\pm$.070	.206 $\pm$.055
19 - 6	.837 $\pm$.096	.833 $\pm$.047
20 - 6	.817 $\pm$.108	.867 $\pm$.184
6 - 7	.282 $\pm$.074	.223 $\pm$.039
8 - 7	.636 $\pm$.058	.596 $\pm$.075
21 - 7	.821 $\pm$.070	.803 $\pm$.116
22 - 7	.925 $\pm$.142	.777 $\pm$.119

Table 5. Total Stop Delay in Minutes - Original
Signal Timings

APPROACH LINK	OBSERVED $\pm$ s.d.	SIMULATED $\pm$ s.d.
9 - 1	76.67 $\pm$ 28.88	58.20 $\pm$ 3.63
2 - 1	20.10 $\pm$ 3.71	20.81 $\pm$ 2.90
10 - 1	10.60 $\pm$ 2.42	10.13 $\pm$ 2.08
11 - 1	19.60 $\pm$ 3.21	19.91 $\pm$ 4.59
1 - 2	24.88 $\pm$ 5.43	19.12 $\pm$ 4.45
3 - 2	14.88 $\pm$ 5.07	12.24 $\pm$ 1.64
12 - 2	10.78 $\pm$ 2.61	8.81 $\pm$ 1.34
13 - 2	22.05 $\pm$ 8.01	14.77 $\pm$ 1.94
2 - 3	31.85 $\pm$ 6.73	16.79 $\pm$ 3.14
4 - 3	19.88 $\pm$ 8.88	15.89 $\pm$ 3.92
14 - 3	32.08 $\pm$ 6.87	25.55 $\pm$ 4.65
15 - 3	25.55 $\pm$ 11.08	22.07 $\pm$ 3.12
4 - 5	5.93 $\pm$ 2.38	6.56 $\pm$ 1.66
6 - 5	9.53 $\pm$ 2.80	9.76 $\pm$ 2.73
17 - 5	11.63 $\pm$ 3.06	10.66 $\pm$ 2.48
18 - 5	10.20 $\pm$ 4.66	8.46 $\pm$ 1.69
5 - 6	6.10 $\pm$ 2.75	5.87 $\pm$ 2.08
7 - 6	11.35 $\pm$ 4.32	3.72 $\pm$ 0.93
19 - 6	14.80 $\pm$ 2.55	7.73 $\pm$ 1.83
20 - 6	12.98 $\pm$ 6.24	11.99 $\pm$ 3.03
6 - 7	19.98 $\pm$ 4.79	11.60 $\pm$ 2.92
8 - 7	37.25 $\pm$ 6.95	31.29 $\pm$ 4.12
21 - 7	23.53 $\pm$ 4.42	21.01 $\pm$ 3.75
22 - 7	28.48 $\pm$ 7.39	23.98 $\pm$ 3.14

Table 6. Stop Delay per Vehicle in Seconds - Original Signal Timings

APPROACH LINK	OBSERVED $\pm$ s.d.	SIMULATED $\pm$ s.d.
9 - 1	18.23 $\pm$ 4.30	16.19 $\pm$ 0.77
2 - 1	13.74 $\pm$ 2.52	12.37 $\pm$ 1.56
10 - 1	24.14 $\pm$ 4.47	23.32 $\pm$ 3.61
11 - 1	26.02 $\pm$ 4.09	27.93 $\pm$ 2.94
1 - 2	6.07 $\pm$ 1.25	5.42 $\pm$ 1.24
3 - 2	7.99 $\pm$ 2.24	6.42 $\pm$ 0.90
12 - 2	32.87 $\pm$ 7.30	31.24 $\pm$ 9.29
13 - 2	37.07 $\pm$ 10.25	31.59 $\pm$ 7.05
2 - 3	8.17 $\pm$ 1.19	4.46 $\pm$ 0.84
4 - 3	8.94 $\pm$ 3.88	7.39 $\pm$ 1.74
14 - 3	31.11 $\pm$ 4.88	30.90 $\pm$ 5.26
15 - 3	20.98 $\pm$ 10.37	20.32 $\pm$ 2.52
4 - 5	1.86 $\pm$ 0.67	2.16 $\pm$ 0.45
6 - 5	6.10 $\pm$ 1.91	6.94 $\pm$ 1.91
17 - 5	23.54 $\pm$ 2.69	24.00 $\pm$ 5.28
18 - 5	33.34 $\pm$ 7.88	26.87 $\pm$ 3.79
5 - 6	1.89 $\pm$ 0.77	1.92 $\pm$ 0.74
7 - 6	7.19 $\pm$ 2.25	2.48 $\pm$ 0.59
19 - 6	22.90 $\pm$ 3.96	27.77 $\pm$ 3.61
20 - 6	25.95 $\pm$ 6.72	32.21 $\pm$ 7.50
6 - 7	5.51 $\pm$ 0.94	3.64 $\pm$ 0.85
8 - 7	19.87 $\pm$ 2.79	17.59 $\pm$ 2.68
21 - 7	24.79 $\pm$ 2.93	25.63 $\pm$ 4.62
22 - 7	25.83 $\pm$ 7.15	22.30 $\pm$ 4.14

every link. Each MOE was statistically evaluated to determine if the simulated and observed data were the same. All of the calculations done for the statistical analysis can be found in Appendix B.

The volumes of vehicle trips were compared by use of the chi-squared test to determine if the statistical distributions of the volumes on the approaches for the entire network were the same. It was found that the distributions of the observed and simulated volumes of vehicle trips were statistically the same for $\alpha = 0.25$.

The three remaining MOE's were analyzed using a Student t-test with α (two-sided) = 0.20. Before performing the Student t-tests, the observed and simulated variances for each MOE and link had to be compared to determine if they were the same. Using the F statistic with a two-sided 95% confidence interval, it was found that about one third of the links had simulated and observed variances that were statistically not the same. Those links which had variances that were statistically the same were analyzed using the Student t-test to determine if the means were the same. It was found that only about one half of the comparisons proved to be statistically the same. These results were not adequate to unequivocally state that the UTCS-ls simulation program is capable of replicating field observed MOE's.

Secondary Statistical Analysis

Having shown that the UTCS-ls simulation program did not adequately reproduce the field MOE's, the next logical step was to determine how the simulated data differed from the field data. To analyze the

differences, a two-way analysis of variance (ANOVA) procedure was used. Only six of the eight intersections were included in the analysis of variance because errors in collecting the field data were made on one approach of each of the remaining two intersections.

The first step in the analysis of variance procedure was to test for homogeneity of the variances. The Bartlett test was performed on the variances of each MOE for all the links. The variances for all three MOE's were found to be nonhomogeneous. The standard deviation (square root of the variance) was plotted versus the sample mean for each MOE. Each plot showed a definite pattern that would indicate that a square root or $\log_{10}$ transformation of the data would result in the homogeneity of variances. Both transformations were applied to the data for all three MOE's. The $\log_{10}$ transformation indicated homogeneity of variances for the total stop delay and stop delay per vehicle, and the square root transformation indicated homogeneity of variances for the stops per vehicle. The Bartlett test was applied to the variances of the data which were transformed as stated. All three MOE's were found to have homogeneous variances.

Having shown that the variances were homogeneous, the ANOVA procedure was performed on each MOE. A six by four matrix was developed for each MOE with the columns representing the signalized intersections (factor level B) and the rows representing the direction of travel (factor level A). Each cell of a matrix contained the difference between the means of the observed and simulated data for the specified link. The two-way analysis of variance was performed on each matrix. Since there was only one observation per cell, the error sums of

squares (SSE) term was equal to zero. The between treatments mean square error (MSTR) term replaced the error mean square (MSE) term as the denominator for the statistical analysis of the interactions and main effects. The MSTR term is equal to the MSE term from a one-way analysis of variance performed on the same data. The P value (level of significance) was determined for the interactions and main effects for each MOE. The stops per vehicle and total stop delay MOE's had no significant interactions, but had significantly large P values for both main effects. A large P value indicates that no main effects exist, and that all the cell means for the factor in question are statistically the same. It was concluded from the analysis of variance that the simulated and observed data for the stops per vehicle and total stop delay differed only by a constant on all links.

The P value for the interaction analysis for the stop delay per vehicle was very small, indicating strong interaction between the factors. No conclusions could be made about the main effects for this MOE while interaction existed between the factors.

Application of UTCS-1s

The chi-squared test performed on the volume of vehicle trips showed that the simulated program was capable of reproducing the real world traffic flow distribution on a network. All ensuing work on this project considered the simulated volume of vehicle trips on each link to be indicative of the real world conditions.

The analysis of variance showed that the simulated stops per vehicle and total stop delay data differed from the observed data by a

constant for the existing signal timing conditions on the validation network. It was expected that the constant would not vary for different signal timing conditions and that the changes in the simulated data (for stops per vehicle and total stop delay) for two signal timing schemes on a network would be the same as the real world changes on that network. Thus, the changes in these two MOE's could be used to predict changes in driver benefits.

The stop delay per vehicle MOE could not be used for any future network evaluations since no statistical conclusions pertaining to its predictive capabilities could be attained.

CHAPTER 4: SIGNAL TIMING OPTIMIZATION PROCEDURE OF THE VALIDATION NETWORK

Many macroscopic computer programs for optimizing traffic signal timings have been developed during the past several years. TRANSYT-6, the latest developed package, was chosen to optimize the signal timings for this project. TRANSYT-6 was developed by the Road Research Laboratory in England (see Appendix A for a discussion of TRANSYT-6).

When using the TRANSYT-6 program, it was found that it had no capabilities of optimizing signalized intersections which required more than two phases. A technique including the use of TRANSYT-6, delay/difference-of-offset (see Appendix A), and accepted traffic engineering principles was employed to optimize the signal timing.

The signal timing optimization procedure required that the critical intersection be determined. The critical intersection was found by calculating the minimum green time for the critical lane volume for each approach of each intersection for a given cycle length. The critical intersection was the intersection which required the greatest minimum green time. Using the critical intersection, the green and yellow phase lengths for the through movements only (excluding left turn phases) were totalled. This total was coded into the TRANSYT-6 program as the cycle length to be split between the major and minor streets at all intersections. Left turn minimum times were

added to the splits obtained from TRANSYT-6 for those intersections that had separate left turn phases. The additional time was split between the major and minor streets according to the TRANSYT-6 proportions for the given intersection. The final green phase for the major street at each intersection was used in the delay/difference-of-offset program to determine the optimum offsets between successive intersections.

Timing schemes for 75, 80, 85, 90, and 100 second cycles were developed using the procedure described above. The splits, offsets and coding for the signal control facing each approach are shown for the different cycle lengths in Tables 8, 9, 10, 11, and 12. Table 7 explains the signal control coding.

The UTCS-1s model was applied to each of the alternate timing schemes that were developed for the validation network. The expected changes in the total number of stops and the total stop delay on the entire network for each timing scheme and the changes in fuel consumption due to both were calculated. Also, a qualitative analysis of the CO emissions and fuel consumption due to average network speeds was performed. The results of the calculations are summarized in Table 13.

The expected changes in the total number of stops on the network were found by multiplying the difference between the original cycle and final cycle stops per vehicle for a link by the final volume of vehicle trips on that link, and summing the results for all the links. The expected changes in the total stop delay on the network was found by finding the difference between the original cycle and final cycle total stop delay on each link, and summing the results of all the

Table 7. UTCS-1s Signal Control Coding

0	YIELD OR YELLOW
1	GREEN
2	RED
3	RED WITH GREEN RIGHT ARROW
4	RED WITH GREEN LEFT ARROW
5	STOP OR RED WITH RIGHT TURN PERMITTED
6	RED WITH GREEN DIAGONAL ARROW
7	NO TURNS - GREEN THRU ARROW
8	RED WITH LEFT AND RIGHT GREEN ARROWS
9	NO LEFT TURN - GREEN THRU AND RIGHT

Source: Reference (18).

Table 8. Signal Settings - 75 Second Cycle

NODE	INTERVAL	DURATION (SEC)	OFFSET (SEC)	SIGNAL CODES FACING APPROACH			
				9 - 1	11 - 1	2 - 1	10 - 1
1	1	41	0	9	2	9	2
1	2	4	41	0	2	0	2
1	3	16	45	2	1	2	1
1	4	4	61	2	0	2	0
1	5	5	65	4	2	4	2
1	6	5	70	0	2	0	2
				1 - 2	13 - 2	3 - 2	12 - 2
2	1	44	29	9	2	9	2
2	2	4	73	0	2	0	2
2	3	15	2	2	1	2	1
2	4	5	17	2	0	2	0
2	5	3	22	4	2	4	2
2	6	4	25	0	2	0	2
				2 - 3	15 - 3	4 - 3	14 - 3
3	1	41	13	1	2	1	2
3	2	4	54	0	2	0	2
3	3	14	58	2	1	2	2
3	4	12	72	2	1	2	1
3	5	4	9	2	0	2	0
				3 - 4	16 - 4	5 - 4	
4	1	45	23	9	2	1	
4	2	5	68	9	2	0	
4	3	20	73	1	1	2	
4	4	5	18	9	0	2	

Table 8, cont.

NODE	INTERVAL	DURATION (SEC)	OFFSET (SEC)	SIGNAL CODES FACING APPROACH			
				4 - 5	18 - 5	6 - 5	17 - 5
5	1	48	56	1	2	1	2
5	2	4	29	0	2	0	2
5	3	19	33	2	1	2	1
5	4	4	52	2	0	2	0
				5 - 6	20 - 6	7 - 6	19 - 6
6	1	50	0	1	2	1	2
6	2	5	50	0	2	0	2
6	3	15	55	2	1	2	1
6	4	5	70	2	0	2	0
				6 - 7	22 - 7	8 - 7	21 - 7
7	1	46	27	1	2	1	2
7	2	4	73	0	2	0	2
7	3	20	2	2	1	2	1
7	4	5	22	2	0	2	0
				7 - 8	24 - 8	25 - 8	23 - 8
8	1	32	30	1	2	1	2
8	2	5	62	0	2	0	2
8	3	6	67	2	4	2	4
8	4	4	73	2	0	2	0
8	5	8	2	2	9	2	9
8	6	4	10	2	0	2	0
8	7	11	14	4	2	4	2
8	8	5	25	0	2	0	2

Table 9. Signal Settings - 80 Second Cycle

NODE	INTERVAL	DURATION (SEC)	OFFSET (SEC)	SIGNAL CODES FACING APPROACH			
				9 - 1	11 - 1	2 - 1	10 - 1
1	1	44	0	9	2	9	2
1	2	4	44	0	2	0	2
1	3	18	48	2	1	2	1
1	4	4	66	2	0	2	0
1	5	5	70	4	2	4	2
1	6	5	75	0	2	0	2
				1 - 2	13 - 2	3 - 2	12 - 2
2	1	48	32	9	2	9	2
2	2	4	0	0	2	0	2
2	3	16	4	2	1	2	1
2	4	5	20	2	0	2	0
2	5	3	25	4	2	4	2
2	6	4	28	0	2	0	2
				2 - 3	15 - 3	4 - 3	14 - 3
3	1	41	15	1	2	1	2
3	2	4	56	0	2	0	2
3	3	16	60	2	1	2	2
3	4	15	76	2	1	2	1
3	5	4	11	2	0	2	0
				3 - 4	16 - 4	5 - 4	
4	1	48	23	9	2	1	
4	2	5	71	9	2	0	
4	3	22	76	1	1	2	
4	4	5	18	9	0	2	

Table 9, cont.

NODE	INTERVAL	DURATION (SEC)	OFFSET (SEC)	SIGNAL CODES FACING APPROACH			
				4 - 5	18 - 5	6 - 5	17 - 5
5	1	50	57	1	2	1	2
5	2	4	27	0	2	0	2
5	3	22	31	2	1	2	1
5	4	4	53	2	0	2	0
				5 - 6	20 - 6	7 - 6	19 - 6
6	1	54	75	1	2	1	2
6	2	5	49	0	2	0	2
6	3	16	54	2	1	2	1
6	4	5	70	2	0	2	0
				6 - 7	22 - 7	8 - 7	21 - 7
7	1	48	21	1	2	1	2
7	2	4	69	0	2	0	2
7	3	23	73	2	1	2	1
7	4	5	16	2	0	2	0
				7 - 8	24 - 8	25 - 8	23 - 8
8	1	35	58	1	2	1	2
8	2	5	13	0	2	0	2
8	3	6	18	2	4	2	4
8	4	4	24	2	0	2	0
8	5	10	28	2	9	2	9
8	6	4	38	2	0	2	0
8	7	11	42	4	2	4	2
8	8	5	53	0	2	0	2

Table 10. Signal Settings - 85 Second Cycle

NODE	INTERVAL	DURATION (SEC)	OFFSET (SEC)	SIGNAL CODES FACING APPROACH			
				9 - 1	11 - 1	2 - 1	10 - 1
1	1	48	0	9	2	9	2
1	2	4	48	0	2	0	2
1	3	19	52	2	1	2	1
1	4	4	71	2	0	2	0
1	5	5	75	4	2	4	2
1	6	5	80	0	2	0	2
				1 - 2	13 - 2	3 - 2	12 - 2
2	1	51	33	9	2	9	2
2	2	4	84	0	2	0	2
2	3	17	3	2	1	2	1
2	4	5	20	2	0	2	0
2	5	4	25	4	2	4	2
2	6	4	29	0	2	0	2
				2 - 3	15 - 3	4 - 3	14 - 3
3	1	46	9	1	2	1	2
3	2	4	55	0	2	0	2
3	3	16	59	2	1	2	2
3	4	15	75	2	1	2	1
3	5	4	5	2	0	2	0
				3 - 4	16 - 4	5 - 4	
4	1	50	19	9	2	1	
4	2	5	69	9	2	0	
4	3	25	74	1	1	2	
4	4	5	14	9	0	2	

Table 10, cont.

NODE	INTERVAL	DURATION (SEC)	OFFSET (SEC)	SIGNAL CODES FACING APPROACH			
				4 - 5	18 - 5	6 - 5	17 - 5
5	1	54	56	1	2	1	2
5	2	4	25	0	2	0	2
5	3	23	29	2	1	2	1
5	4	4	52	2	0	2	0
				5 - 6	20 - 6	7 - 6	19 - 6
6	1	57	75	1	2	1	2
6	2	5	47	0	2	0	2
6	3	18	52	2	1	2	1
6	4	5	70	2	0	2	0
				6 - 7	22 - 7	8 - 7	21 - 7
7	1	51	19	1	2	1	2
7	2	4	70	0	2	0	2
7	3	25	74	2	1	2	1
7	4	5	14	2	0	2	0
				7 - 8	24 - 8	25 - 8	23 - 8
8	1	36	53	1	2	1	2
8	2	5	4	0	2	0	2
8	3	6	9	2	4	2	4
8	4	4	15	2	0	2	0
8	5	14	19	2	9	2	9
8	6	4	33	2	0	2	0
8	7	11	27	4	2	4	2
8	8	5	48	0	2	0	2

Table 11. Signal Settings - 90 Second Cycle

NODE	INTERVAL	DURATION (SEC)	OFFSET (SEC)	SIGNAL CODES FACING APPROACH			
				9 - 1	11 - 1	2 - 1	10 - 1
1	1	51	0	9	2	9	2
1	2	4	51	0	2	0	2
1	3	21	55	2	1	2	1
1	4	4	76	2	0	2	0
1	5	5	80	4	2	4	2
1	6	5	85	0	2	0	2
				1 - 2	13 - 2	3 - 2	12 - 2
2	1	54	35	9	2	9	2
2	2	4	89	0	2	0	2
2	3	19	3	2	1	2	1
2	4	5	22	2	0	2	0
2	5	4	27	4	2	4	2
2	6	4	31	0	2	0	2
				2 - 3	15 - 3	4 - 3	14 - 3
3	1	51	4	1	2	1	2
3	2	4	55	0	2	0	2
3	3	16	59	2	1	2	2
3	4	15	75	2	1	2	1
3	5	4	0	2	0	2	0
				3 - 4	16 - 4	5 - 4	
4	1	55	14	9	2	1	
4	2	5	69	9	2	0	
4	3	25	74	1	1	2	
4	4	5	9	9	0	2	

Table 11, cont.

NODE	INTERVAL	DURATION (SEC)	OFFSET (SEC)	SIGNAL CODES FACING APPROACH			
				4 - 5	18 - 5	6 - 5	17 - 5
5	1	58	50	1	2	1	2
5	2	4	18	0	2	0	2
5	3	24	22	2	1	2	1
5	4	4	46	2	0	2	0
				5 - 6	20 - 6	7 - 6	19 - 6
6	1	60	69	1	2	1	2
6	2	5	39	0	2	0	2
6	3	20	44	2	1	2	1
6	4	5	64	2	0	2	0
				6 - 7	22 - 7	8 - 7	21 - 7
7	1	51	11	1	2	1	2
7	2	4	62	0	2	0	2
7	3	30	66	2	1	2	1
7	4	5	6	2	0	2	0
				7 - 8	24 - 8	25 - 8	23 - 8
8	1	39	42	1	2	1	2
8	2	5	81	0	2	0	2
8	3	6	86	2	4	2	4
8	4	4	2	2	0	2	0
8	5	14	6	2	9	2	9
8	6	4	20	2	0	2	0
8	7	13	24	4	2	4	2
8	8	5	37	0	2	0	2

Table 12. Signal Settings - 100 Second Cycle

NODE	INTERVAL	DURATION (SEC)	OFFSET (SEC)	SIGNAL CODES FACING APPROACH			
				9 - 1	11 - 1	2 - 1	10 - 1
1	1	56	0	9	2	9	2
1	2	4	56	0	2	0	2
1	3	26	60	2	1	2	1
1	4	4	86	2	0	2	0
1	5	5	90	4	2	4	2
1	6	5	95	0	2	0	2
				1 - 2	13 - 2	3 - 2	12 - 2
2	1	58	39	9	2	9	2
2	2	4	97	0	2	0	2
2	3	23	1	2	1	2	1
2	4	5	24	2	0	2	0
2	5	6	29	4	2	4	2
2	6	4	35	0	2	0	2
				2 - 3	15 - 3	4 - 3	14 - 3
3	1	56	97	1	2	1	2
3	2	4	53	0	2	0	2
3	3	18	57	2	1	2	2
3	4	18	75	2	1	2	1
3	5	4	93	2	0	2	0
				3 - 4	16 - 4	5 - 4	
4	1	60	7	9	2	1	
4	2	5	67	9	2	0	
4	3	30	72	1	1	2	
4	4	5	2	9	0	2	

Table 12, cont.

NODE	INTERVAL	DURATION (SEC)	OFFSET (SEC)	SIGNAL CODES FACING APPROACH			
				4 - 5	18 - 5	6 - 5	17 - 5
5	1	66	35	1	2	1	2
5	2	4	1	0	2	0	2
5	3	26	5	2	1	2	1
5	4	4	31	2	0	2	0
				5 - 6	20 - 6	7 - 6	19 - 6
6	1	67	55	1	2	1	2
6	2	5	22	0	2	0	2
6	3	23	27	2	1	2	1
6	4	5	50	2	0	2	0
				6 - 7	22 - 7	8 - 7	21 - 7
7	1	56	89	1	2	1	2
7	2	4	45	0	2	0	2
7	3	35	49	2	1	2	1
7	4	5	84	2	0	2	0
				7 - 8	24 - 8	25 - 8	23 - 8
8	1	44	20	1	2	1	2
8	2	5	64	0	2	0	2
8	3	8	69	2	4	2	4
8	4	4	77	2	0	2	0
8	5	16	81	2	9	2	9
8	6	4	97	2	0	2	0
8	7	14	1	4	2	4	2
8	8	5	15	0	2	0	2

Table 13. Summary of Expected Changes for the Various Signal Timings

CYCLE LENGTH (SEC)	AVERAGE SPEED (MPH)	Δ STOPS PER HR	Δ DELAY PER HR	Δ FUEL CONSUMPTION DUE TO STOPS & IDLING	Δ^* FUEL CONSUMPTION DUE TO AVERAGE SPEED	Δ^{**} CO DUE TO AVERAGE SPEED
ORIG (100)	20.34					
100	20.59	-20.0	-2 HR	-486 GALLONS/YEAR	DECREASE	DECREASE
90	20.70	+100.9	-4.3	-194 GALLONS/YEAR	DECREASE	DECREASE
85	20.89	+426.4	-8.1	+1028 GALLONS/YEAR	DECREASE	DECREASE
80	21.13	+412.3	-10.0	+591 GALLONS/YEAR	DECREASE	DECREASE
75	19.64	-16.54	+10.6	+1853 GALLONS/YEAR	INCREASE	INCREASE

* FUEL CONSUMPTION DECREASES AS SPEED INCREASES (FOR LOW SPEEDS)

** CO EMISSIONS DECREASES WITH DECREASED FUEL CONSUMPTION

links. The expected change in fuel consumption was found by multiplying the expected change in the total number of stops and the expected change in the total stop delay by the following factors:

1. Fuel consumption (due to stopping from a cruising speed of 40 mph and returning to speed) = 11.83 gallons per 1000 repetitions (19).
2. Fuel consumption (due to idling) = 368 gallons per 1,000 hours (20).

The CO emissions and the fuel consumption due to average speed were analyzed qualitatively because they were both dependent on the network average speed (21), and the accuracy of the simulated average network speed is unknown. However, it is assumed that the direction of change in the speed between the original and final signal timings is the same as the actual direction of change. The results of the analyses performed on the different timing schemes were presented to the Indiana State Highway Commission for choice and implementation of one of the signal-timing schemes.

CHAPTER 5: ANALYSES OF THE NEW TIMING SCHEME

The analysis of the simulated data obtained from the use of the UTCS-1s model described in Chapter 3 concluded that the model was capable of reproducing the observed vehicle trips on a network, and that the observed and simulated data for the stops per vehicle and total stop delay differed by a constant. The research reported in this chapter was an attempt to determine if the same conclusions could be reached by using the UTCS-1s model for a different timing scheme on the same network, and to determine the capabilities of the model to be used to predict changes in MOE's for two signal-timing schemes.

Six alternative timing schemes were developed for analysis by the UTCS-1s model. The results of the analysis of the different timing schemes were presented to the Indiana State Highway Commission which chose to implement the 80 second cycle scheme. Two analyses were performed using observed field data and simulated data collected for the validation network with the new signal-timing scheme. First, a two-way analysis of variance was conducted to determine if the observed and simulated data for the new signal scheme varied by only a constant. Second, a three-way analysis of variance was performed to determine the predictive capabilities of the UTCS-1s model.

Two-way Analysis of Variance

After allowing two weeks for the traffic to acclimate itself to

the new signal timings, field data was collected using the intersection delay method described in Chapter 8 of the "Manual of Traffic Engineering Studies" (22). Ten eight-minute observations were obtained in the field for each link, and ten eight-minute replicates were simulated by the UTCS-1s model. All of the simulated and observed data for four MOE's - volume of vehicle trips, stops per vehicle, total stop delay, and stop delay per vehicle - was coded onto computer cards, and the means and standard deviations of each link and MOE were computed.

The chi-squared test was performed on the distributions of the simulated and observed volume of vehicle trips which were found to be statistically not the same (see Appendix C) for all calculations discussed in this chapter). Since it was mandatory for the model to be simulating the actual conditions, the input data to the UTCS-1s model for the hourly volumes had to be adjusted. The mean value for the volume of vehicle trips on each approach link was expanded to an hourly volume and used in the input data for the model. Ten eight-minute simulated replicates were again obtained. The means and standard deviations for the four MOE's were computed and are summarized in Tables 14, 15, 16, and 17. The chi-square test was performed on the distributions of the observed and newly simulated volume of vehicle trips, and were found to be statistically the same.

A two-way analysis of variance was performed on the remaining three MOE's. After a log10 transformation was applied to the raw data, the Bartlett test was performed. The results showed that the variances of the transformed data were homogeneous for each MOE. The two-way analysis of variance was conducted in the same manner as was

Table 14. Volume of Vehicle Trips - Final
Signal Timings

APPROACH LINK	OBSERVED	SIMULATED
9 - 1	275.60	275.90
2 - 1	107.10	110.10
10 - 1	30.50	30.30
11 - 1	55.70	49.40
1 - 2	262.00	269.00
3 - 2	109.30	124.70
12 - 2	23.80	24.20
13 - 2	34.00	29.20
2 - 3	247.30	258.60
4 - 3	131.60	137.10
14 - 3	64.10	64.00
15 - 3	73.60	73.60
4 - 5	193.40	206.90
6 - 5	87.30	91.90
17 - 5	31.70	31.60
18 - 5	19.50	18.80
5 - 6	199.20	208.50
7 - 6	91.30	93.10
19 - 6	22.70	23.20
20 - 6	33.30	33.30
6 - 7	203.70	225.20
8 - 7	107.00	108.10
21 - 7	57.30	57.40
22 - 7	79.70	79.10

Table 15. Stops per Vehicle - Final Signal Timings

APPROACH LINK	OBSERVED $\pm$ s.d.	SIMULATED $\pm$ s.d.
9 - 1	.587 $\pm$.108	.664 $\pm$.037
2 - 1	.625 $\pm$.099	.665 $\pm$.086
10 - 1	.816 $\pm$.092	.064 $\pm$.068
11 - 1	1.201 $\pm$.279	1.068 $\pm$.098
1 - 2	.272 $\pm$.035	.271 $\pm$.038
3 - 2	.570 $\pm$.094	.667 $\pm$.039
12 - 2	.850 $\pm$.110	.832 $\pm$.157
13 - 2	1.078 $\pm$.169	.836 $\pm$.140
2 - 3	.595 $\pm$.157	.414 $\pm$.065
4 - 3	.292 $\pm$.042	.518 $\pm$.047
14 - 3	1.056 $\pm$.121	.893 $\pm$.076
15 - 3	.821 $\pm$.053	.768 $\pm$.066
4 - 5	.233 $\pm$.038	.296 $\pm$.052
6 - 5	.385 $\pm$.078	.352 $\pm$.084
17 - 5	.786 $\pm$.099	.815 $\pm$.065
18 - 5	.841 $\pm$.052	.830 $\pm$.099
5 - 6	.244 $\pm$.028	.225 $\pm$.035
7 - 6	.653 $\pm$.067	.764 $\pm$.041
19 - 6	.817 $\pm$.087	.776 $\pm$.106
20 - 6	.880 $\pm$.116	.806 $\pm$.115
6 - 7	.342 $\pm$.057	.390 $\pm$.028
8 - 7	.800 $\pm$.035	.847 $\pm$.053
21 - 7	.971 $\pm$.110	.874 $\pm$.093
22 - 7	.961 $\pm$.147	.891 $\pm$.052

Table 16. Total Stop Delay in Minutes - Final
Signal Timings

APPROACH LINK	OBSERVED $\pm$ s.d.	SIMULATED $\pm$ s.d.
9 - 1	39.90 $\pm$ 13.19	49.02 $\pm$ 4.00
2 - 1	20.72 $\pm$ 6.59	15.75 $\pm$ 2.65
10 - 1	12.12 $\pm$ 3.64	13.77 $\pm$ 2.13
11 - 1	45.70 $\pm$ 24.31	113.22 $\pm$ 28.06
1 - 2	23.66 $\pm$ 4.31	24.52 $\pm$ 8.49
3 - 2	22.78 $\pm$ 5.15	26.54 $\pm$ 3.36
12 - 2	9.30 $\pm$ 4.14	9.27 $\pm$ 0.97
13 - 2	16.18 $\pm$ 5.41	10.79 $\pm$ 1.57
2 - 3	34.58 $\pm$ 12.34	20.85 $\pm$ 5.04
4 - 3	14.42 $\pm$ 7.59	25.45 $\pm$ 2.94
14 - 3	49.78 $\pm$ 13.42	39.13 $\pm$ 12.60
15 - 3	25.95 $\pm$ 8.87	22.02 $\pm$ 3.26
4 - 5	8.57 $\pm$ 3.32	15.59 $\pm$ 2.64
6 - 5	6.69 $\pm$ 2.16	11.74 $\pm$ 5.34
17 - 5	9.82 $\pm$ 2.14	10.57 $\pm$ 1.25
18 - 5	3.80 $\pm$ 1.33	6.17 $\pm$ 1.65
5 - 6	7.45 $\pm$ 1.99	10.78 $\pm$ 2.66
7 - 6	4.81 $\pm$ 1.50	13.58 $\pm$ 5.27
19 - 6	7.32 $\pm$ 1.64	8.75 $\pm$ 1.81
20 - 6	12.20 $\pm$ 6.79	14.44 $\pm$ 4.68
6 - 7	7.82 $\pm$ 3.21	12.86 $\pm$ 2.14
8 - 7	13.90 $\pm$ 1.94	29.92 $\pm$ 6.14
21 - 7	34.08 $\pm$ 9.46	26.91 $\pm$ 13.86
22 - 7	47.95 $\pm$ 16.64	35.03 $\pm$ 10.25

Table 17. Stop Delay per vehicle in Seconds - Final
Signal Timings

APPROACH LINK	OBSERVED $\pm$ s.d.	SIMULATED $\pm$ s.d.
9 - 1	8.59 $\pm$ 2.06	10.67 $\pm$ 0.84
2 - 1	11.42 $\pm$ 2.94	8.59 $\pm$ 1.42
10 - 1	24.10 $\pm$ 5.51	27.25 $\pm$ 4.03
11 - 1	47.40 $\pm$ 18.42	140.08 $\pm$ 41.95
1 - 2	5.44 $\pm$ 0.66	5.45 $\pm$ 1.74
3 - 2	12.53 $\pm$ 2.54	12.77 $\pm$ 1.35
12 - 2	22.48 $\pm$ 5.13	23.31 $\pm$ 3.43
13 - 2	28.18 $\pm$ 6.96	22.59 $\pm$ 3.63
2 - 3	8.25 $\pm$ 2.40	4.83 $\pm$ 1.02
4 - 3	6.47 $\pm$ 3.14	11.12 $\pm$ 0.81
14 - 3	46.02 $\pm$ 8.55	36.59 $\pm$ 10.68
15 - 3	20.67 $\pm$ 4.90	17.95 $\pm$ 2.38
4 - 5	2.62 $\pm$ 0.79	4.51 $\pm$ 0.68
6 - 5	4.58 $\pm$ 1.39	7.49 $\pm$ 3.03
17 - 5	18.65 $\pm$ 2.34	20.09 $\pm$ 2.10
18 - 5	11.75 $\pm$ 3.43	19.56 $\pm$ 4.09
5 - 6	2.25 $\pm$ 0.56	3.08 $\pm$ 0.77
7 - 6	3.15 $\pm$ 0.91	8.77 $\pm$ 3.35
19 - 6	19.68 $\pm$ 4.88	22.54 $\pm$ 3.80
20 - 6	28.22 $\pm$ 6.42	26.02 $\pm$ 8.03
6 - 7	2.29 $\pm$ 0.82	3.41 $\pm$ 0.53
8 - 7	7.85 $\pm$ 1.33	16.49 $\pm$ 2.37
21 - 7	35.40 $\pm$ 7.86	27.54 $\pm$ 10.61
22 - 7	35.54 $\pm$ 10.82	26.26 $\pm$ 5.56

described in Chapter 3. The denominator for the F statistic calculations was the treatment mean square error (MSTR) term which is equal to the mean square error (MSE) term from a one-way analysis of variance on the same data.

The results of the two-way analysis of variance for all three MOE's show that the values in each cell are strongly interactive. The high degree of interaction means that the values in the cells of each matrix are not the same. For the stops per vehicle and total stop delay, this is opposite from the conclusion reached from the two-way analysis of variance that was performed on the data from the original signal-timing conditions.

Analysis of the Predictive Capabilities of UTCS-1s

The final test that was performed for this project was done to determine the predictive capabilities of the UTCS-1s model. A three-way analysis of variance was used to compare the difference between the simulated data for the original cycle (100 second) and the simulated data for the final cycle (80 second) with the difference between the observed field data for the original cycle (100 second) and the observed field data for the final cycle (80 second). Simplified, it was desired to compare the matrix containing $(X_{sim100} - X_{sim80})$ for each cell with the matrix containing $(X_{obs100} - X_{obs80})$ for each cell. The analysis was conducted for three MOE's, stops per vehicle, total stop delay, and stop delay per vehicle. The three factor levels for the analysis were the approach direction, the intersection number, and the type of data (observed or simulated). It was predetermined that only the type of data factor level was pertinent; that is, it was desired to determine if $(X_{sim100} - X_{sim80})$ equalled $(X_{obs100} - X_{obs80})$. The results of the other two factor levels were considered meaningless because it was expected that both $(X_{sim100} - X_{sim80})$ and $(X_{obs100} - X_{obs80})$ would differ for each approach direction and intersection number.

The denominator that was used for the F statistic test was the average of the pure error terms of the simulated data for the original and final conditions. The pure error term is equal to the MSE term

from a one-way analysis on the same date. Only the pure error terms from the simulated data were included in the calculations of the denominator because they were smaller than the pure error terms for the observed data, resulting in a conservative test for the predictive capabilities of the UTCS-1s model. The pure error term for the observed data would reflect the large variability of the actual traffic conditions due to the different quitting times of various organizations. Hence, the observed pure error term would include the error about each eight-minute mean as well as about the vehicle population mean. This pure error would have over estimated the actual pure error.

The data was transformed using a log 10 transformation and the Bartlette test for homogeneity of variances was performed on the pure error terms of the two simulated conditions. The variances for the total stop delay and stop delay per vehicle were homogeneous. The variances for the stops per vehicle were not homogeneous. However, when only one apparent outlying variance was excluded from the analysis, the variances for the stops per vehicle were found to be homogeneous. It was concluded that all three MOE's had homogeneous variances.

The three-way analysis of variance was performed using the N-way analysis of variance routine from SPSS. Using the previously described pure error for the denominator, the level of significance for all three MOE's was found to be close to zero. The extremely small level of significance implies that the predictive capabilities of the UTCS-1s model are nonexistent for the conditions tested.

The F statistic was reversed, and the size of the denominator to accept the predictive capabilities of the UTCS-1s model was found for

a level of significance equal to 0.25. A pooled variance of six times the size used for the stops per vehicle would have been required to accept the predictive capabilities of the model. Similarly, variances 30 and 17 times the size of those used for the total stop delay and stop delay per vehicle would have been necessary to accept that the model was capable of predicting changes for these MOE's. Since the pooled variances required to accept the predictive capabilities of the UTCS-1s model are large multiples of the pooled variances used in the calculations, it cannot be argued that tests performed were excessively conservative.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

The major objective of this project was to validate the capabilities of the UTCS-1s model to reproduce actual measures of stops and delay on a linear network. The secondary objective was to apply the UTCS-1s model to determine the optimal signal-timing scheme on three linear networks in central Indiana.

It was expected that the primary objective would be a formality since three reports had previously concluded that the UTCS-1 or UTCS-1s models were capable of reproducing field MOE's. However, this project obtained results that were contrary to those previously obtained. It was found for the network that was studied that the UTCS-1s model could not reproduce four observed MOE's, nor could it predict the expected changes in those MOE's. A comprehensive review of the previous reports revealed apparent deficiencies in either the methodology or the statistical analyses that were used. Two conclusions were reached from the work done for this project.

1. The UTCS-1s model is not a valid simulation model for the conditions tested for this research.
2. The UTCS-1s model appears to have not been conclusively validated in previous work.

The secondary objective of using the UTCS-1s model to determine optimal signal timings on linear networks was abandoned since the

model was not shown conclusively to be an acceptable tool.

The results of the statistical analyses performed for this project yield one important inference. The "load factor" (utilization of an intersection) may affect the capabilities of the model to predict changes in MOE's. When the two-way analysis of variance was performed on the differences of the observed and simulated data for the original conditions (100 second cycle), the results showed that the differences were statistically the same. The results of the same test on the final data (80 second cycle) showed that the differences were not statistically the same. The major difference between the original and final conditions was the amount of excess green time on all of the links. The original cycle length had a substantial amount of excess green time; platooned and straggling vehicles could pass through the intersection with several seconds of green time remaining on the approach before the signal changed. During the final cycle length, only the platooned vehicles could proceed through an intersection; most straggling vehicles were stopped because of a phase change.

Two areas of further research should be pursued:

1. The exact conditions for which the UTCS-1s model can reproduce field occurrences should be identified.
2. The load factors at which the UTCS-1s model can be used for predictive capabilities should be identified.

The objective to find a model to either optimize signal timing schemes or show the change in various MOE's for different signal

schemes was not realized in this research. The UTCS-1s model could not reproduce the field data that was collected for the four MOE's. The Transyt program was found to have several deficiencies, but is continuously being improved and may one day be applicable to all conditions. The Federal Highway Administration is developing a program entitled "Sigop II". This program will combine the "hill climbing" routine of the Transyt program with the better portions of Sigop I. Sigop II will be able to handle multi-phase signals as well as allow the engineer to code into the program the exact turning percentages. It would appear that the availability of a signal optimization computer model is not too far in the future.

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APPENDICES

APPENDIX A

DISCUSSION OF COMPUTER MODELS

DESCRIPTION OF THE UTCS-1s MODEL

The UTCS-1s network simulation model is a microscopic model capable of continuously monitoring each vehicle as it passes over a street network. The program is comprised of three modules - the pre-processor, the simulator, and the post-processor. The pre-processor performs diagnostic tests on the input data, and prints out error messages for these tests. The simulator contains thirty routines which emit and monitor vehicles on the network, and gather performance data for each link as well as the entire network. The post-processor contains routines that perform statistical comparisons of two or more simulation runs.

To use the UTCS-1s model, the network is reduced to a series of links and nodes, and coded together with the other necessary input data (see Table A1). The input requirements and coding information are comprehensively discussed in the user's manual (23). The coded input data is checked by the pre-processor for format conformity, continuity of link geometry, and inclusion of all the necessary data. After the diagnostic errors are corrected, the input data is submitted into the simulator module where it is combined with the embedded data (see Table A2). The simulation module, which is controlled by the routine SIMUL, emits vehicles onto the network until equilibrium is attained. As each vehicle leaves a source

Table A1. Summary of Input Data for UTCS-1s

-
- NETWORK GEOMETRY BY LINK: LENGTH IN FEET, GRADE IN PERCENT, TURNING CAPACITY IN NUMBER OF VEHICLES.
 - OPERATION DATA BY LINK: NUMBER OF TRAVEL LANES, TARGET SPEED, QUEUE DISCHARGE RATE (HEADWAY IN TENTHS OF SECONDS), START-UP DELAY (USUALLY 3.7 SECONDS), PEDESTRIAN VOLUME (CODE FOR NONE TO HEAVY), LANE USE (CODE FOR LANE RESTRICTIONS SUCH AS LEFT TURN ONLY).
 - TURNING MOVEMENTS BY LINK: NUMBER OR PERCENT OF VEHICLES PROCEEDING STRAIGHT OR TURNING AT THE DOWNSTREAM END OF A LINK (THE USE OF NUMBERS OR PERCENTAGES MUST BE CONSISTENT ON A LINK, BUT CAN VARY BETWEEN LINKS).
 - SIGNAL CONTROLS BY NODE: SIGNAL OFFSET IN SECONDS, PHASE LENGTH IN SECONDS AND CONTROL FOR EACH APPROACH DURING EACH PHASE, NODES THAT ARE NOT INTERSECTIONS ARE CODED AS HAVING A CONTINUOUS GREEN PHASE.
 - FLOW RATES BY SOURCE LINK: PEAK HOUR VOLUME THAT IS EMITTED FROM EACH SOURCE NODE IN NUMBER OF VEHICLES.
-

Source: Reference (24).

Table A2. Summary of Embedded Data for UTCS-1s

-
- DISTRIBUTION OF LEADING AND LAGGING LEFT TURN PROBABILITIES.
 - DISTRIBUTION OF YELLOW PHASE RESPONSE.
 - DISTRIBUTION OF ACCEPTABLE GAPS FOR TRAFFIC DISCHARGING FROM A STOP SIGN.
 - DISTRIBUTION OF ACCEPTABLE GAPS FOR LEFT TURNING VEHICLES AT SIGNALIZED INTERSECTIONS.
 - VALUE OF ACCEPTABLE LAG FOR LANE SWITCHING.
 - INTERSECTION TURNING SPEED.
 - MAXIMUM NUMBER OF LINKS IN THE NETWORK.
 - MAXIMUM NUMBER OF NODES IN THE NETWORK.
 - MAXIMUM NUMBER OF ENTRY LINKS IN THE NETWORK.
 - MAXIMUM NUMBER OF VEHICLES ACCOMMODATED ON THE NETWORK AT ANY GIVEN INSTANT.
 - DISTRIBUTION OF SPILLBACK PROBABILITIES.
 - DISTRIBUTION OF PEDESTRIAN CONFLICT DELAYS, BY TYPE OF FLOW AND TYPE OF INTERACTION.
 - DISTRIBUTION OF INTRA-LINK TARGET SPEEDS.
 - DISTRIBUTION OF QUEUE DISCHARGE HEADWAYS.
 - DISTRIBUTION OF LOST-TIME FOR THE FIRST VEHICLE IN A QUEUE.
-

Source: Reference (25).

node, it is stochastically assigned vehicle and driver characteristics. During every one-second interval after achieving equilibrium, SIMUL performs six functions. First, all vehicles located in queues at the start of the interval are processed. Second, all other vehicles on the network and not in a queue are processed. Third, new vehicles are released onto the network through the entry links as per the specified flow rates for each entry link. Fourth, vehicles entering the network from internal sources are processed. Fifth, the traffic signals are updated. Sixth, the vehicle and link statistics are accumulated, and a set of diagnostic tests are performed. The six functions are repeated until the end of the subinterval is reached; SIMUL will then call for the accumulated link and network data to be printed (see Tables A3 and A3). The accumulated data could be stored on tapes and compared with other results by the post-processor. However, the post-processor module is not available at Purdue University. Permission from the computing center would have been required for each run of UTCS-1s with the post-processor module because the program would have exceeded the maximum size allowed by the computing center.

Table A3. Summary of Link Output Data from UTCS-1s

-
- LINK IDENTIFICATION.
 - VEHICLE MILES TRAVELED: TOTAL MILES TRAVELED ON THE LINK DURING THE SIMULATION INTERVAL.
 - VEHICLE TRIPS: TOTAL NUMBER OF VEHICLES DISCHARGED FROM THE LINK DURING THE SIMULATION INTERVAL.
 - MOVING TIME(IN VEHICLE MINUTES): ACCUMULATIVE VEHICLE MOVING TIME ON THE LINK DURING THE SIMULATION INTERVAL.
 - TOTAL DELAY(VEHICLE MINUTES): COMPUTED AS THE DIFFERENCE BETWEEN THE TOTAL TRAVEL TIME AND THE THEORETICAL TRAVEL TIME AT THE TARGET SPEED.
 - M/T RATIO: RATIO OF THE MOVING TIME AT THE TARGET SPEED TO THE ACTUAL TOTAL TRAVEL TIME.
 - TOTAL TIME(VEHICLE MINUTES): TOTAL TRAVEL TIME ON THE LINK DURING THE SIMULATION INTERVAL.
 - TRAVEL TIME/VEHICLE(SECONDS): THE AVERAGE TRAVEL TIME PER VEHICLE ON THE LINK DURING THE SIMULATION INTERVAL.
 - TOTAL DELAY/VEHICLE(SECONDS): THE AVERAGE TOTAL DELAY PER VEHICLE ON THE LINK DURING THE SIMULATION INTERVAL.
 - AVERAGE SPEED
 - AVERAGE OCCUPANCY: AVERAGE NUMBER OF VEHICLES ON THE LINK DURING THE SIMULATION INTERVAL.
-

Table A3, cont.

-
- STOPS/VEHICLE: THE PERCENTAGE OF VEHICLES STOPPING AT LEAST ONCE DURING THE SIMULATION INTERVAL.
 - AVERAGE SATURATION PERCENTAGE: THE AVERAGE OCCUPANCY OF THE LINK DIVIDED BY THE CAPACITY OF THE LINK.
 - CYCLE FAILURE: THE NUMBER OF TIMES A QUEUE FAILS TO CLEAR FROM THE LINK DURING THE SIMULATION INTERVAL.
 - STOP DELAY(VEHICLE MINUTES): ACCUMULATIVE TIME THAT ALL VEHICLES ARE DELAYED DUE TO THE RED SIGNAL PHASE DURING THE SIMULATION INTERVAL.
 - TOTAL QUEUE DELAY(VEHICLE MINUTES): THE TOTAL DELAY ON THE LINK DUE TO THE LEAD VEHICLES IN THE TRAVEL STREAM IMPEDING THE FOLLOWING VEHICLE(S) FROM ATTAINING THE TARGET SPEED.
 - QUEUE DELAY/VEHICLE(SECONDS): TOTAL QUEUE DELAY DIVIDED BY THE VEHICLE TRIPS ON THE LINK DURING THE SIMULATION INTERVAL.
-

Source: Reference (26).

Table A4. Summary of Network Output Data from UTCS-1s

-
- VEHICLE MILES
 - VEHICLE MINUTES
 - VEHICLE TRIPS
 - STOPS PER VEHICLE
 - M/T RATIO
 - AVERAGE SPEED
 - MEAN OCCUPANCY
 - DELAY/VEHICLE: THE TOTAL DELAY DIVIDED BY THE TOTAL NUMBER OF VEHICLE TRIPS.
 - TOTAL DELAY
 - DELAY/VEHICLE-MILE: THE TOTAL DELAY DIVIDED BY THE TOTAL VEHICLE MILES.
 - TRAVEL TIME/VEHICLE-MILE: TOTAL VEHICLE MINUTES DIVIDED BY THE TOTAL VEHICLE MILES.
 - STOP DELAY
 - STOP DELAY PER VEHICLE
 - QUEUE DELAY
 - QUEUE DELAY PER VEHICLE
-

Note: Definitions for the network output are the same as for the the link output except where noted.

Source: Reference (27).

TRANSYT-6

The TRANSYT-6 computer program is a traffic network study tool developed by the Road Research Laboratory in England. The program was developed to optimize the splits and offsets of the signals on a network for a given cycle length. The TRANSYT-6 program is macroscopic and deterministic. It calculates performance measures for all vehicles on the network at once; whereas, a microscopic program would calculate performance measures for each vehicle.

The TRANSYT-6 program makes four assumptions about the traffic flow on the network being analyzed:

1. All major junctions in the network have signals or are controlled by a priority rule.
2. All the intersections in the network have a common cycle length, or a cycle length of half this value.
3. Traffic entering the network does so at a constant specified rate on each approach.
4. The proportion of traffic turning left or right at each signal remain constant throughout the cycle.

The program divides the cycle length into n increments (n is specified in the input data) and develops traffic flow histograms based on #3 above for each entry link (see Figure A1). During every cycle length the platoons are moved along each link toward the next signal. Dispersion of the vehicles within the platoon is accounted

Figure A1. Traffic Flow Histogram

(Source: Reference 28)

for by applying an exponential function which is dependent on the time required to traverse the link. A traffic flow histogram is developed for each downstream intersection based on the arrival of the vehicles released from the upstream intersection and the splits and offsets of the signal at the downstream intersection. The performance measures are calculated for each intersection from the histogram that has been developed.

The splits and offsets for each intersection are optimized by the "hill climbing" process. After the performance measures for the original signal setting have been found, the program alters the offsets of the signals by a predetermined number of increments, and recalculates the performance measures. This process is repeated until the performance measures are optimized. The incremental adjustment is changed and the optimization process is repeated. Several incremental adjustments are used in order to obtain the true signal optimization. The program also optimizes the splits at each signal.

The output from the program includes a performance index, various delay measures, and the optimum signal splits and offsets at each intersection for the given cycle length. An optional output is a set of traffic flow histograms for every approach for the optimum conditions.

Input for the TRANSYT-6 program is extremely complicated and the documentation in the User's Manual is confusing. Input includes program control information, a listing of the nodes, a listing of the links (in the order in which they are to be analyzed), the "hill

climbing" increment sequence, the initial signal settings (may be set to zero and allow the program to calculate the initial timings) and minimum required green on each approach (must be given), and vehicular flows (average vehicles per hour) along each link.

Although the TRANSYT-6 program is the best signal optimization program presently available, there are several deficiencies in its use. First, the documentation and coding for the input are extremely complicated, particularly when listing the links in the order in which they are to be solved. Second, the program can be applied to signals that have only two phases, thus eliminating optimization of signals with left or right-turn phases. Third, the percentage of turning vehicles from the major street are assumed by the program.

Delay Difference

The delay/difference-of-offset computer program is a macroscopic program developed to assist in determining the best offset between successive traffic signals. The key word in the preceding statement is "assist". The delay/difference-of-offset program cannot optimize the signal offsets for a network; rather, its function is to show relative queue sizes and delay time for all offset possibilities. The traffic engineer uses the program printout in conjunction with other factors (i.e. maximizing band widths in one or both directions) to determine the most desirous offset.

The use of the delay/difference-of-offset program is uncomplicated. Coding for the input data and description of the output is discussed in NCHRP Report 124. Input data includes the link number, the cycle length, the green phase length for the upstream and downstream

signals, the yellow phase length, lane saturation factor (0.472 for an average headway of 2.1 seconds), link length, number of lanes, traffic volumes, average speed, and the opposing link. Three measures of effectiveness are calculated and printed for all offsets which vary from zero to $C-1$ (C = cycle length) by one-second increments. The three MOE's are QSUM , the total delay-in-queue during one signal cycle (in vehicle-seconds); DPV , the average delay per vehicle (in vehicle-seconds per vehicle); and QAVE , the average queue length (in vehicles).

When using the delay/difference-of-offset program several factors must be considered. First, because of the macroscopic nature of the program, no significant platoon dispersion can be accounted for. This factor is not critical on short links, but could result in errors in the MOE's on longer links. Second, the deterministic properties mean that the vehicles not in a queue will arrive at a given intersection uniformly over a time period. Third, turning movements at the downstream intersection and the delay associated with the turns are ignored.

Calculations for the three MOE's are done for all possible offsets. The queue size at the downstream intersection is found from the equation $Q_t = Q_{t-1} + QCR$; where Q_t = the queue size at time equal to t seconds, Q_{t-1} = the queue size for time equal to $t-1$, QCR = the queue change rate. During the downstream red phase, the QCR will equal a combination of the arriving straight through flow and the flow turning onto the link. During the downstream green phase, the QCR will equal the approaching flows minus the average discharge rate. The delay-in-queue is calculated by summing the queue size

for each one-second increment over a one-cycle period. The delay per vehicle is found by the equation $d = \frac{c(1-\lambda)^2}{2(1-\lambda x)} + \frac{x^2}{2q(1-x)}$ where c = the cycle length, λ = the effective green/cycle, and $x = q/\lambda$.

APPENDIX B

CALCULATIONS FOR THE ORIGINAL

SIGNAL TIMINGS

Table B1. Chi-squared Test Comparing Simulated and Observed Volumes of Vehicle Trips

$$H_0: V_{sim} = V_{obs} \quad H_1: V_{sim} \neq V_{obs} \quad n = 30$$

$$\alpha = .25 \quad \chi^2_{29, .25} = 33.93$$

$$\chi^2 = \sum_{i=1}^n \frac{(V_{sim} - V_{obs})^2}{V_{obs}}$$

$$\begin{aligned} \chi^2 = & \frac{(215.90-247.80)^2}{247.80} + \frac{(100.90-88.20)^2}{88.20} + \frac{(26.00-27.20)^2}{27.20} + \\ & \frac{(42.50-45.50)^2}{45.50} + \frac{(211.80-246.30)^2}{246.30} + \frac{(114.80-110.10)^2}{110.10} + \\ & \frac{(17.70-19.80)^2}{19.80} + \frac{(28.80-35.10)^2}{35.10} + \frac{(226.40-233.90)^2}{233.90} + \\ & \frac{(129.10-129.60)^2}{129.60} + \frac{(49.70-61.90)^2}{61.90} + \frac{(64.10-74.10)^2}{74.10} + \\ & \frac{(88.20-100.20)^2}{100.20} + \frac{(40.40-43.90)^2}{43.90} + \frac{(179.70-190.30)^2}{190.30} + \\ & \frac{(84.70-94.40)^2}{94.40} + \frac{(26.60-29.40)^2}{29.40} + \frac{(18.90-17.90)^2}{17.90} + \\ & \frac{(183.40-192.50)^2}{192.50} + \frac{(90.20-93.40)^2}{93.40} + \frac{(16.60-19.50)^2}{19.50} + \\ & \frac{(22.60-29.10)^2}{29.10} + \frac{(191.70-215.70)^2}{215.70} + \frac{(107.20-112.40)^2}{112.40} + \\ & \frac{(49.50-56.70)^2}{56.70} + \frac{(65.20-65.60)^2}{65.60} + \frac{(209.10-208.80)^2}{208.80} + \\ & \frac{(125.50-132.10)^2}{132.10} + \frac{(65.00-69.50)^2}{69.50} + \frac{(21.70-31.20)^2}{31.20} = \\ & 29.84 \end{aligned}$$

$$29.84 < 33.93$$

DO NOT REJECT H_0

Table B2. Statistical Test for Homogeneity of Variance by Link - Stops per Vehicle

$$H_0: \sigma_{\text{sim}}^2 = \sigma_{\text{obs}}^2 \quad H_1: \sigma_{\text{sim}}^2 \neq \sigma_{\text{obs}}^2 \quad \alpha = .05 \text{ (Two sided)}$$

$$F_{(.05/2, 9, 9)} = 4.03 \quad F = \frac{S_M^2}{S_m^2}$$

<u>Link</u>	<u>F Statistic</u>	<u>Link</u>	<u>F Statistic</u>
9-1	$F = \frac{.096^2}{.032^2} = 9.0^*$	4-3	$F = \frac{.081^2}{.050^2} = 2.62$
2-1	$F = \frac{.099^2}{.066^2} = 2.25$	14-3	$F = \frac{.091^2}{.072^2} = 1.60$
10-1	$F = \frac{.108^2}{.076^2} = 2.02$	15-3	$F = \frac{.202^2}{.054^2} = 13.99^*$
11-1	$F = \frac{.119^2}{.072^2} = 2.73$	3-4	F
1-2	$F = \frac{.052^2}{.042^2} = 1.53$	5-4	$F = \frac{.104^2}{.054^2} = 3.71$
3-2	$F = \frac{.068^2}{.047^2} = 2.09$	16-4	$F = \frac{.082^2}{.077^2} = 1.13$
12-2	$F = \frac{.233^2}{.109^2} = 4.57^*$	4-5	$F = \frac{.053^2}{.026^2} = 4.16^*$
13-2	$F = \frac{.199^2}{.146^2} = 1.86$	6-5	$F = \frac{.159^2}{.049^2} = 10.53^*$
2-3	$F = \frac{.064^2}{.050^2} = 1.64$	17-5	$F = \frac{.073^2}{.064^2} = 1.30$

Table B2, cont.

<u>Link</u>	<u>F Statistic</u>	<u>Link</u>	<u>F Statistic</u>
18-5	$F = \frac{.129^2}{.096^2} = 1.81$	21-7	$F = \frac{.116^2}{.070^2} = 2.75$
5-6	$F = \frac{.066^2}{.038^2} = 3.02$	22-7	$F = \frac{.142^2}{.119^2} = 1.42$
7-6	$F = \frac{.070^2}{.055^2} = 1.62$	7-8	$F = \frac{.074^2}{.046^2} = 2.59$
19-6	$F = \frac{.096^2}{.047^2} = 4.17^*$	25-8	$F = \frac{.071^2}{.056^2} = 1.61$
20-6	$F = \frac{.184^2}{.108^2} = 2.90$	23-8	$F = \frac{.097^2}{.061^2} = 2.53$
6-7	$F = \frac{.074^2}{.039^2} = 3.60$	24-8	$F = \frac{.090^2}{.070^2} = 1.65$
8-7	$F = \frac{.075^2}{.058^2} = 1.67$		

*Reject H_0 .

Note: Spaces are left for the links on which mistakes were made when collecting the field data.

Table B3. Statistical Test for Homogeneity of Variance by Link - Total Stop Delay

$H_0: \sigma_{sim}^2 = \sigma_{obs}^2$		$H_1: \sigma_{sim}^2 \neq \sigma_{obs}^2$		$\alpha = .05$ (Two sided)	
$F_{(.05/2, 9, 9)} = 4.03$		$F^* = \frac{S_M^2}{S_m^2}$			
Link	F Statistic	Link	F Statistic		
9-1	$F = \frac{28.88^2}{3.63^2} = 63.30^*$	4-3	$F = \frac{8.88^2}{3.92^2} = 5.13^*$		
2-1	$F = \frac{3.71^2}{2.90^2} = 1.64$	14-3	$F = \frac{6.87^2}{4.65^2} = 2.18$		
10-1	$F = \frac{2.42^2}{2.08^2} = 1.35$	15-3	$F = \frac{11.08^2}{3.12^2} = 12.61^*$		
11-1	$F = \frac{4.59^2}{3.21^2} = 2.04$	3-4	$F =$		
1-2	$F = \frac{5.43^2}{4.45^2} = 1.49$	5-4	$F = \frac{5.24^2}{4.02^2} = 1.70$		
3-2	$F = \frac{5.07^2}{1.64^2} = 9.56^*$	16-4	$F = \frac{1.53^2}{1.33^2} = 1.32$		
12-2	$F = \frac{2.61^2}{1.34^2} = 3.79$	4-5	$F = \frac{2.38^2}{1.66^2} = 2.06$		
13-2	$F = \frac{8.01^2}{1.94^2} = 17.05^*$	6-5	$F = \frac{2.80^2}{2.73^2} = 1.05$		
2-3	$F = \frac{6.73^2}{3.14^2} = 4.59^*$	17-5	$F = \frac{3.06^2}{2.48^2} = 1.52$		

Table B3, cont.

<u>Link</u>	<u>F Statistic</u>	<u>Link</u>	<u>F Statistic</u>
18-5	$F = \frac{4.66^2}{1.69^2} = 7.60^*$	21-7	$F = \frac{4.42^2}{3.75^2} = 1.39$
5-6	$F = \frac{2.75^2}{2.08^2} = 1.75$	22-7	$F = \frac{7.39^2}{3.14^2} = 5.54^*$
7-6	$F = \frac{4.32^2}{.93^2} = 21.58^*$	7-8	$F = \frac{9.93^2}{5.81^2} = 2.92$
19-6	$F = \frac{2.55^2}{1.83^2} = 1.94$	25-8	$F = \frac{5.72^2}{3.26^2} = 3.08$
20-6	$F = \frac{6.24^2}{3.03^2} = 4.24^*$	23-8	$F =$
6-7	$F = \frac{4.79^2}{2.92^2} = 2.69$	24-8	$F = \frac{6.65^2}{3.13^2} = 4.51^*$
8-7	$F = \frac{6.95^2}{4.12^2} = 1.69$		

*Reject H_0 .

Note: Spaces are left for the links on which mistakes were made when collecting the field data.

Table B4. Statistical Test for Homogeneity of Variance by Link - Stop Delay per Vehicle

$$H_0: \sigma_{\text{sim}}^2 = \sigma_{\text{obs}}^2 \quad H_1: \sigma_{\text{sim}}^2 \neq \sigma_{\text{obs}}^2 \quad \alpha = .05 \text{ (Two-sided)}$$

$$F_{(.05/2, 9, 9)} = 4.03 \quad F = \frac{S_M^2}{S_m^2}$$

<u>Link</u>	<u>F Statistic</u>	<u>Link</u>	<u>F Statistic</u>
9-1	$F = \frac{4.30^2}{.77^2} = 31.19^*$	4-3	$F = \frac{3.88^2}{1.74^2} = 4.97^*$
2-1	$F = \frac{2.52^2}{1.56^2} = 2.61$	14-3	$F = \frac{5.26^2}{4.88^2} = 1.16$
10-1	$F = \frac{4.47^2}{3.61^2} = 1.53$	15-3	$F = \frac{10.37^2}{2.52^2} = 16.93^*$
11-1	$F = \frac{4.09^2}{2.94^2} = 1.94$	3-4	$F =$
1-2	$F = \frac{1.25^2}{1.24^2} = 1.02$	5-4	$F = \frac{3.14^2}{2.99^2} = 1.10$
3-2	$F = \frac{2.24^2}{.90^2} = 6.19^*$	16-4	$F = \frac{2.50^2}{2.50^2} = 1.00$
12-2	$F = \frac{9.29^2}{7.30^2} = 1.62$	4-5	$F = \frac{.67^2}{.45^2} = 2.22$
13-2	$F = \frac{10.25^2}{7.05^2} = 2.11$	6-5	$F = \frac{1.91^2}{1.91^2} = 1.00$
2-3	$F = \frac{1.19^2}{.84^2} = 1.42$	17-5	$F = \frac{5.28^2}{2.69^2} = 3.85$

Table B4, cont.

<u>Link</u>	<u>F Statistic</u>	<u>Link</u>	<u>F Statistic</u>
18-5	$F = \frac{7.88^2}{3.79^2} = 4.32^*$	21-7	$F = \frac{4.62^2}{2.93^2} = 2.49$
5-6	$F = \frac{.77^2}{.74^2} = 1.08$	22-7	$F = \frac{7.15^2}{4.14^2} = 2.98$
7-6	$F = \frac{2.25^2}{.59^2} = 14.54^*$	7-8	$F = \frac{1.94^2}{1.36^2} = 2.03$
19-6	$F = \frac{3.96^2}{3.61^2} = 1.20$	25-8	$F = \frac{2.39^2}{1.50^2} = 2.54$
20-6	$F = \frac{7.50^2}{6.72^2} = 1.25$	23-8	$F =$
6-7	$F = \frac{.94^2}{.85^2} = 1.22$	24-8	$F = \frac{6.46^2}{6.31^2} = 1.05$
8-7	$F = \frac{2.79^2}{2.68^2} = 1.08$		

*Reject H_0 .

Note: Spaces are left for the links on which mistakes were made when collecting the field data.

Table B5. Hypotheses and General Equation for Student t-test

$$H_0: \bar{X}_{\text{sim}} - \bar{X}_{\text{obs}} = 0$$

$$H_1: \bar{X}_{\text{sim}} - \bar{X}_{\text{obs}} \neq 0$$

$$\alpha = .20$$

$$t_{(.20/2, 9)} = 1.383$$

$$t = \frac{\bar{X}_{\text{sim}} - \bar{X}_{\text{obs}}}{\sqrt{(n_{\text{sim}} - 1)S_{\text{sim}}^2 + (n_{\text{obs}} - 1)S_{\text{obs}}^2}} \quad \sqrt{\frac{n_{\text{sim}} n_{\text{obs}} (n_{\text{sim}} + n_{\text{obs}} - 2)}{n_{\text{sim}} + n_{\text{obs}}}}$$

$$\sqrt{\frac{n_{\text{sim}} n_{\text{obs}} (n_{\text{sim}} + n_{\text{obs}} - 2)}{n_{\text{sim}} + n_{\text{obs}}}} = \sqrt{\frac{10 \cdot 10 \cdot 18}{10 + 10}} = 9.487$$

Table B6. Student t-test Comparing Simulated and Observed Data - Stops per Vehicle

Link

9-1

2-1

$$t = \frac{.665 - .731}{\sqrt{9(.099)^2 + 9(.066)^2}} \cdot 9.487 = 1.75^*$$

10-1

$$t = \frac{.795 - .770}{\sqrt{9(.108)^2 + 9(.076)^2}} \cdot 9.487 = 0.60$$

11-1

$$t = \frac{.852 - .804}{\sqrt{9(.119)^2 + 9(.072)^2}} \cdot 9.487 = 0.91$$

1-2

$$t = \frac{.242 - .381}{\sqrt{9(.052)^2 + 9(.042)^2}} \cdot 9.487 = 6.58^*$$

3-2

$$t = \frac{.256 - .319}{\sqrt{9(.047)^2 + 9(.068)^2}} \cdot 9.487 = 2.41^*$$

12-2

13-2

$$t = \frac{.889 - .875}{\sqrt{9(.199)^2 + 9(.146)^2}} \cdot 9.487 = 0.18$$

Table B6, cont.

Link2-3

$$t = \frac{.409 - .561}{\sqrt{9(.050)^2 + 9(.064)^2}} \cdot 9.487 = 5.92^*$$

4-3

$$t = \frac{.441 - .675}{\sqrt{9(.050)^2 + 9(.081)^2}} \cdot 9.487 = 7.77^*$$

14-3

$$t = \frac{.858 - .882}{\sqrt{9(.091)^2 + 9(.072)^2}} \cdot 9.487 = 0.65$$

15-35-4

$$t = \frac{.615 - .532}{\sqrt{9(.104)^2 + 9(.054)^2}} \cdot 9.487 = 2.24^*$$

16-4

$$t = \frac{.609 - .386}{\sqrt{9(.077)^2 + 9(.082)^2}} \cdot 9.487 = 6.27^*$$

4-56-517-5

$$t = \frac{.753 - .874}{\sqrt{9(.073)^2 + 9(.064)^2}} \cdot 9.487 = 3.94^*$$

Table B6, cont.

Link18-5

$$t = \frac{.750 - .846}{\sqrt{9(.129)^2 + 9(.096)^2}} \cdot 9.487 = 1.89^*$$

5-6

$$t = \frac{.238 - .140}{\sqrt{9(.066)^2 + 9(.038)^2}} \cdot 9.487 = 4.07^*$$

7-6

$$t = \frac{.206 - .510}{\sqrt{9(.055)^2 + 9(.070)^2}} \cdot 9.487 = 10.80^*$$

19-6

$$t = \frac{.833 - .837}{\sqrt{9(.047)^2 + 9(.096)^2}} \cdot 9.487 = 0.12$$

20-6

$$t = \frac{.867 - .817}{\sqrt{9(.184)^2 + 9(.108)^2}} \cdot 9.487 = 0.74$$

6-7

$$t = \frac{.223 - .282}{\sqrt{9(.039)^2 + 9(.074)^2}} \cdot 9.487 = 2.23^*$$

8-7

$$t = \frac{.596 - .636}{\sqrt{9(.075)^2 + 9(.058)^2}} \cdot 9.487 = 1.33$$

Table B6, cont.

Link21-7

$$t = \frac{.803 - .821}{\sqrt{9(.116)^2 + 9(.070)^2}} \cdot 9.487 = 0.42$$

22-7

$$t = \frac{.777 - .925}{\sqrt{9(.119)^2 + 9(.142)^2}} \cdot 9.487 = 2.53^*$$

7-8

$$t = \frac{.486 - .431}{\sqrt{9(.046)^2 + 9(.074)^2}} \cdot 9.487 = 2.00^*$$

25-8

$$t = \frac{.671 - .680}{\sqrt{9(.056)^2 + 9(.071)^2}} \cdot 9.487 = 0.31$$

24-8

$$t = \frac{.897 - .952}{\sqrt{9(.070)^2 + 9(.090)^2}} \cdot 9.487 = 1.53^*$$

*Reject H_0 .

Note: Spaces are left for those links that have variances which are not homogeneous.

Table B7. Student t-test Comparing Simulated and Observed Data - Total Stop Delay

Link

9-1

2-1

$$t = \frac{20.81 - 20.10}{\sqrt{9(2.90)^2 + 9(3.71)^2}} \cdot 9.487 = 0.48$$

10-1

$$t = \frac{10.13 - 10.60}{\sqrt{9(2.08)^2 + 9(2.42)^2}} \cdot 9.487 = 0.47$$

11-1

$$t = \frac{19.91 - 19.60}{\sqrt{9(4.59)^2 + 9(3.21)^2}} \cdot 9.487 = 0.18$$

1-2

$$t = \frac{19.12 - 24.88}{\sqrt{9(4.45)^2 + 9(5.43)^2}} \cdot 9.487 = 2.59^*$$

3-2

12-2

$$t = \frac{8.81 - 10.78}{\sqrt{9(1.34)^2 + 9(2.61)^2}} \cdot 9.487 = 2.12^*$$

13-2

2-3

$$t = \frac{16.79 - 31.85}{\sqrt{9(3.14)^2 + 9(6.73)^2}} \cdot 9.487 = 6.41^*$$

Table B7, cont.

Link4-3

$$t = \frac{15.89 - 19.88}{\sqrt{9(3.92)^2 + 9(8.88)^2}} \cdot 9.487 = 1.30$$

14-3

$$t = \frac{25.55 - 32.08}{\sqrt{9(4.65)^2 + 9(6.87)^2}} \cdot 9.487 = 2.49^*$$

15-35-4

$$t = \frac{18.13 - 56.60}{\sqrt{9(4.02)^2 + 9(5.24)^2}} \cdot 9.487 = 13.63^*$$

16-4

$$t = \frac{8.32 - 6.33}{\sqrt{9(1.53)^2 + 9(1.33)^2}} \cdot 9.487 = 3.10^*$$

4-5

$$t = \frac{6.56 - 5.93}{\sqrt{9(1.66)^2 + 9(2.38)^2}} \cdot 9.487 = 0.69$$

6-5

$$t = \frac{9.76 - 9.53}{\sqrt{9(2.73)^2 + 9(2.80)^2}} \cdot 9.487 = 0.19$$

17-5

$$t = \frac{10.66 - 11.63}{\sqrt{9(2.48)^2 + 9(3.06)^2}} \cdot 9.487 = 0.78$$

18-5

Table B7, cont.

Link5-6

$$t = \frac{5.87 - 6.10}{\sqrt{9(2.08)^2 + 9(2.75)^2}} \cdot 9.487 = 0.21$$

7-619-6

$$t = \frac{7.73 - 14.80}{\sqrt{9(1.83)^2 + 9(2.55)^2}} \cdot 9.487 = 7.12^*$$

20-6

$$t = \frac{11.99 - 12.98}{\sqrt{9(3.03)^2 + 9(6.24)^2}} \cdot 9.487 = 0.45$$

6-7

$$t = \frac{11.60 - 19.98}{\sqrt{9(2.92)^2 + 9(4.79)^2}} \cdot 9.487 = 4.72^*$$

8-7

$$t = \frac{31.29 - 37.25}{\sqrt{9(4.12)^2 + 9(6.95)^2}} \cdot 9.487 = 2.33^*$$

21-7

$$t = \frac{21.01 - 23.53}{\sqrt{9(3.75)^2 + 9(4.42)^2}} \cdot 9.487 = 1.37$$

22-77-8

$$t = \frac{44.89 - 38.90}{\sqrt{9(5.81)^2 + 9(9.93)^2}} \cdot 9.487 = 1.65^*$$

Table B7, cont.

Link
25-8

$$t = \frac{32.29 - 44.15}{\sqrt{9(3.26)^2 + 9(5.72)^2}} \cdot 9.487 = 5.70^*$$

24-8

$$t = \frac{13.02 - 21.78}{\sqrt{9(3.13)^2 + 9(6.65)^2}} \cdot 9.487 = 3.77^*$$

*Reject H_0 .

Note: Spaces are left for those links that have variances which are not homogeneous.

Table B8. Student t-test Comparing Simulated and Observed Data -
Stop Delay per Vehicle

Link

9-1

2-1

$$t = \frac{12.37 - 13.74}{\sqrt{9(1.56)^2 + 9(2.52)^2}} \cdot 9.487 = 1.46^*$$

10-1

$$t = \frac{23.32 - 24.14}{\sqrt{9(3.61)^2 + 9(4.47)^2}} \cdot 9.487 = 0.45$$

11-1

$$t = \frac{27.93 - 26.02}{\sqrt{9(2.94)^2 + 9(4.09)^2}} \cdot 9.487 = 1.20$$

1-2

$$t = \frac{5.42 - 6.07}{\sqrt{9(1.24)^2 + 9(1.25)^2}} \cdot 9.487 = 1.17$$

3-2

12-2

$$t = \frac{31.24 - 32.87}{\sqrt{9(9.29)^2 + 9(7.30)^2}} \cdot 9.487 = 0.44$$

13-2

$$t = \frac{31.59 - 37.07}{\sqrt{9(7.05)^2 + 9(10.25)^2}} \cdot 9.487 = 1.393^*$$

Table B8, cont.

Link2-3

$$t = \frac{4.46 - 8.17}{\sqrt{9(0.84)^2 + 9(1.19)^2}} \cdot 9.487 = 8.05^*$$

4-3

$$t = \frac{7.39 - 8.94}{\sqrt{9(1.74)^2 + 9(3.88)^2}} \cdot 9.487 = 1.15$$

14-3

$$t = \frac{30.90 - 31.11}{\sqrt{9(5.26)^2 + 9(4.88)^2}} \cdot 9.487 = 0.09$$

15-35-4

$$t = \frac{12.45 - 17.01}{\sqrt{9(2.99)^2 + 9(3.14)^2}} \cdot 9.487 = 3.33^*$$

16-4

$$t = \frac{12.41 - 8.83}{\sqrt{9(2.50)^2 + 9(2.50)^2}} \cdot 9.487 = 3.20^*$$

4-5

$$t = \frac{2.16 - 1.86}{\sqrt{9(.45)^2 + 9(.67)^2}} \cdot 9.487 = 1.18$$

Table B8, cont.

Link6-5

$$t = \frac{6.94 - 6.10}{\sqrt{9(1.91)^2 + 9(1.91)^2}} \cdot 9.487 = 0.98$$

17-5

$$t = \frac{24.00 - 23.54}{\sqrt{9(5.28)^2 + 9(2.69)^2}} \cdot 9.487 = 0.25$$

18-5

$$t = \frac{26.87 - 33.34}{\sqrt{9(3.79)^2 + 9(7.88)^2}} \cdot 9.487 = 2.34^*$$

5-6

$$t = \frac{1.92 - 1.89}{\sqrt{9(.74)^2 + 9(.77)^2}} \cdot 9.487 = 0.09$$

7-619-6

$$t = \frac{27.77 - 22.90}{\sqrt{9(3.61)^2 + 9(3.96)^2}} \cdot 9.487 = 2.87^*$$

20-6

$$t = \frac{32.21 - 25.95}{\sqrt{9(7.50)^2 + 9(6.72)^2}} \cdot 9.487 = 1.97^*$$

Table B8, cont.

Link6-7

$$t = \frac{3.64 - 5.51}{\sqrt{9(.85)^2 + 9(.94)^2}} \cdot 9.487 = 4.67^*$$

8-7

$$t = \frac{17.59 - 19.87}{\sqrt{9(2.68)^2 + 9(2.79)^2}} \cdot 9.487 = 1.86^*$$

21-7

$$t = \frac{25.63 - 24.79}{\sqrt{9(4.62)^2 + 9(2.93)^2}} \cdot 9.487 = 0.49$$

22-7

$$t = \frac{22.30 - 25.83}{\sqrt{9(4.14)^2 + 9(7.15)^2}} \cdot 9.487 = 1.35$$

7-8

$$t = \frac{12.91 - 11.09}{\sqrt{9(1.36)^2 + 9(1.94)^2}} \cdot 9.487 = 2.43^*$$

25-8

$$t = \frac{15.46 - 20.12}{\sqrt{9(1.50)^2 + 9(2.39)^2}} \cdot 9.487 = 5.22^*$$

Table B8, cont.

Link24-8

$$t = \frac{35.78 - 41.64}{\sqrt{9(6.46)^2 + 9(6.31)^2}} \cdot 9.487 = 2.05^*$$

*Reject H_0 .

Note: Spaces are left for those links that have variances which are not homogeneous.

Table B9. Bartlett Test for Homogeneity of Variances - Stops per Vehicle - Raw Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\bar{S}^2 = .001786$$

$$\text{Log } \bar{S}^2 = -2.748216$$

$$\Sigma \text{Log } S^2 = -68.938994$$

$$M = 2.3026(9) [24(-2.748216) - (-68.938994)] = 61.793$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{M}{C} = 59.50$$

$$\chi^2_{(23, .001)} = 49.73$$

REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table B10. Bartlett Test for Homogeneity of Variances - Total Stop Delay - Raw Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\bar{S}^2 = 7.3494579$$

$$\text{Log } \bar{S}^2 = .866255$$

$$\Sigma \text{Log } S^2 = 12.747693$$

$$M = 2.3026(9) [24(.866255) - 12.747693] = 166.67$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{M}{C} = 160.476$$

$$\chi^2_{(23, .001)} = 49.73$$

REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table B11. Bartlett Test for Homogeneity of Variances - Stop Delay per Vehicle - Raw Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\bar{S}^2 = 3.941955$$

$$\text{Log } \bar{S}^2 = .595712$$

$$\Sigma \text{Log } S^2 = 5.142367$$

$$M = 2.3026(9) [24(.595712) - 5.142367] = 189.717$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{M}{C} = 182.67$$

$$\chi^2_{(23, .001)} = 49.73$$

REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table B12. Bartlett Test for Homogeneity of Variances - Stops per Vehicle - Square Root Transformation of Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\bar{S}^2 = .0007205$$

$$\text{Log } \bar{S}^2 = -3.1424$$

$$\Sigma \text{Log } S^2 = -77.050149$$

$$M = 2.3026(9) [24(-3.1424) - (-77.050149)] = 33.849$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{33.849}{1.0386} = 32.59$$

$$\chi^2_{(23, .001)} = 49.73$$

DO NOT REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table B13. Bartlett Test for Homogeneity of Variances - Total Stop Delay-Log10 Transformation of Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \sum \text{Log } S^2]$$

$$C = 1 + \frac{n+1}{1(v)(n)}$$

$$\bar{S}^2 = .00274202$$

$$\text{Log } \bar{S}^2 = -2.5619$$

$$\sum \text{Log } S^2 = -62.675$$

$$M = 2.3026(9) [24(-2.5619) - (-62.675)] = 24.63$$

$$C = 1 + \frac{24+1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{24.63}{1.0386} = 23.72$$

$$\chi^2_{(23, .001)} = 49.73$$

DO NOT REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\sum \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table B14. Bartlett Test for Homogeneity of Variances - Stop Delay
per Vehicle- Log10 Transformation of Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\bar{S}^2 = .001898312$$

$$\text{Log } \bar{S}^2 = -2.7216$$

$$\Sigma \text{Log } S^2 = -66.862$$

$$M = 2.3026(9) [24(-2.7216) - (-66.862)] = 31.97$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{31.97}{1.0386} = 30.78$$

$$\chi^2_{(23, .001)} = 49.73$$

DO NOT REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table B15. Matrix of Data for Two-way Analysis of Variance - Stops per Vehicle - Log10 Transformation of Data

DIRECTION OF TRAVEL	INTERSECTION NUMBER						
	1	2	3	5	6	7	
S-Bd	.0082	.1266	.1094	-.0141	-.1122	.0564	$Y_{1.} = .1743$
N-Bd	.0406	.0581	.1571	.0436	.2622	.0257	$Y_{2.} = .5873$
E-Bd	-.0132	.0067	.0136	.0674	.0012	.0111	$Y_{3.} = .0868$
W-Bd	-.0250	-.0059	.0422	.0551	.0246	.0796	$Y_{4.} = .1706$
	$Y_{.1} = .0106$	$Y_{.2} = .1855$	$Y_{.3} = .3223$	$Y_{.5} = .1520$	$Y_{.6} = .1758$	$Y_{.7} = .1728$	$Y_{...} = 1.019$

$\bar{X}_{obs} - \bar{X}_{sim}$ in each cell

DIRECTION OF TRAVEL

Table B16. Two-way Analysis of Variance - Stops per Vehicle

<u>Source</u>	<u>SS</u>	<u>d.f.</u>	<u>MS</u>	<u>F</u>
Approach (A)	.02539	5	.00508	1.41
Intersection (B)	.0123	3	.0041	1.139
Inter x App (AB)	.08158	15	.0054	1.51
Pure Error			.0036	

$$SSA = \sum \frac{y_{.i}^2}{nb} - \frac{y_{...}^2}{nab} = \frac{(.1743)^2 + (.5873)^2 + (.0868)^2 + (.1706)^2}{1(6)} - \frac{(1.019)^2}{(1)(4)(6)} \\ = 0.2539$$

$$SSB = \frac{\sum y_{.i.}^2}{na} - \frac{y_{...}^2}{nab} = \frac{(.0106)^2 + (.1855)^2 + (.3223)^2 + (.1520)^2 + (.1758)^2 + (.1728)^2}{(1)(4)} \\ - \frac{(1.019)^2}{(1)(4)(6)} = .0123$$

$$SSTO = \sum_i \sum_j \sum_k y_{ijk}^2 - \frac{y_{...}^2}{nab} = .1192699$$

$$SSAB + SSTO - SSE - SSA - SSB = .08158$$

$$SSA \quad P > .10$$

$$SSB \quad P > .10$$

$$SSAB \quad P = .10$$

Table B17. Matrix of Data for Two-way Analysis of Variance - Total Stop Delay - Log10 Transformation of Data

		INTERSECTION NUMBER							
		1	2	3	5	6	7		
DIRECTION OF TRAVEL	S-Bd	.0916	.1130	.2756	-.0644	.0004	.2361	$Y_{1..} = .6523$	
	N-Bd	-.0227	.0645	.0752	-.0149	.4718	.0600	$Y_{2..} = .6339$	
	E-Bd	.0189	.0807	.0964	.0350	-.0411	.0471	$Y_{3..} = .2370$	
	W-Bd	-.0025	.1541	.0395	.0557	.0090	.0534	$Y_{4..} = .3092$	
		$Y_{1.} = .0853$	$Y_{2.} = .4123$	$Y_{3.} = .4867$	$Y_{5.} = .0114$	$Y_{6.} = .4401$	$Y_{7.} = .3966$	$Y_{...} = 1.8324$	

Table B18. Two-way Analysis of Variance - Total Stop Delay

<u>Source</u>	<u>SS</u>	<u>d.f.</u>	<u>MS</u>	<u>F</u>
Approach (A)	.0232793	5	.0046558	.3398
Intersection (B)	.0514096	3	.0171365	1.25
Inter x App (AB)	.2318038	15	.0154535	1.128
Pure Error			.0137	

$$SSA = \sum \frac{y_{i.}^2}{nb} - \frac{y_{...}^2}{nab} = \frac{(.6523)^2 + (.6339)^2 + (.2370)^2 + (.3092)^2}{(1)(6)} - \frac{1.8324^2}{(1)(4)(6)}$$

$$SSA = .0232793$$

$$SSB = \sum \frac{y_{.j}^2}{na} - \frac{y_{...}^2}{nab} = \frac{(.0853)^2 + (.4123)^2 + (.4867)^2 + (.0114)^2 + (.4401)^2 + (.3966)^2}{(1)(4)} - \frac{(1.8324)^2}{(1)(4)(6)} = .0514096$$

$$SSTO = \sum_i \sum_j \sum_k y_{ijk}^2 - \frac{y_{...}^2}{nab} = .3064927$$

$$SSAB = SSTO - SSE - SSA - SSB = .2318038$$

$$SSA \quad P > .50$$

$$SSB \quad P > .10$$

$$SSAB \quad P > .10$$

Table B19. Matrix of Data for Two-way Analysis of Variance - Stop Delay per Vehicle - Log10 Transformation of Data

$\bar{X}_{obs} - \bar{X}_{sim}$ in each cell

INTERSECTION NUMBER

	1	2	3	5	6	7	
S-Bd	.0394	.0488	.2654	-.0840	-.0143	.1841	$Y_{1..} = .4394$
N-Bd	.0429	.0831	.0767	-.0609	.4604	.0534	$Y_{2..} = .6554$
E-Bd	.0129	.0282	.0036	-.0021	-.0866	-.0113	$Y_{3..} = -.0553$
W-Bd	-.0343	.0652	-.0169	.0874	-.0970	.0561	$Y_{4..} = .0605$
	$Y_{.1} = .0609$	$Y_{.2} = .2253$	$Y_{.3} = .3288$	$Y_{.5} = -.0596$	$Y_{.6} = .2625$	$Y_{.7} = .2821$	$Y_{...} = 1.100$

DIRECTION OF TRAVEL

Table B20. Two-way Analysis of Variance - Stop Delay per Vehicle

<u>Source</u>	<u>SS</u>	<u>d.f.</u>	<u>MS</u>	<u>F</u>
Approach (A)	.05447	5	.01089	1.147
Intersection (B)	.028238	3	.009413	.99
Inter x App (AB)	.250092	15	.0166728	1.76
Within Error			.0095	

$$SSA = \sum \frac{y_{i.}^2}{nb} - \frac{y_{...}^2}{nab} = \frac{(.4394)^2 + (.6554)^2 + (-.0553)^2 + (.0605)^2}{(1)(6)} - \frac{(1.10)^2}{(1)(4)(6)}$$

$$SSA = .05447$$

$$SSB = \sum \frac{y_{.j}^2}{na} - \frac{y_{...}^2}{nab} = \frac{(.0609)^2 + (.2253)^2 + (.3288)^2 + (-.0596)^2 + (.2625)^2 + (.2821)^2}{(1)(4)} - \frac{1.10^2}{(4)(6)(1)} = .028238$$

$$SSTO = \sum_i \sum_j \sum_k y_{ijk}^2 - \frac{y_{...}^2}{nab} = .3328$$

$$SSAB = SSTO - SSE - SSA - SSB = .250092$$

$$SSA \quad P > .10$$

$$SSB \quad P > .10$$

$$SSAB \quad P = .03$$

APPENDIX C
CALCULATIONS FOR THE FINAL
SIGNAL TIMINGS

Table C1. Chi-squared Test Comparing Simulated and Observed Volumes

$$H_0: V_{\text{sim}} = V_{\text{obs}}$$

$$H_1: V_{\text{sim}} \neq V_{\text{obs}}$$

$$n = 30$$

$$\alpha = .25$$

$$\chi^2_{(23, .25)} = 27.14$$

$$\chi^2 = \sum_{i=1}^n \frac{(V_{\text{sim}} - V_{\text{obs}})^2}{V_{\text{obs}}}$$

$$\begin{aligned} \chi^2 = & \frac{(217.0-275.6)^2}{275.6} + \frac{(98.6-107.1)^2}{107.1} + \frac{(25.8-30.5)^2}{30.5} + \\ & \frac{(40.9-55.7)^2}{55.7} + \frac{(212.4-262.0)^2}{262.0} + \frac{(113.7-109.3)^2}{109.3} + \\ & \frac{(18.0-23.8)^2}{23.8} + \frac{(28.3-34.0)^2}{34.0} + \frac{(227.7-247.3)^2}{247.3} + \\ & \frac{(128.0-131.6)^2}{131.6} + \frac{(50.3-64.1)^2}{64.1} + \frac{(64.9-73.6)^2}{73.6} + \\ & \frac{(181.8-193.4)^2}{193.4} + \frac{(87.4-87.3)^2}{87.3} + \frac{(25.7-31.7)^2}{31.7} + \\ & \frac{(17.6-19.5)^2}{19.5} + \frac{(184.1-199.2)^2}{199.2} + \frac{(91.9-91.3)^2}{91.3} + \\ & \frac{(17.1-22.7)^2}{22.7} + \frac{(22.9-33.3)^2}{33.3} + \frac{(194.0-203.7)^2}{203.7} + \\ & \frac{(108.5-107.0)^2}{107.0} + \frac{(49.1-57.3)^2}{57.3} + \frac{(63.5-79.7)^2}{79.7} = \end{aligned}$$

$$48.08$$

$$\text{REJECT } V_{\text{sim}} = V_{\text{obs}}$$

Table C2. Chi-squared Test Comparing Simulated and Observed Volumes for the Adjusted Simulated Volumes

$$H_0: V_{\text{sim}} = V_{\text{obs}}$$

$$H_1: V_{\text{sim}} \neq V_{\text{obs}}$$

$$n = 30$$

$$\alpha = .25$$

$$\chi^2_{(23,.25)} = 27.14$$

$$\chi^2 = \sum_{i=1}^n \frac{(V_{\text{sim}} - V_{\text{obs}})^2}{V_{\text{obs}}}$$

$$\begin{aligned} \chi^2 = & \frac{(275.9-275.6)^2}{275.6} + \frac{(110.1-107.1)^2}{107.1} + \frac{(30.3-30.5)^2}{30.5} + \\ & \frac{(49.4-55.7)^2}{55.7} + \frac{(269.0-262.0)^2}{262.0} + \frac{(124.7-109.3)^2}{109.3} + \\ & \frac{(24.2-23.8)^2}{23.8} + \frac{(29.2-34.0)^2}{34.0} + \frac{(258.6-247.3)^2}{247.3} + \\ & \frac{(137.1-131.6)^2}{131.6} + \frac{(64.0-64.1)^2}{64.1} + \frac{(73.6-73.6)^2}{73.6} + \\ & \frac{(206.9-193.4)^2}{193.4} + \frac{(91.9-87.3)^2}{87.3} + \frac{(31.6-31.7)^2}{31.7} + \\ & \frac{(18.8-19.5)^2}{19.5} + \frac{(208.5-199.2)^2}{199.2} + \frac{(93.1-91.3)^2}{91.3} + \\ & \frac{(23.2-22.7)^2}{22.7} + \frac{(33.3-33.3)^2}{33.3} + \frac{(225.2-203.7)^2}{203.7} + \\ & \frac{(108.1-107.0)^2}{107.0} + \frac{(57.4-57.3)^2}{57.3} + \frac{(79.1-79.7)^2}{79.7} = \end{aligned}$$

8.53

DO NOT REJECT

Table C3. Bartlett Test for Homogeneity of Variances - Stops per Vehicle- Log10 Transformation of Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{s}^2) - \Sigma \text{Log } s^2]$$

$$C = 1 + \frac{n+1}{1(v)(n)}$$

$$\bar{s}^2 = .000709653$$

$$\text{Log } \bar{s}^2 = -3.148986$$

$$\Sigma \text{Log } s^2 = -77.606$$

$$M = 2.3026(9) [24 (-3.148986) - (-77.606)] = 42.075$$

$$C = 1 + \frac{24+1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{42.075}{1.0386} = 40.51$$

$$\chi^2_{(23, .001)} = 49.73$$

DO NOT REJECT HOMOGENEITY

NOTE: $\bar{s}^2$ and $\Sigma \text{Log } s^2$ are calculated by Condescriptive (SPSS).

Table C4. Bartlett Test for Homogeneity of Variances - Total Stop Delay- Log10 Transformation of Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \overline{S^2}) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\overline{S^2} = .003464943$$

$$\text{Log } \overline{S^2} = -2.460309$$

$$\Sigma \text{Log } S^2 = -60.245$$

$$M = 2.3026(9) [24(-2.460309) - (-60.245)] = 24.818$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{24.818}{1.0386} = 23.90$$

$$\chi^2_{(23, .001)} = 49.73$$

DO NOT REJECT HOMOGENEITY

NOTE: $\overline{S^2}$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table C5. Bartlett Test for Homogeneity of Variances - Stop Delay per Vehicle - Log10 Transformation of Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\bar{S}^2 = .002290815$$

$$\text{Log } \bar{S}^2 = -2.640013$$

$$\Sigma \text{Log } S^2 = -64.822$$

$$M = 2.3026(9) [24(-2.640013) - (-64.822)] = 30.2911$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{30.2911}{1.0386} = 29.17$$

$$\chi^2_{(23, .001)} = 49.73$$

DO NOT REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table C6. Matrix of Data for Two-way Analysis of Variance - Stops per Vehicle - Log10 Transformation of Data

DIRECTION OF TRAVEL	INTERSECTION NUMBER						
	1	2	3	5	6	7	
S-Bd	-.0608	.0017	.1495	-.1028	.0371	-.0609	$Y_{1..} = -.0362$
N-Bd	-.0290	-.0727	-.2512	.0429	-.0697	-.0244	$Y_{2..} = -.4041$
E-Bd	-.0263	.0124	.0717	.0179	.0239	.0456	$Y_{3..} = .1452$
W-Bd	.0432	.1113	.0295	.0077	.0384	.0293	$Y_{4..} = .2594$
							$Y_{1.} = -.0729$ $Y_{2.} = .0527$ $Y_{3.} = -.0005$ $Y_{5.} = -.0343$ $Y_{6.} = .0297$ $Y_{7.} = -.0104$ $Y_{..} = -.0357$

$\bar{X}_{obs} - \bar{X}_{sim}$ in each cell

Table C7. Two-way Analysis of Variance - Stops per Vehicle

<u>Source</u>	<u>SS</u>	<u>d.f.</u>	<u>MS</u>	<u>F</u>
Approach	.0421099	5	.0084219	2.406
Intersection	.0025114	3	.0008371	0.24
Inter x App (AB)	.1000226	15	.0066681	1.905
Pure Error			.0035	

$$SSA = \sum \frac{y_{i.}^2}{nb} - \frac{y_{...}^2}{nab} = \frac{(-.0362)^2 + (-.4041)^2 + (.1452)^2 + (.2594)^2}{1(6)} - \frac{(-.0357)^2}{(1)(4)(6)}$$

$$SSA = .0421099$$

$$SSB = \frac{\sum y_{.i}^2}{na} - \frac{y_{...}^2}{nab} = \frac{(-.0729)^2 + (.0527)^2 + (-.0005)^2 + (-.0343)^2 + (.0297)^2 + (-.0104)^2}{1(4)} - \frac{(-.0357)^2}{(1)(4)(6)} = .0025114$$

$$SSTO = \sum_i \sum_j \sum_k y_{ijk}^2 - \frac{y_{...}^2}{nab} = .1446439$$

$$SSAB = SSTO - SSE - SSA - SSB = .1000226$$

$$SSAB \quad P \approx .02$$

$$SSA \quad P \approx .04$$

$$SSB \quad P > .50$$

Table C8. Matrix of Data for Two-way Analysis of Variance - Total Stop Delay - Log10 Transformation of Data
 $\bar{X}_{obs} - \bar{X}_{sim}$ in each cell

DIRECTION OF TRAVEL	INTERSECTION NUMBER						
	1	2	3	5	6	7	
S-Bd	-.1091	-.0041	.1996	-.2812	-.1644	-.2374	$Y_{1..} = -.5966$
N-Bd	.0977	-.0733	-.2946	-.2178	-.4423	-.3289	$Y_{2..} = -1.2592$
E-Bd	-.0716	-.0426	.1088	-.0384	-.0791	.1221	$Y_{3..} = -.0008$
W-Bd	-.4268	.1621	.0477	.2293	.0321	.1261	$Y_{4..} = .1705$
	$Y_{.1.} = -.5098$	$Y_{.2.} = .0421$	$Y_{.3.} = .0615$	$Y_{.5.} = -.3081$	$Y_{.6.} = -.6537$	$Y_{.7.} = -.3181$	$Y_{...} = -1.6861$

Table C9. Two-way Analysis of Variance - Total Stop Delay

<u>Source</u>	<u>SS</u>	<u>d.f.</u>	<u>MS</u>	<u>F</u>
Approach	.2099756	5	.0419951	2.41
Intersection	.1037663	3	.0345887	1.99
Inter x App (AB)	.5597581	15	.0373172	2.14
Pure Error			.0174	

$$SSA = \sum \frac{y_{i.}^2}{nb} - \frac{y_{...}^2}{nab} = \frac{(-.5966)^2 + (-1.2592)^2 + (-.0008)^2 + (.1705)^2}{1(6)} - \frac{(-1.6861)^2}{(1)(4)(6)}$$

$$SSA = .2099756$$

$$SSB = \frac{\sum \sum y_{.j.}^2}{na} - \frac{y_{...}^2}{nab} = \frac{(-.5098)^2 + (.0421)^2 + (.0615)^2 + (-.3081)^2 + (.6537)^2 + (-.3181)^2}{1(4)} - \frac{(-1.6861)^2}{1(4)(6)} = .1037663$$

$$SSTO = \sum \sum \sum y_{ijk}^2 - \frac{y_{...}^2}{nab} = .8703500$$

$$SSAB = SSTO - SSE - SSA - SSB = .5597581$$

$$SSAB \quad P < .005$$

$$SSA \quad P = .03$$

$$SSB \quad P = .10$$

Table C10. Matrix of Data for Two-way Analysis of Variance - Stop Delay per Vehicle - Log10 Transformation of Data

$\bar{X}_{obs} - \bar{X}_{sim}$ in each cell

DIRECTION OF TRAVEL	INTERSECTION NUMBER						
	1	2	3	5	6	7	
S-Bd	-.1037	.0125	.2220	-.2485	-.1371	-.1904	$Y_{1..} = -.4452$
N-Bd	.1140	-.0135	-.2770	-.1951	-.4336	-.3238	$Y_{2..} = -1.1290$
E-Bd	-.0591	-.0219	.1103	-.0330	-.0664	.1201	$Y_{3..} = .0500$
W-Bd	-.4742	.0911	.0533	-.2321	.0421	.1227	$Y_{4..} = -.3971$
	$Y_{.1.} = -.5230$	$Y_{.2.} = .0682$	$Y_{.3.} = .1086$	$Y_{.5.} = -.7087$	$Y_{.6.} = -.5950$	$Y_{.7.} = -.2714$	$Y_{...} = -1.9213$

Table C11. Two-way Analysis of Variance - Stop Delay per Vehicle

<u>Source</u>	<u>SS</u>	<u>d.f.</u>	<u>MS</u>	<u>F</u>
Approach (A)	.118364	5	.0236728	2.06
Intersection (B)	.1511701	3	.05039	4.38
Inter x App (AB)	.5172428	15	.03448	3.00
Pure Error			.0115	

$$SSA = \sum \frac{y_{i.}^2}{nb} - \frac{y_{...}^2}{nab} = \frac{(-.4452)^2 + (-1.1290)^2 + (.0500)^2 + (-.3971)^2}{1(6)} - \frac{(-1.9213)^2}{1(4)(6)}$$

$$SSA = .118364$$

$$SSB = \frac{\sum y_{.j}^2}{na} - \frac{y_{...}^2}{nab} = \frac{(-.5230)^2 + (.0682)^2 + (.1086)^2 + (-.7087)^2 + (-.5950)^2 + (-.2714)^2}{1(4)} - \frac{(-1.9213)^2}{1(4)(6)} = .1511701$$

$$SSTO = \sum_i \sum_j \sum_k y_{ijk}^2 - \frac{y_{...}^2}{nab} = .7867769$$

$$SSAB = SSTO - SSE - SSA - SSB = .5172428$$

$$SSAB \quad P < .001$$

$$SSA \quad P = .07$$

$$SSB \quad P = .005$$

Table C12. Bartlett Test for Homogeneity of Variances - Stops per Vehicle - Log10 Transformation of Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\bar{S}^2 = .000929726$$

$$\text{Log } \bar{S}^2 = -3.031657$$

$$\Sigma \text{Log } S^2 = -76.271$$

$$M = 2.3026(9) [24(-3.031657) - (-76.271)] = 72.76$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{72.76}{1.0386} = 70.06$$

$$\chi^2_{(23, .001)} = 49.73$$

REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table C13. Bartlett Test for Homogeneity of Variances - Stops per Vehicle - Log10 Transformation of Data - Minus Link 6-5

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\bar{S}^2 = .0007348393$$

$$\text{Log } \bar{S}^2 = -3.133831$$

$$\Sigma \text{Log } S^2 = -74.004$$

$$M = 2.3026(9) [23(-3.133831) - (-74.004)] = 39.9134$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{39.9134}{1.0386} = 38.43$$

$$\chi^2_{(22, .001)} = 48.27$$

DO NOT REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table C14. Bartlett Test for Homogeneity of Variances -Total Stop Delay - Log10 Transformation of Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\bar{S}^2 = .001919238$$

$$\text{Log } \bar{S}^2 = -2.71688$$

$$\Sigma \text{Log } S^2 = -67.558$$

$$M = 2.3026(9) [24(-2.76188) - (-67.558)] = 48.76$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{48.76}{1.0386} = 46.95$$

$$\chi^2_{(23, .001)} = 49.73$$

DO NOT REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table C15. Bartlett Test for Homogeneity of Variances - Stop Delay
per Vehicle - Log10 Transformation of Data

$$\chi^2 = \frac{M}{C}$$

$$M = 2.3026 (v) [n(\text{Log } \bar{S}^2) - \Sigma \text{Log } S^2]$$

$$C = 1 + \frac{n + 1}{1(v)(n)}$$

$$\bar{S}^2 = .001690658$$

$$\text{Log } \bar{S}^2 = -2.771934$$

$$\Sigma \text{Log } S^2 = -68.798$$

$$M = 2.3026(9) [24(-2.77.934) - (-68.798)] = 47.07$$

$$C = 1 + \frac{24 + 1}{3(9)(24)} = 1.0386$$

$$\chi^2 = \frac{47.07}{1.0386} = 45.33$$

$$\chi^2_{(23, .001)} = 49.73$$

DO NOT REJECT HOMOGENEITY

NOTE: $\bar{S}^2$ and $\Sigma \text{Log } S^2$ are calculated by Condescriptive (SPSS).

Table C16. Summary of Three-way Analysis of Variance

STOPS/VEHICLE

$$F = \frac{.035}{.00465} = 7.53$$

$$P \approx .005$$

TOTAL STOP DELAY

$$F = \frac{.382}{.0096} = 39.79$$

$$P \approx 0$$

STOP DELAY/VEHICLE

$$F = \frac{.190}{.00845} = 22.49$$

$$P \approx 0$$

Note: The numerators are the Main Effects from the SPSS three-way analysis of variance. The denominators are the average of the MSE terms from a one-way analysis of variance on the original and the final simulated data.

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