**SCHOOL OF
CIVIL ENGINEERING**

INDIANA

DEPARTMENT OF TRANSPORTATION

JOINT HIGHWAY RESEARCH PROJECT

**FHWA/IN/JHRP-94/6
Final Report**

**PREDICTING TRAFFIC IMPACTS AT
TWO-LANE HIGHWAY WORK ZONES**

**Michael J. Cassidy
Young Tae Son**

PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-94/6

Final Report

**PREDICTING TRAFFIC IMPACTS AT
TWO-LANE HIGHWAY WORK ZONES**

Michael J. Cassidy

Young Tae Son

FINAL REPORT

PREDICTING TRAFFIC IMPACTS AT TWO-LANE HIGHWAY WORK ZONES

Michael J. Cassidy
Young Tae Son

Joint Highway Research Project

Project No: C-36-17TT
File No: 8-4-46

Conducted in cooperation with the
Indiana Department of Transportation
and

Federal Highway Administration

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views of policies of the Federal Highway Administration and the Indiana Department of Transportation. This report does not constitute a standard, specification or regulation.

Purdue University
West Lafayette, IN 47907
June, 1994

1. Report No. JHRP-94/6	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Predicting Traffic Impacts at Two-Lane Highway Work Zones		5. Report Date June, 1994	
		6. Performing Organization Code	
7. Author(s) Michael J. Cassidy Young Tae Son		8. Performing Organization Report No.	
9. Performing Organization Name and Address Joint Highway Research Project Civil Engineering Building Purdue University		10. Work Unit No.	
		11. Contract or Grant No. Indiana HPR-2091	
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract <p>Maintenance or reconstruction activity on a two-lane highway often requires a lane closure. The implementation of "one-way traffic control," required to maintain traffic flow throughout the work zone, typically produces significant motorist delay. This report describes the adaptation and application of queueing models, originally derived for intersections controlled by vehicle-actuated traffic signals, to estimate delay at two-lane highway work zones. The models estimate expected delay as a function of directional traffic demand rates, work zone physical length and observed traffic measures. Validation efforts using simulation suggest that the models accurately predict the impacts of two-lane highway lane closures.</p>			
17. Key Words Highway Work Zones Two-Lane Highways Vehicle Delay Queueing Model		18. Distribution Statement No Restrictions. This document is available through the National Technical Information Services. Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages vii & 79	22. Price

Digitized by the Internet Archive
in 2011 with funding from
LYRASIS members and Sloan Foundation; Indiana Department of Transportation

PREDICTING TRAFFIC IMPACTS AT TWO-LANE HIGHWAY WORK ZONES

Implementation Report

Construction or maintenance activity on a two-lane highway often requires a lane closure. As only a single lane serves traffic in both travel directions, right-of-way to traverse the work zone is sequentially allocated to each directional movement by flaggers stationed at both ends of the work zone. Motorist delays resulting from the implementation of this alternating traffic control are often significant. Thus, a-priori evaluation of the resulting delays becomes useful for determining expected impacts created by proposed work activity and for identifying appropriate work zone operating strategies such as work zone physical length, hours of operation and/or the need for detour routes to minimize impacts.

Principles of queueing theory were used to derive models for estimating expected delay as a function of directional traffic demand rates, work zone physical length and observed traffic measures prevailing at work zones. The models capture stochastic effects of expected delay as a function of work zone operating conditions. To evaluate the accuracy of the proposed stochastic models, a computer simulation model was developed. Based upon the outcomes generated by the simulation model, the delay models appear to adequately predict the impacts of two-lane highway lane closures.

To simplify and expedite the implementation of the proposed methodologies, all formulated procedures have been fully computerized. A user manual for executing the computer software is included in the final report. The software can be run on IBM-compatible personal computers (versions 286 or higher) and a math co-processor is required on 286 machines. It is a free standing PC package using standard DOS commands.

TABLE OF CONTENTS

LIST OF TABLES	vii
LIST OF FIGURES	vii
 1. INTRODUCTION	 1
1.1. Previous Research	2
1.2. Research Objectives and Scope.....	4
1.3. Report Overview.....	5
 2. QUEUEING DELAY MODEL.....	 7
2.1. Introduction.....	7
2.2. Fluid Approximations.....	9
2.3 Stochastic Modeling.....	15
2.4. Estimation of Moments.....	19
2.4.1. Saturated Green Time.....	20
2.4.2. Green Time Extension.....	22
2.4.3. Travel Time.....	24
2.5. Extending Deterministic Models for Over-Saturated Condition.....	26
 3. EMPIRICAL OBSERVATIONS.....	 28
3.1. Data Collection.....	28
3.2. Data Analysis.....	32
 4. SIMULATION MODEL.....	 35
4.1. Microscopic Simulation Model.....	35
4.1.1. Threshold Headways.....	37
4.2. Evaluation of Model Accuracy.....	40
4.2.1. Experimental Design.....	40

4.2.2. Validation Findings.....	40
4.2.3. Empirical Validation Data.....	43
5. SUMMARY AND CONCLUSIONS.....	45
REFERENCES.....	46
APPENDIX A: PARAMETER VALUES FOR EACH WORK ACTIVITY TYPE.....	48
APPENDIX B: USER MANUAL <i>work</i> - Software for Analyzing One-Way Traffic Control Impacts.....	49

LIST OF TABLES

Table 3-1 Summary of Empirical Observation.....	29
Table 3-2 Observed Traffic Demand Rates.....	33
Table 3-3 Observed Cycle Length Statistics.....	34
Table 4-1 Scenarios Evaluated Through Simulation.....	41
Table 4-2 Estimated Average Delays.....	42
Table 4-3 Field-Measured and Predicted Average Delay with Queueing Model (for Subject Direction).....	44
Table A-1 Model Parameter Values.....	48

LIST OF FIGURES

Figure 1-1 One-Way Traffic Control.....	1
Figure 2-1(a) Queueing Length vs Time (Two-Lane Highway Work Zone).....	10
Figure 2-1(b) Queueing Length vs Time (Vehicle-Actuated Intersection One-way Street).....	11
Figure 2-2 Evolution of Random Queue.....	16
Figure 2-3 Queueing Diagram Depicting Over-Saturated Condition.....	27
Figure 3-1 Example Data File.....	31
Figure 4-1 Microscopic Simulation Model.....	36
Figure 4-2 Maximum Likelihood Estimation.....	39
Figure B-1 Example Input Information.....	55
Figure B-2 Output - Example Problem 1.....	57
Figure B-3 Output - Example Problem 2.....	59
Figure B-4 Output - Example Problem 3.....	62

1. INTRODUCTION

A two-lane highway is defined as a two-directional roadway with one lane available for traffic traveling in each direction [TRB, 1985]. Maintenance, construction or rehabilitation activity on a two-lane highway often requires a lane closure. The highway's remaining lane serves two-directional traffic within the "work zone" by providing alternating right-of-way. Flaggers, stationed at both ends of the work zone, sequentially allocate right-of-way to each directional movement (vehicles may or may not be constrained to follow a "pilot car" while traversing the work zone). This operating scheme, commonly referred to as "one-way traffic control", is illustrated in Figure 1-1.

Motorist delays resulting from the implementation of one-way traffic control are often significant [California, 1978]. Thus, a priori evaluation of the resulting delays becomes useful

Figure 1-1
One-Way Traffic Control

1) for determining expected operational impacts created by proposed work activity and 2) for identifying appropriate work zone operating strategies such as work zone physical length, hours of operation and/or the need of detour routes to minimize impacts.

1.1. Previous Research

Previous research concerning delay prediction under one-way traffic control has been sparse. Ceder and Regueres [1990] used simulation to obtain the average work zone delays and compared these outcomes with the average delays estimated using Webster's delay model [1966] for fixed time signalized intersections. Differences in delay values yielded from the two models exhibited a tendency to increase exponentially with decreasing cycle time. To capture the discrepancy between the two models, regression was used. The regression-based error expression was added to Webster's equation. This "extended" model was constructed for the special case of equal right-of-way times for both directions of travel and was "calibrated" for work zones of relatively short physical length.

Aside from the obvious application limitations inherent in this approach, the fundamental soundness of the resulting prediction model is suspect. The regression-based error term developed in this previous work reflects only the characteristics prevailing under the (narrow) range of operating conditions evaluated in the study. More importantly, Webster's equation is a steady-state model for predicting delay at fixed-time signalized intersections, while cycle length and right-of-way times are variable under one-way traffic control.

Cassidy and Han [1993] proposed a technique for estimating vehicle delays and queue lengths on two-lane highways operating under one-way traffic control. The model used deterministic queueing analysis techniques to formulate equations for computing average motorist delays and queue lengths occurring over the given period. The procedure estimated average required right-of-way times and relied upon empirically estimated values for traffic stream characteristics such as average queue discharge rate.

The model exploited a deterministic queueing approach, which assumed uniform vehicle arrival

and departure rates and used only average values for relevant parameters. Thus, the model does not consider the variability inherent in one-way traffic control.

Cassidy, Son and Rosowsky [1994] made an effort to capture the stochastic nature of work zone operations. The work employed statistical estimation and Monte-Carlo simulation to identify distributions of average delay as a function of conditions prevailing at the work zone. Approximate analysis techniques were then used to compute user-specified percentile values of average delay per operating sequence per direction of travel. Percentile values of average delay were used to probabilistically evaluate operating conditions. The approximate techniques produced easy to use, closed-form delay expressions. However, the use of Monte-Carlo simulation to simply generate random variables has several inherent deficiencies :

1. The approach implicitly assumes that a randomly arriving vehicle is equally likely to arrive in any cycle irrespective of cycle length. In fact, a randomly arriving vehicle is more likely to arrive during a longer cycle.
2. The variability in discharging headways exhibited by queued vehicles will be a function of the number in queue. This is not reflected in the approach used for generating values of saturation flow rate.
3. The generated delay measure reflect an average value which is exceeded in a specified percentage of cycles. This measure is not equivalent to a percentile value of individual vehicle delay which might better characterize work zone impacts.

Most notably, the predicted delays reflect average values per cycle rather than an expected value over some extended time period of interest. A single expected value would characterize operating conditions more definitively. Moreover, an expected value would not require the analyst to subjectively select a priori some percentile value for assessing conditions.

Although not directly applied to two-lane highway work zone operations, Newell [1969] used fluid and diffusion queueing approximations to analyze the behavior of vehicle-actuated signals at the intersection of two one-way streets with no turning traffic. Recognizing that one-

way traffic control operations behave in a very similar manner to this "special case" of a vehicle-actuated intersection, Newell's procedure can be extended to model two-lane highway work zones.

1.2. Research Objectives and Scope

The objective behind this research has been to formulate analytical expressions (i.e., equations) for estimating expected vehicle delay as a function of work zone operating conditions such as work zone physical length, work activity type and directional traffic demands. The work has employed fluid queueing approximations previously developed by Newell [1969] for estimating delay at vehicle-actuated intersections of two one-way streets. The model captures stochastic affects on expected delay as a function of directional traffic demands, work zone physical length and observed traffic stream measures prevailing at under-saturated work zone operations. The term under-saturated denotes that directional queues are completely served during each allocation of right-of-way.

For over-saturated conditions (i.e., operations where residual queueing prevails), deterministic queueing techniques are used for predicting average delays over a specified time interval of interest [Cassidy, Son and Rosowsky, 1993].

To render the proposed techniques simple and straightforward to use, the models have been computerized as part of a user-friendly software package. As such, application of the derived procedures is relatively simple and timely. A "User Manual" for this software is contained in Appendix B of this report.

To insure that the resulting predictions accurately estimate delay, model predictions have been carefully validated using both empirical measurements and the outcomes generated from a microscopic simulation model developed as part of this research project.

To insure broad applicability, delay prediction techniques have been developed for a number of differing work activity types. These activity types are :

- asphalt-concrete overlays (with pilot car operation)
- chip-seal resurfacing (with pilot car operation)
- general construction (i.e., shoulder work , saw cutting, pavement marking) without pilot car
- general construction with pilot car

Where a work activity type not addressed above is to be analyzed, approximate predictions can be generated by specifying one of the four work activity types above that most closely "matches" the activity in question.

1.3. Report Overview

The models derived for each activity type are generally identical. Major differences between the models are reflected only in the distributions of prevailing traffic stream parameters. For example, the queue discharge rates and work zone travel speeds under asphalt-concrete overlay (A-C) activities are significantly different from those prevailing under chip-seal operations.

This report therefore details all tasks involved in developing models for evaluating asphalt-concrete overlay operations. The relevant operational parameters under all other work activity types are summarized in Appendix A.

Chapter 2 of this report presents the derivations of the stochastic queueing model to estimate work zone operating characteristics and the resulting directional average delays. Included in chapter 2 is a description of the queueing-based assessment technique for over-saturated conditions. Chapter 3 describes empirical data collection and analysis. Chapter 4 describes

development of the microscopic simulation model and the simulation experiments associated with validating the proposed procedures.

A summary and conclusions are presented in the fifth chapter of this report. Appendix A presents parameter values for work activity other than A-C operations. Appendix B presents a "User Manual" for executing the computer software developed in this project.

2. QUEUEING DELAY MODEL

2.1. Introduction

Given that the implementation of one-way traffic control typically results in significant motorist delay [California, 1978], a-priori evaluation of work zone operation should be performed to identify expected impacts and/or to establish suitable work zone strategies (i.e., the physical length of the lane closure, hours of work zone operation, the need for diversion routes, etc).

The work presented in this chapter has used principles of queueing theory to derive closed-form expressions for estimating expected delay as a function of work zone operating conditions. The work has exploited fluid approximations and stochastic models originally developed by G.F. Newell [1969] for predicting delay at the intersection of two one-way streets controlled by a vehicle-actuated traffic signal. Traffic stream characteristics under one-way traffic control are similar to those prevailing at the stop bar of a signalized intersection [Cassidy and Han, 1993; Ceder and Rogueros 1990]. Thus, signalized intersection delay models serve as a logical foundation for work zone delay prediction models.

The primary difference between traffic signal and work zone operation is the significance of lost time. For traffic signals, clearance intervals (i.e., yellow times) are fixed and account for a small portion of the overall cycle length. In contrast, the lost times occurring under one-way traffic control include platoon travel times through extended work zone sections as well as the lost times prevailing at either end of the lane closure during the initiation of directional right-of-way. As lost time accounts for a significant portion of the cycle length and is stochastic in nature, Newell's delay expressions for signalized intersections were altered to capture these effects.

Work zone operation also differs from typical signalized intersection operation in that flaggers commonly extend right-of-way well beyond queue dissipation to accommodate arriving vehicles. Thus, expressions were derived to account for the influence of large green time extensions (although inclusion of these effects were ultimately found to provide little

improvement in model accuracy).

Recognizing again that queueing characteristics at a work zone entrance are similar to those at the stop bar of a signalized intersection, terminology typically associated with signal operation have been adopted for describing traffic flow characteristics under one-way traffic control.

- Effective Green Time, G , is the right-of-way time utilized by a single directional movement in one cycle. It is the elapsed time between the first vehicle and last vehicle entry, traveling in the same direction, during a single allocation of right-of way.
- Cycle Length, C , is the time required for one complete operational sequence. For example, cycle length may be defined as the elapsed time between successive allocations of effective green time for a single directional movement.
- Saturation Green Time, g , reflects the portion of the effective green in which queued vehicles are discharged into the work zone. It is the elapsed time between the first vehicle and last queued vehicle entry.
- Saturation Flow Rate, S , reflects queue discharge rate into the work zone during saturated green time.
- Start-Up Lost Time, L , is defined as the elapsed time between the last vehicle in the opposing direction exiting the work zone and the entry of the first queued vehicle traveling in the subject direction.
- Green Time Extension, E , is the unsaturated green time. It reflects that portion of the effective green time extending from queue dissipation to the final vehicle entry into the work zone. Discharge rate during this period is equal to vehicle arrival rate.

- Effective Red Time, R , is the amount of time per cycle that effective green time is not allocated to a given directional movement.

2.2. Fluid Approximations

To illustrate the characteristics of one-way traffic control, we begin by evaluating operation using fluid approximations. The evolution of opposing vehicle queues at the work zone is depicted in Figure 2-1(a). During cycle j , traffic, presumed to behave like a fluid, arrives in direction i at rate q_i , where $i = 1$ or 2 . A queue in direction i builds during the red time of the j th cycle, R_{ij} . During the "saturated" green time of the j th cycle in direction i , g_{ij} , vehicles discharge into the work zone at rate S_i .

Figure 2-1(a) is identical to the queueing diagram for the intersection of two one-way streets controlled by a vehicle-actuated (V-A) signal presented in Figure 2-1(b). The two figures exhibit only minor differences. For work zone operation, values of R_{ij} are not only functions of the saturated green time in the opposing direction, but also the travel time of both directional platoons through the work zone and an added lost time at the opposing end of the work zone. We define T_{ij} as the amount of time for the rear of a platoon to traverse the work zone in direction i during the j th cycle. Values of T_{ij} may well vary by direction [Ceder,1993] while values of L are small relative to cycle length and are therefore treated deterministically and independent of travel direction.

Finally, directional effective green time, G_{ij} , is often extended by flaggers at the work zone entrance well beyond queue dissipation to accommodate arriving vehicles. Thus,

$$G_{ij} = g_{ij} + E_{ij} \quad (2.1)$$

where:

$$E_{ij} = \text{green time extension beyond queue dissipation in direction } i \text{ during } j\text{th cycle}$$

Figure 2-1 (a)

Queue Length vs Time

(Two-Lane Highway Work Zone)

Figure 2-1(b)
 Queue Length vs Time
 (Vehicle-Actuated Intersection - One Way Street)

Vehicles in each direction are treated like a fluid with a uniform arrival rate of q_i and a queue discharge rate of S_i .

Defining $t=0$ as the end of G_{ij-1} (i.e., the end of effective green time in direction i during the j -th cycle) and $Q_i(t)$ as the queue length at time t in direction i ,

$$\begin{aligned} Q_i(t) &= q_i \cdot t & 0 < t < t_R \\ &= q_i \cdot t - S_i \cdot (t - t_R) & t_R < t < t_g \\ &= 0 & t_g < t < t_G \end{aligned} \quad (2.2)$$

where t_R , t_g and t_G represent the end times of the red, saturated green and total green periods, respectively.

Assuming R_{ij} is known and noting that directional queues do not increase during their respective green periods,

$$q_1 (T_{1j} + g_{2j} + E_{2j} + T_{2j} + 2L) = (S_1 - q_1)g_{1j} \quad (2.3)$$

$$q_2 (T_{2j} + g_{1j} + E_{1j} + T_{1j+1} + 2L) = (S_2 - q_2)g_{2j+1} \quad (2.4)$$

By defining lost time, Y_{ij} , as the portion of cycle j where saturated green periods are not occurring for either travel direction,

$$Y_{1j} = T_{1j} + E_{2j} + T_{2j} + 2L \quad (2.5)$$

$$Y_{2j} = T_{2j} + E_{1j} + T_{1j+1} + 2L \quad (2.6)$$

Directional red time, R_{ij} , is the sum of total directional lost time and the saturated green

period for the opposing direction.

$$R_{1j} = g_{2j} + Y_{1j} \quad (2.7)$$

$$R_{2j+1} = g_{1j} + Y_{2j} \quad (2.8)$$

From Equations (2.3) and (2.4), the saturated green times become

$$g_{1j} = \frac{q_1(g_{2j} + Y_{1j})}{(S_1 - q_1)} \quad (2.9)$$

$$g_{2j+1} = \frac{q_2(g_{1j} + Y_{2j})}{(S_2 - q_2)} \quad (2.10)$$

For Equations (2.9) and (2.10), the saturated directional green time during a given cycle can be evaluated from its value in the previous cycle, i.e.,

$$g_{2j+1} = \frac{q_1 q_2 g_{2j}}{(S_1 - q_1)(S_2 - q_2)} + \frac{\frac{q_1 q_2}{S_1 S_2} (Y_{1j} - Y_{2j}) + \frac{q_2}{S_2} Y_{2j}}{(1 - q_1/S_1)(1 - q_2/S_2)} \quad (2.11)$$

Assuming work zone operation is under-saturated (i.e., residual queueing does not occur), the fluid approximation infers that as $j \rightarrow \infty$, $Y_{ij} \rightarrow Y_i$, $E_{ij} \rightarrow E_i$ and $g_{ij} \rightarrow g_i$ [Newell, 1969].

$$g_2 = \frac{\frac{q_1 q_2}{S_1 S_2} (Y_1 - Y_2) + \frac{q_2}{S_2} Y_2}{(1 - q_1/S_1 - q_2/S_2)} \quad (2.12)$$

The subscripts in Equation (2.12) can be reversed for estimating g_1 . If $Y_1 = Y_2$, Equation (2.12) is the same as the formula derived by Newell and g_{2j} can be expressed as

$$g_{2j} = g_2 + (g_{21} - g_2) a^{j-1} \quad (2.13)$$

Where :

$$a = \frac{q_1 q_2}{(s_1 - q_1)(s_2 - q_2)}$$

Finally, cycle length, C , becomes the sum of Y_1 , g_1 , g_2 and E_1

$$\begin{aligned} C &= Y_1 + E_1 + g_1 + g_2 \\ &= Y_1 + E_1 + \frac{\frac{q_1}{S_1} Y_1 + \frac{q_2}{S_2} Y_2}{(1 - q_1/S_1 - q_2/S_2)} \end{aligned} \quad (2.14)$$

The total delay for all queued vehicles in direction 1 during time interval t to $t+dt$ is $Q_1(t)dt$. Thus, the total directional delay per cycle, W_1 , becomes

$$\begin{aligned} W_1 &= \int_0^{g_2 + Y_1 + g_1} Q_1(t) dt \\ &= \frac{q_1}{2} \frac{(g_2 + Y_1)^2}{(1 - q_1/S_1)} \end{aligned} \quad (2.15)$$

Once again, delays for the opposing direction can be estimated by reversing the subscripts.

And the average delay per vehicle for both directions, w_j , is

$$w_j = \frac{\frac{q_1 q_2}{S_1 S_2}}{2(q_1 + q_2)(1 - \frac{q_1}{s_1} - \frac{q_2}{s_2})} \left[\left((Y_1 - Y_2) + \frac{S_2}{q_2} Y_1 \right) (S_1 - q_1) + \left((Y_2 - Y_1) + \frac{S_1}{q_1} Y_2 \right) (S_2 - q_2) \right] \quad (2.16)$$

If one were to assume $Y_1 = Y_2$, an inappropriate presumption for work zones according to Ceder [1993], the resulting expression for average vehicle delay in both directions becomes identical to the expression derived by Newell [1969] for V-A intersections.

2.3. Stochastic Modeling

The delay expression reflecting fluid approximations (Equation (2.15)) does not account for fluctuations in vehicle arrival and departure processes and other stochastic properties of work zone operation. Figure 2-2 depicts the possible realizations of directional queue length versus time, $Q_i(t)$ [Darroch, Newell and Morris, 1964]. The solid line in Figure 2-2 represents the expected evolution of queue length conditioned on a known red time. As expressed in Equation (2.15),

$$E(W_i | R_{ij}) = \frac{q_i}{2} \frac{(R_{ij})^2}{(1 - q_i/S_i)} \quad (2.17)$$

where the subscript j is used in Equation (2.17) to denote the cyclic variability of parameters.

Treating directional vehicle arrivals to time t , $A_i(t)$, as a stationary process

$$E \{A_i(t)\} = q_i \cdot t \quad (2.18)$$

We exploit Newell's assumption that there is a variance to mean ratio of the arrival process, I_{ia} , of the order 1 that is independent of the mean.

$$Var \{A_i(t)\} = I_{ia} q_i t \quad (2.19)$$

We also define the departure process during the saturated green time, $D_i(t)$, identically to Newell.

Figure 2-2
Evolution of Random Queue

Namely,

$$E \{D_i(t)\} = S_i(t-a_i) \quad (2.20)$$

where a_i is a correction due to "start-up" delays immediately following the initiation of the green period and $t=0$ at this green initiation. The variance of directional vehicle departure time t is

$$Var \{D_i(t)\} = V_i + I_{id}S_i g_i \quad (2.21)$$

where the variance to mean ratio I_{id} is again of order 1. Start-up delays can be captured in the

term V_i . Given the very long cycle times expected, V_i is small relative to the second term in Equation (2.21).

The dashed lines in Figure 2-2 denote two possible realizations of the random queue length $Q_i'(t)$ (one above the average and one below) caused by fluctuations in vehicle arrival and/or departure rates. If the queue dissipates before the end of the expected saturated green time, the queue could be negative at the end of this time. If the queue does not dissipate, the queue is positive at the end of expected saturated green time. Whether the directional queue in cycle j dissipates before or after the end of the expected saturated green period, the shaded triangular area representing the added delay (which may be positive or negative) in Figure 2-2 can be approximated knowing that the slope of $Q_i(t)$ during the saturated green time is approximately $(q_i - S_i)$. Thus, the "extra" directional delay caused by fluctuating arrival and departure processes, W_{ie} , becomes

$$W_{ie}|R_{ij} = \frac{1}{2} \frac{(Q_i^2(E(g_{ij}|R_{ij}) + R_{ij}))}{(S_i - q_i)} \quad (2.22)$$

where queue length at the end of the expected saturated green period is the difference between cumulative arrivals and departures,

$$Q_i (E(g_{ij}|R_{ij}) + R_{ij}) = A_i (E(g_{ij}|R_{ij}) + R_{ij}) - D_i (E(g_{ij}|R_{ij}) + R_{ij}) \quad (2.23)$$

Taking the expectation of Equation (2.22),

$$E(W_{ie}|R_{ij}) = \frac{1}{2} \frac{E(Q_i^2(E(g_{ij}|R_{ij}) + R_{ij}))}{(S_i - q_i)} \quad (2.24)$$

The expected number of vehicles in queue at the end of the expected saturation green period is 0, thus

$$\begin{aligned}
E(Q_i^2(E(g_{ij}|R_{ij}+R_{ij}))) &= Var(Q_i(E(g_{ij}+R_{ij}))) \\
&= Var(A_i(E(g_{ij}|R_{ij})+R_{ij}))+Var(D_i(E(g_{ij}|R_{ij}))) \\
&= \frac{I_i q_i R_{ij}}{(1-q_i/S_i)} + V_i
\end{aligned} \tag{2.25}$$

Adding Equation (2.24) to the expected delay as expressed by the fluid approximation (Equation (2.17)), the total expected delay due to variation in the arrival and departure processes becomes

$$E(W_{ij}|R_{ij}) = \frac{q_i R_{ij}^2}{2(1-q_i/S_i)} \left(1 + \frac{I_i}{S_i(1-q_i/S_i)} + \frac{V_i}{S_i q_i R_{ij}^2} \right) \tag{2.26}$$

where $I_i = I_{ia} + I_{id}$

Taking the expectation over the distribution of R_{ij} ,

$$E(W_{ij}) = \frac{q_i}{2(1-q_i/S_i)} \left[E^2(R_{ij}) + Var(R_{ij}) + \frac{(I_i)E(R_{ij})}{S_i(1-q_i/S_i)} + \frac{V_i}{S_i q_i} \right] \tag{2.27}$$

Equations (2.26) and (2.27) are identical to expressions previously derived for signalized intersections [Newell, 1969]. At this point, we adapt the intersection delay equations above to account for the operating characteristics unique to one-way traffic control at two-lane highway work zones. Namely, the stochastic affects on delay extend beyond fluctuating arrivals and departures. Variability in the times required to process platoons through the work zone, T_{ij} , and the correlated influence of green time extensions, E_{ij} , influence vehicle delays (although the latter influence was ultimately found to be insignificant).

The expected red time in direction 1 during the j th cycle is the sum of several previously defined random variables.

$$\begin{aligned}
E(R_{1j}) &= E(T_{1j} + g_{2j} + E_{2j} + T_{2j} + 2L) \\
&= E(T_{1j}) + E(g_{2j}) + E(E_{2j}) + E(T_{2j}) + 2L
\end{aligned} \tag{2.28}$$

Given that each of the n random variables composing R_{1j} , X_i , have a finite second moment,

$$\text{Var}(\sum_{i=1}^n X_i) = \sum_{i=1}^n \text{Var} X_i + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{Cov}(X_i, X_j) \tag{2.29}$$

Evaluation of a large empirical data base [Cassidy, Son and Rosowsky, 1993] indicated that, with the exception of T_{1j} and g_{2j} , the random variables in Equation (2.28) are generally uncorrelated or only slightly correlated. Added time to "process" platoons through the work zone, T_{1j} does increase queue length in the opposing direction (and, thus, g_{2j}). Therefore,

$$\begin{aligned}
\text{Cov}(g_{2j}, T_{1j}) &= E(T_{1j} \cdot g_{2j}) - E(T_{1j}) \cdot E(g_{2j}) \\
&= \frac{q_2}{S_2 - q_2} \text{Var}(T_{1j})
\end{aligned} \tag{2.30}$$

Given that lost time, L , is treated deterministically,

$$\text{Var}(R_{1j}) = \frac{(S_2 + q_2)}{(S_2 - q_2)} \text{Var}(T_{1j}) + \text{Var}(g_{2j}) + \text{Var}(E_{2j}) + \text{Var}(T_{2j}) \tag{2.31}$$

2.4. Estimation of Moments

To exploit the expression for expected directional delay (Equation (2.27)), the first and second moments of g_{ij} and E_{ij} are required.

2.4.1. Saturated Green Time

By exploiting previously used assumptions concerning the independence of arrival and departure processes from one cycle to the next [Darroch, Newell and Morris, 1964; Dunne and Potts, 1965; Newell, 1969], the conditional mean saturated green times given R_{ij} derived by the fluid approximation are approximately equal to g_{ij} . That is, $E(g_{ij}) = E(E(g_{ij}|R_{ij}))$. Thus,

$$E(g_{1j}) = \frac{q_1}{S_1 - q_1} [E(T_{1j}) + E(g_{2j}) + E(E_{2j}) + E(T_{2j}) + 2L] \quad (2.32)$$

$$E(g_{2j+1}) = \frac{q_2}{S_2 - q_2} [E(T_{2j}) + E(g_{1j}) + E(E_{1j}) + E(T_{1j+1}) + 2L] \quad (2.33)$$

With a stationary process,

$$E(g_1) = \frac{q_1}{S_1 - q_1} [E(T_1) + E(g_2) + E(E_2) + E(T_2) + 2L] \quad (2.34)$$

$$E(g_2) = \frac{q_2}{S_2 - q_2} [E(T_2) + E(g_1) + E(E_1) + E(T_1) + 2L] \quad (2.35)$$

From Equations (2.34) and (2.35), the expected saturated green time (for direction 1) is

$$E(g_1) = \frac{q_1/S_1}{1 - q_1/S_1 - q_2/S_2} \left[E(T_1) + E(T_2) + \frac{q_2}{S_2} E(E_1) + \left(1 - \frac{q_2}{S_2}\right) E(E_2) + 2L \right] \quad (2.36)$$

where subscripts are reversed to estimate $E(g_2)$.

As the saturated green time given the red duration is the sum of the conditional expected value of g_{ij} and the additional term accounting for fluctuations in arrivals and departures [Newell, 1969],

$$g_{ij}|R_{ij} \approx E(g_{ij}|R_{ij}) + \frac{[A_i(R_{ij} + E(g_{ij}|R_{ij})) - D_i(E(R_{ij}))]}{(S_i - q_i)} \quad (2.37)$$

The conditional variance of saturated green time can be expressed as

$$\begin{aligned} Var(g_{ij}/R_{ij}) &= Var \left[\frac{[A_i(R_{ij} + E(g_{ij}|R_{ij})) - D_i(E(R_{ij}))]}{(S_i - q_i)} \right] \\ &= \frac{I_i q_i R_{ij}}{S_i^2 \left(1 - \frac{q_i}{S_i}\right)^3} + \frac{V_i}{(S_i - q_i)^2} \end{aligned} \quad (2.38)$$

and the unconditional variance becomes

$$Var(g_{ij}) = E(Var(g_{ij}/R_{ij})) + Var(E(g_{ij}/R_{ij})) \quad (2.39)$$

Thus, for one-way traffic control operations, again assuming a stationary process

$$\begin{aligned}
Var(g_1) = & \frac{I_1 q_1 E(T_1 + g_2 + E_2 + T_2 + 2L)}{S_1^2 (1 - q_1/S_1)^3} + \frac{V_1}{(S_1 - q_1)^2} \\
& + \frac{q_1^2}{(S_1 - q_1)^2} \left[Var(T_1) \frac{S_2 + q_2}{S_2 - q_2} + Var(g_2) + Var(E_2) + Var(T_2) \right]
\end{aligned} \tag{2.40}$$

$$\begin{aligned}
Var(g_2) = & \frac{I_2 q_2 E(T_2 + g_1 + E_1 + T_1 + 2L)}{S_2^2 (1 - q_2/S_2)^3} + \frac{V_2}{(S_2 - q_2)^2} \\
& + \frac{q_2^2}{(S_2 - q_2)^2} \left[Var(T_2) \frac{S_1 + q_1}{S_1 - q_1} + Var(g_1) + Var(E_1) + Var(T_1) \right]
\end{aligned} \tag{2.41}$$

Combining Equations (2.40) and (2.41), the variance of saturated green time for a given direction is expressed without reference to the saturated green time for the opposing direction.

2.4.2. Green Time Extension

We assume flaggers extend directional right-of-way beyond queue dissipation whenever the arriving vehicle's headway is not greater than some value H (where the value of H can be estimated empirically using discrete choice techniques described in section 4.1.2). Hence, the decision to extend directional green time is a function of the vehicle arrival distribution.

As vehicle inter-arrival times can be assumed exponential, independent, identically distributed random variables,

$$E(X_k) = \frac{1}{q_i} \quad (2.42)$$

where:

$$\begin{aligned} X_k &= k^{\text{th}} \text{ inter-arrival time} \\ q_i &= \text{directional flow rate} \end{aligned}$$

Letting the random variable N be the number of vehicles discharged during the green time extension, and given $N=n$, the length of the extended green time is $X_1 + X_2 + \dots + X_n$ and $E[E_i|N=n] = E(X_1 + X_2 + \dots + X_n) = n E(X_1) = n/q_i$. For each event (i.e., vehicle arrival), the probability that the headway is less than or equal to H is $P(H \geq x_k) = e^{-q_i H}$. Random variable N has a geometric distribution with parameter $p = e^{-q_i H}$ and an expected value of $(1-p)/p$.

$$E(E_i) = E\left(N \cdot \frac{1}{q_i}\right) = \frac{1 - e^{-q_i H}}{e^{-q_i H}} \cdot \frac{1}{q_i} \quad (2.43)$$

The variance of E_i is also obtained by conditioning on the number of vehicles discharged during the green time extension.

$$\begin{aligned} \text{Var}(E_i) &= E(\text{Var}(E_i|N)) + \text{Var}(E(E_i|N)) \\ &= \frac{1 - e^{-q_i H}}{e^{-q_i H}} \cdot \frac{1}{q_i^2} + \frac{1 - e^{-q_i H}}{e^{-2q_i H}} \cdot \frac{1}{q_i^2} \end{aligned} \quad (2.44)$$

2.4.3. Travel Time

Values of work zone travel time, T_i , clearly vary as a function of work zone physical length, ℓ . Thus, the speed of the final vehicle through a work zone, v_i , becomes the generalizable measure.

$$E(T_i) = E\left(\frac{\ell}{v_i}\right) = \ell \cdot E\left(\frac{1}{v_i}\right) \quad (2.45)$$

The moments of v_i , which vary as a function of work activity type [Cassidy, Son and Rosowsky, 1993], can be empirically measured.

Expanding the term $\frac{1}{v_i}$ in a Taylor series with constant C ,

$$\frac{1}{v_i} = A_0 + A_1(v_i - C) + A_2(v_i - C)^2 + A_3(v_i - C)^3 + \dots \quad (2.46)$$

A_j is evaluated by differentiating with $j = 1, 2, 3, \dots$

$$A_j = \frac{1}{j!} \frac{d^j}{dX^j} \left(\frac{1}{v_i}\right) \Big|_C \quad (2.47)$$

Letting $C = E(v_i)$ and taking the expectation,

$$E\left(\frac{1}{v_i}\right) = \frac{1}{E(v_i)} - \frac{1}{E^2(v_i)} E(v_i - E(v_i)) + \frac{1}{E^3(v_i)} E(v_i - E(v_i))^2 - \frac{1}{E^4(v_i)} E(v_i - E(v_i))^3 + \dots \quad (2.48)$$

By definition, $E(v_i - E(v_i)) = 0$. Similarly, for any distribution that is approximately symmetric,

$E(v_i - E(v_i))^a \approx 0$ with odd positive integer a . Thus,

$$E\left(\frac{1}{v_i}\right) \approx \frac{E^2(v_i) + \text{Var}(v_i)}{E^3(v_i)} \quad (2.49)$$

And the expected directional travel time of the final vehicle through the work zone becomes,

$$E(T_i) \approx \ell \cdot \frac{E^2(v_i) + \text{Var}(v_i)}{E^3(v_i)} \quad (2.50)$$

The variance of travel time is expressed as

$$\begin{aligned} \text{Var}(T_i) &= \ell^2 \cdot \text{Var}\left(\frac{1}{v_i}\right) \\ &= \ell^2 \cdot \left(E\left(\frac{1}{v_i}\right)^2 - E^2\left(\frac{1}{v_i}\right) \right) \end{aligned} \quad (2.51)$$

Expanding the term $\left(\frac{1}{v_i}\right)^2$ in a Taylor's series and taking the expectation, we determine

$$E\left(\frac{1}{v_i}\right)^2 \approx \frac{E^2(v_i) + 3\text{Var}(v_i)}{E^4(v_i)} \quad (2.52)$$

$$\text{Var}\left(\frac{1}{v_i}\right) \approx \frac{E^2(v_i) + 3\text{Var}(v_i)}{E^4(v_i)} - \left(\frac{E^2(v_i) + \text{Var}(v_i)}{E^3(v_i)} \right)^2 \quad (2.53)$$

2.5. Extending Deterministic Models for Oversaturated Condition

Applying the above models to evaluate oversaturated conditions at a work zone entrance is relatively simple. The basic phenomena can be represented by a queueing diagram illustrated in Figure 2-3.

For a known or assumed directional arrival flow, the cumulative arrivals to time t , $A(t)$, can be constructed as shown in Figure 2-3. The dashed line in Figure 2-3 represents the capacity of the subject work zone entrance. Its slope is equal to $(G/C)s$ [Hurdle, 1988]. This dashed line has been drawn tangent to $A(t)$ at time zero, signifying the time when the work zone entrance first becomes oversaturated. The departure curve, $D(t)$, in Figure 2-3 represents the time-dependent rate at which vehicles enter the work zone. Of primary importance is the recognition that the area between the curves $A(t)$ and $D(t)$ represents the total vehicle delay at the work zone entrance. Average delay is this total value divided by $A(t) - A(0)$. The dashed line in Figure 2-3 thus divides the area (i.e., the total delay) into two components : uniform delay below the dashed line and overflow delay above.

Equation (2-12) is used to identify if and when oversaturated conditions prevail at a work zone entrance. Where (2-12) yields a required green time, G_r , larger than permissible by policy/judgement, the analyst is then required to specify the actual right-of-way time which will prevail at the work zone entrance. This allowable green time, G_a , should reflect the largest value judged to be acceptable (i.e., the largest time interval over which flaggers are willing to extend right-of-way). The value of G_a will dictate the horizontal distance (i.e., the time interval on the queueing diagram) over which queue discharge will occur.

The effective red time (i.e., the horizontal distance over which vehicles do not enter the work zone) is the sum of the required/actual green time in the opposing direction, the start-up lost times and one "round-trip" travel time through the work zone.

To include the delay component created by reduced vehicle speeds within the work zone, the cumulative number of departing vehicles within the time interval of interest is observed from the queueing diagram. The product of this value of $D(t)$ and the average travel time delay (i.e.,

the difference between "actual" and "normal" work zone travel times) is added to the total queueing delay.

The fact that this analytical approach does not account for delays created by "random effects" will generally not be a concern. Added delays created by operational stochasticity will typically be very small relative to the deterministic delay estimate.

To eliminate the tedium created by requiring the user to evaluate delay by constructing an appropriate queueing diagram, the methodology has been computerized (Appendix B).

Figure 2-3
Queueing Diagram Depicting Over-saturated Condition
(Source : Hurdle, 1988)

3. EMPIRICAL OBSERVATIONS

The delay prediction models described in the previous chapter rely upon empirical estimates of arrival rates, work zone travel speeds, queue discharge rates, start-up lost time and green time extensions. The variables q_i and q_o representing work zone traffic demands in each direction and work zone length ℓ must be known or assumed input to the prediction model. To insure that derived methodologies accommodate a broad range of application, empirical data were collected from a number of different work zone locations operating under a variety of work zone activity types. The work has exploited a large empirical data base collected in California as part of an earlier research project sponsored by the California Department of Transportation.

To some extent, traffic operations at two-lane highway work zones represent idealized scenarios. For example, traffic moves through a single channel (i.e., lane). Thus, virtually no vehicle over-taking maneuvers occur. Moreover, the work zone areas used for data collection in this research typically had few, if any, and minor access and egress points. Thus, for all practical purposes, conservation of vehicles was maintained (i.e., vehicles entering and exiting the work zone were essentially the same). The data collection techniques employed in the research have sought to capitalize on these idealized prevailing conditions. Chapter 3 summarizes data collection and analysis tasks to derive suitable estimates. Table 3-1 summarizes the sites from which data were collected. In total, over 70 hours of operational data were collected from California test sites reflecting 4 types of work activity.

3.1. Data Collection

The data collection team consisted of two persons, each equipped with a lap-top computer with synchronized internal clocks. A program (written in BASIC language) was developed to record the actual times in which computer keys were pressed. Specific keys of the lap-top computer were designated for recording the occurrence times of specific events. The resulting

Table 3-1
Summary of Empirical Observation

SITE No.	LOCATION	OBSERVATION DATE(S)	WORK ACTIVITY	WORK ZONE LENGTH(S)	PILOT CAR	HOURS OF OBSERV.
1*	Highway 28 Carnelian Bay	6/17/91	A-C	3,031 ft	Yes	6
2*	Highway 28 Tahoe City	6/19/91	A-C	5,070 ft	Yes	3
3	Highway 89 Truckee	6/20/91	A-C	4,181 ft	Yes	3.5
4	Highway 193 Newcastle	6/21/91	Pavement Markers	5,964 ft	No	0.5
5	Highway 267 Placer Cnty	6/24/91	A-C	6,481 ft	Yes	7
6	Highway 193 Georgetown	7/8/91 - 7/10/91	Chip-Seal	2,495 ft - 4.15 mi	Yes	11.5
7	Highway 267 Truckee	7/10/91	A-C	5,691	Yes	1.5
8	Highway 49	7/15/91 - 7/16/91	Chip-Seal	3.1 - 3.4 mi	Yes	13.5
9	Highway 49/89 Sierraville	6/17/91	Chip-Seal	3.5 mi	Yes	5
10	Highway 49 Placer Cnty	6/8/92	Saw Cutting	1,091 - 1,526 ft	No	2
11	Highway 50 El Dorado Cnty	6/9/92 - 6/10/92	Saw Cutting	1,380 ft	No	5
12	Highway 89 El Dorado Cnty	6/11/92 - 6/12/92	Shoulder Work	2,962 - 3,421 ft	No	6
13	Highway 108 Tuolumne Cnty	6/22/92	Shoulder Work	985 ft	No	5.5
14	Highway 88 Alpine Cnty	6/23/92	Striping	8,828 ft	Yes	3.5
15**	Highway 50 El Dorado Cnty	6/10/92	A-C	3,760	Yes	3.5

* Pilot study site; observations collected in 1 direction only

** Validation site; delay data collected

computer files were programmed to display observation times with notations defining the specific event associated with each recorded time.

The two data collectors positioned themselves at opposite ends of the work zone (along side the flaggers). Using the lap-top computers, the data collectors simultaneously recorded the actual times of relevant events. Specifically, the real-time recorded observations were:

1. The times at which the flaggers initiated right-of-way for the subject direction of travel.
2. The times at which each queued vehicle actually "entered" the work zone (i.e., the times the front bumper of each vehicle crossed an imaginary line at the flagger's station).
3. The times at which the last queued vehicle "entered" the work zone.
4. The times of any additional vehicles entering the work zone after the queue had dissipated.
5. The times at which the flagger terminated right-of-way for the subject direction of travel.
6. The times at which vehicles traveling in the opposing direction exited the designated work zone area.

An example computer print-out for a single cycle is presented in Figure 3-1.

The data collectors individually recorded these event times at each end of the work zone over repeated cycles. These data provide virtually all relevant information for defining motorist delays at the work zone.

- The elapsed time between the exit of the last vehicle in the opposing platoon and the entry of the first queued vehicle in the subject travel direction reflects start-up lost time, L .
- The elapsed times between successive queued vehicle entries into the work zone represent discharge or saturation headway which is the inverse of saturation flow rate, S .
- The elapsed times between entry of the last queued vehicle and the final vehicle entry in the same direction (each cycle) represents the green time extension, E .

```
13:55:33 Flagman initiates ROW
13:55:40 Car enters
13:55:44 Car enters
13:55:48 Car enters
13:55:50 Car enters
13:55:53 Truck enters
13:55:58 Car enters
13:56:01 Car enters
13:56:02 Car enters
13:56:05 Car enters
13:56:07 Car enters
13:56:10 Last CAR in Queue
13:56:15 Car enters
13:56:18 Flagman terminates ROW
13:59:30 1st vehicle opposing direction
14:02:58 Last vehicle opposing direction
14:03:03 Flagman initiates ROW
```

Figure 3-1
Example Data File

- Given the prevailing "first-in, first-out" queueing discipline and the absence of major access points within the work zone, the sequential work zone entry and exit times define work zone travel times (and thus speeds). Typically, vehicle travel times were sampled for first and last vehicles in each platoon.

Some amount of error likely occurred when measuring travel times based on vehicle entry and exit times. Such errors could have occurred as a result of vehicles joining or leaving platoons via the minor access points within the designated work zone area. However, even under extreme scenarios, measured errors would generally lead to computed speed errors of less than 1 mph. This is well within the range of random speed fluctuations naturally occurring within the work zone. Moreover, the measured sample travel times were augmented with numerous "floating car runs" where travel times were measured in a *test car* operated by the data collection team.

- Cycle lengths were measured as previously defined.
- As queues often extended beyond view of the data collectors, vehicle arrival times were generally not recorded simultaneously with vehicle discharge times. This means that hourly traffic demands can only be approximated (rather than precisely determined) from the resulting data sets. This approximation is not a concern given that relevant parameters (i.e. work zone travel speeds, saturation headways and lost times) will not vary as a function of small changes in traffic demand. Moreover, vehicle arrival times were separately sampled upstream of work zone entrances to confirm arrival patterns.

Data were typically collected over 90 minute time intervals.

3.2. Data Analysis

For illustration purposes, table 3-2 presents directional hourly demand rates over each 90-minute observation interval measured at site numbers 3,5 and 7 - each of which represents work zones operating under A-C overlay activities.

Table 3-2 Observed Traffic Demand Rates

Site Number	Observation Time	Demand (vph)		
		Northbound	Southbound	Total
3	8:00-9:30 am	201	165	366
	10:00-11:30 am	227	243	470
5	8:00-9:00 am	217	167	384
	10:00-11:30 am	272	225	497
	12:00-1:30 am	227	258	485
7	1:30-3:00 pm	215	302	517

Table 3-3 presents statistics for observed cycle length for each 90-minute interval (in both directions of travel). The observed operations exhibit considerable variation from cycle to cycle. Referring to the values of each coefficient of variation (COV), cycle lengths observed over each 90-minute interval vary from 12 to 41 percent. These variations are attributable to fluctuations in arrival and departure rates as well as occasional interruptions to traffic flow caused by the work activity.

The variability in cycle length is exhibited not only within sites, but between sites as well. Although conditions prevailing at site 7 do not differ dramatically from the other two locations, the site's average cycle lengths exceed the other two locations by a factor of almost two. Evaluation of the data collected at site 7 indicated that the location operates with significantly higher start-up lost times and a higher frequency of random interruptions (reflected in the periodic occurrence of large individual saturation headways).

This observed variability in work zone operation (i.e. cycle length) obviates the need for a probabilistic approach to delay prediction where under-saturated conditions prevail.

Table 3-3 Observed Cycle Length Statistics

Site No.	Observation Time	Travel Direction	Cycle Length		
			Mean (mins)	Variance (mins ²)	COV
3	8:00-9:30 a.m.	Northbound	10.6	3.3	0.17
		Southbound	10.6	3.1	0.17
3	10:00-11:30 a.m.	Northbound	11.7	22.6	0.41
		Southbound	12.6	15.4	0.31
5	8:00-9:30 a.m.	Northbound	10.8	1.9	0.13
		Southbound	10.8	3.2	0.17
5	10:00-11:30 a.m.	Northbound	12.3	3.6	0.15
		Southbound	12.1	2.6	0.13
5	12:00-1:30 p.m.	Northbound	10.5	1.5	0.12
		Southbound	10.0	1.7	0.13
7	1:30-3:00 p.m.	Northbound	20.4	40.6	0.31
		Southbound	19.7	40.1	0.32

4. SIMULATION MODEL

The accuracy of the proposed model was evaluated using a microscopic, stochastic computer simulation model developed as part of this research project. This report section describes the simulation model and simulation-based validation efforts. The final portion of this report section documents the validation tasks exploiting the available empirical data base.

4.1 Microscopic Simulation Model

A schematic flow chart of the FORTRAN-based simulation model is presented in Figure 4-1. The microscopic simulation model is designed to estimate individual vehicles' queueing delay at the work zone entrance and does not generate the delay created by traveling through the work zone at less than desired speed. Queueing delay (alone) is sufficient for validation purposes as work zone travel delay is clearly the difference between actual and desired travel times.

Directional vehicle demand rates, the physical length of the lane closure and the time period to be analyzed are specified inputs. Directional vehicle arrival times, queue discharge headways and work zone travel speeds of last vehicles in platoon are microscopically selected by the model based upon empirically identified distributions. Following this, the simulation model replicates the operational characteristics occurring under one way traffic control.

- Following the initiation of right-of-way in a given direction, queued vehicles discharge into the work zone at so-called "saturation flow rate."
- Once the directional queue has completely dissipated, right-of-way may be extended to serve additional vehicles arriving "shortly after" the queue dissipation time. Specifically, right-of-way is continued until the elapsed time between consecutively arriving vehicles exceeds 12.2 seconds. The 12.2-second limit was empirically derived using discrete choice

Figure 4-1
Microscopic Simulation Model

analysis [Ben-Akiva and Lerman, 1985]

- All discharged vehicles traverse the work zone segment.
- Once the "last vehicle" in the discharging direction has completely traversed the work zone, some minor "lost time," on the order of a few seconds, occurs prior to right-of-way allocation to the opposing directional queue. (Given it's small contribution to operating time, this lost time was deterministically modeled in the simulation). The process is then repeated for the opposing directional movement. Several hours of simulation time were used to initialize (i.e., "warm-up") each experiment to insure the system (i.e., work zone) had reached steady state conditions [Son, Cassidy & Madanat, 1994].

4.1.1. Threshold Headways

During one-way traffic control, the extension of right-of-way beyond queue dissipation reflects the subjective judgement of flaggers. This decision process can be classified as a binary choice to extend or terminate green time based upon the headway of the next arriving vehicle. Thus, the maximum headway that motivates the flagger to extend green time (i.e., the threshold headway) was identified and introduced in the simulation model.

A probit model [Ben-Akiva and Lerman, 1985] was likewise estimated from empirical observations to identify the probability of right-of-way termination (by flaggers) following queue dissipation as a function of the next arriving vehicle's headway length. A mean value of H (a "threshold" headway) was derived from the probit function [Mahmassani and Sheffi, 1981].

The model recognizes variations in threshold values across flaggers. All headways which are larger than the flagger's threshold headway are invariably rejected (right of way terminated). Conversely, flaggers accept all headways smaller than or equal to the threshold headway. It is further assumed that these threshold values follow some probability distribution across the population of flaggers. The mean of this distribution is the relevant parameter in this model.

If we define $Pr(a)$, as the probability that a headway t after queue dissipation is greater than or equal to the flagger's threshold value H_{th} ,

$$\begin{aligned}
 Pr(a) &= P(t \geq H_{th}) \\
 &= P(t \geq \bar{H}_{th} + \epsilon) \\
 &= P(\epsilon \leq t - \bar{H}_{th})
 \end{aligned} \tag{4.1}$$

Where H_{th} is the mean value of thresholds and ϵ is the random deviation or disturbance of each flagger's threshold value from the mean. One logical assumption is to view the disturbance as the sum of a large number of unobserved and independent components. By the central limit theorem, the distribution of the disturbances would tend to be normal.

$$\begin{aligned}
 Pr(a) &= pr(\epsilon \leq t - \bar{H}_{th}) \\
 &= \Phi\left(\frac{t - \bar{H}_{th}}{\sigma}\right)
 \end{aligned} \tag{4.2}$$

where σ is the standard deviation of the disturbance and $\Phi(\bullet)$ denotes the standardized cumulative normal distribution.

Equation (4.2) can be rewritten as

$$\begin{aligned}
 Pr(a) &= \Phi[\beta(t - \bar{H}_{th})] \\
 &= \Phi[\beta t - \alpha]
 \end{aligned} \tag{4.3}$$

where: $\alpha = \beta \bar{H}_{th}$.

Values of $\hat{\alpha}$ and $\hat{\beta}$ (the estimates of α and β) are obtained through Maximum Likelihood Estimation [Benjamin and Cornell, 1970]. The value of H_{th} is estimated using the relation

$$\bar{H}_{th} = \frac{\hat{\alpha}}{\hat{\beta}} \quad (4.4)$$

Right-of-way is invariably extended whenever an arriving vehicle's headway is less than H_{th} and right-of-way is terminated when a headway exceeds H_{th} . Figure 4-2 presents the Maximum Likelihood Estimation results. Using Equation (4.4), H_{th} is estimated to be 12.2 seconds.

Independent Variable	Estimated Coefficient	Standard Error	t - Statistics
one	2.32083	0.25992	8.92911
headway	-0.19006	2.62013e-002	-7.25379
Auxiliary Statistics		at Convergence	Initial
log likelihood		-79.622	-155.96
number of observation		225	
percent correctly predicted		82.667	

Figure 4-2
Maximum Likelihood Estimation

4.2. Evaluation of Model Accuracy

As a means of evaluating the closed-form expressions presented in section 2 of this report, delay estimates yielded from these models were compared with simulated values for a range of specified operating conditions.

4.2.1. Experimental Design

Eighteen work zone operating scenarios were selected to represent commonly observed conditions in the field. The 18 scenarios, presented in Table 4-1, reflect a range of directional traffic demand rates and work zone physical lengths. Each of the 18 scenarios were simulated for 1,000 operating cycles (following a suitable "warm-up" time) to generate average values of directional delay at the work zone entrances. As the microscopic, stochastic simulation model replicates the actual phenomena of work zone operation and all relevant random variables conform to empirically observed distributions, outcomes from the microscopic simulations can be viewed as "exact" (i.e., real-world) solutions.

Delay values generated through simulation were compared with estimates from the closed-form, stochastic models in section 2. As green time extensions, E_i represent relatively small portions of the cycle length, delay estimates were derived from the closed-form expression by 1) incorporating estimated values of E_i as described in section 2.4.2, and 2) assuming $E_i = 0$.

4.2.2. Validation Findings

Table 4-2 presents estimates of average directional delay at the work zone entrance for each of the 18 scenarios. Referring to Table 4-2, differences between delay estimates generated

Table 4-1

Scenarios Evaluated Through Simulation

Scenario No.	Work Zone Section Length (miles)	Flow Rate Direction 1 (vph)	Flow Rate Direction 2 (vph)	Total Flow Rate (vph)
1	1	100	100	200
2	1	100	200	300
3	1	100	300	400
4	1	300	100	400
5	1	200	300	500
6	1	250	250	500
7	1	300	200	500
8	1	300	300	600
9	1.5	100	100	200
10	1.5	100	200	300
11	1.5	100	300	400
12	1.5	200	300	500
13	1.5	300	300	600
14	0.75	100	100	200
15	0.75	100	200	300
16	0.75	100	300	400
17	0.75	200	300	500
18	0.75	300	300	600

Table 4-2

Estimated Average Delays

Scenario No.	Simulation (sec)	(1) Stochastic Model Incorporating E_i (sec)	(2) Stochastic Model $E_i=0$ (sec)	Difference between (1) and (2) (%)
1	279	317	319	0.6
2	319	342	342	0.0
3	360	378	375	0.8
4	300	342	346	1.1
5	383	400	397	0.8
6	377	387	386	0.3
7	348	376	376	0.0
8	415	429	426	0.7
9	412	459	462	0.6
10	456	491	492	0.2
11	528	538	536	0.3
12	561	568	566	0.4
13	600	608	605	0.5
14	224	247	248	0.4
15	257	268	267	0.4
16	283	298	295	1.0
17	311	316	313	0.9
18	372	340	336	1.0

by simulation and by the stochastic models are generally less than 10 percent.

Invariably, the differences in delay as estimated with and without consideration of E_i are negligible. To some extent, the insignificance of E_i might be attributable to pilot car operation. Where a pilot car is utilized, platoon speeds through the work zone are generally much lower than in the absence of a pilot car [California, 1978; Cassidy, Son and Rosowsky, 1993] as platooned motorists are constrained to travel at speeds selected by the pilot car operator. Vehicles entering the work zone after queue dissipation typically travel at "desired" speeds until joining the tail of the slower-moving platoon. As these "late arrivals" subsequently select relatively short headways, their presence creates only minor additional time to clear the work zone before allocating right-of-way to the opposing direction.

In the absence of pilot car operation, however, vehicles allowed entry into the work zone following queue dissipation often do not "catch up" with the through-moving platoon. Thus, the initiation of right-of-way for the opposing direction is postponed (until the final discharging vehicle completely traverses the work zone) which may substantially increase delay.

4.2.3. Empirical Validation Data

Although the microscopic simulation model closely replicates "real-world" conditions, empirical data perhaps facilitate the most convincing validations. The limitation in applying empirical data for the validation of predicted delay distributions stems from an inability to collect a sufficient sample size. A sufficient data collection is not possible given that prevailing work zone operating conditions (specifically vehicle arrival rates) typically vary from hour to hour. Thus, conditions can not be fixed for a time period required to observe 100 or more cycles. In short, a reasonable distribution of average cyclic delays can not be observed in the field.

One can, however, field measure directional delays for finite periods of time and compare

empirically observed average values with average values generated from the queueing models. Such comparisons would verify the predictive capabilities of the models which lie at the foundation of the methodologies for both under-saturated and over-saturated conditions.

The site used for collecting validation data was Highway 50 in El Dorado county, California. Approximately 90 minutes of vehicle delay observations were collected in each direction of travel. Individual vehicle delays were measured as the difference between actual and desired travel times between the work zone entrance and a fixed location upstream of queueing activity. Computed free-flow travel times were subtracted from the actual measured travel times approaching the work zone entrance. Average values were reflected as the summed total delay values divided by the number of arriving vehicles.

The field-measured values of average delay in queue for each direction of travel are compared with deterministically predicted values in Table 4-3. Discrepancies are under 10 percent.

Table 4-3

Field-Measured and Predicted Average Delay with Queueing Model (for subject direction)

Length (ft)	Traffic Volume (vph)		Field- Measured (mins/veh)	Predicted (mins/veh)	Error (%)
	subject dir.	opposite dir.			
3,760	309	207	3.7	4.1	9.7
3,760	396	310	5.0	5.5	9.0
3,760	328	390	5.9	6.3	6.3

5. SUMMARY AND CONCLUSIONS

This report has described tasks associated with the development of a methodology for assessing traffic flow impacts (i.e., delay) resulting from the implementation of one-way traffic control. Methodologies have been formulated for both under-saturated and over-saturated operating conditions.

Stochastic queueing models are used to estimate average delay prevailing at two-lane highway work zone for under-saturated conditions. The models are based upon previously derived expressions for delay estimation at the V-A signalized intersection of one-way streets [Newell, 1969] adapted to accommodate operating characteristics unique to one-way traffic control. The models capture stochastic affects on expected delay as a function of directional traffic demands, work zone physical length and observable traffic stream measures prevailing at under-saturated work zone operations.

For over-saturated conditions, increased delays created by random effects (e.g., variations in traffic stream characteristics) are very small relative to the deterministic delay components. As such, the proposed methodology for assessing over-saturated operation exploits deterministic queueing analysis techniques.

The models presented in this report estimate work zone queueing delay. The additional delay which is incurred by motorists as they travel through the work zone at less than desired speed is merely the difference between the expected work zone travel times and a presumed travel time in the absence of a work zone.

To evaluate the accuracy of the proposed stochastic models, a computer simulation model was developed. Based upon the outcomes generated by the simulation model, the proposed delay expressions appear to adequately reflect the impacts of the work zone operation at a two-lane highway. Validation tasks using empirical data confirm this conclusion.

Finally, to simplify and expedite the application of the proposed methodologies, all formulated procedures have been fully computerized. The resulting software package facilitates application of the methodologies with a minimum of time and effort. A software User's Manual is contained in Appendix B of this report.

REFERENCES

1. BEN-AKIVA, M. and LERMAN, S. (1985). Discrete Choice Analysis. Cambridge, Massachusetts: MIT Publishing.
2. CALIFORNIA (1978). One-Way Traffic Control on Construction Projects. California Department of Transportation Memorandum. Sacramento, California. Unpublished.
3. CASSIDY, M.J. and HAN, L.D. (1993). A Proposed Model for Predicting Motorist Delays at Two-Lane Highway Work Zones. ASCE Journal of Transportation Engineering. 119, 27-42.
4. CASSIDY, M.J., SON, Y.T. and ROSOWSKY, D.V. (1994). Estimating Motorist Delay at Two-Lane Highway Work Zones. Transportation Research-A. In press.
5. CASSIDY, M.J., SON, Y.T. and ROSOWSKY, D.V. (1993). Predicting Vehicle Delay During Maintenance or Reconstruction Activity on Two-Lane Highways, Final Report No. CE-TRA-93-1, Purdue University, West Lafayette, Indiana.
6. CEDER, A. and REGUEROS, A. (1990). Traffic Control (at alternate one-way sections) During Lane Closure Periods of a Two-Way Highway. Proceedings 11th International Symposium on Transportation and Traffic Theory. M. Koshi, Editor. New York: Elsevier Publishing.
7. CEDER, A. (1993). Traffic Behavior During Lane Closure Periods of Two-Lane Road. Proceedings 12th International Symposium on Transportation and Traffic Theory. C. Daganzo, Editor. New York: Elsevier Publishing.

8. DARROCH, J.N., NEWELL, G.F., and MORRIS, R.W.J. (1964). Queues for a Vehicle-Actuated Traffic Light. Operations Research. 12, 882-895.
9. DUNNE, M.C., and POTTS, R.B. (1965). Analysis of a Computer Control of an Isolated Intersection. Proceedings 3rd International Symposium on the Theory of Traffic Flow. New York: Elsevier Publishing.
10. HURDLE, V. F. (1984). Signalized Intersection Delay Models - A Primer the Uninitiated, Transportation Research Record 971, Transportation Research Board, Washington, D. C.
11. MAHMASSANI, H. and SHEFFI, Y.(1981). Using Gap Acceptance Sequences to Estimate Gap Acceptance Functions. Transportation Research-B. 15B, 243-248.
12. NEWELL, G.F. (1969). Properties of Vehicle-Actuated Signals: I One-Way Streets. Transportation Science, Vol. #3, 30-51.
13. Special Report 209 (1985), The Highway Capacity Manual, Transportation Research Board, Washington D.C.
14. Son, Y.T, Cassidy, M.J. & Madanat, S.M., "Evaluating the Appropriateness of the Steady State Assumption for a Highway Queueing System," *accepted for publication*, ASCE Journal of Transportation Engineering, September, 1993.
15. WEBSTER, F.V. and COBB, B.M. (1966). Traffic Signals. Road Research Laboratory Technical Paper 56, Crowthorne, England.

APPENDIX A: PARAMETER VALUES FOR EACH WORK ACTIVITY TYPE

Table A-1 presents field-measured values for relevant operational parameters observed under all four types of work activity. The upper portion of this table presents average parameter values and the lower portion tabulates observed standard deviations required for estimating the average delay per cycle.

Table A-1
Model Parameter Values

Parameters	WORK ACTIVITY TYPE			
	A-C	Chip-Seal	Construction-a	Construction-b
Expected value				
Saturation Flow (vph)	1084	1018	1090	1048
Speed (ft/sec)	34	29	45	30
Lost Time (secs)	30	23	35	15
Variance				
Speed (ft/sec) ²	10.5 ²	7.7 ²	11.0 ²	3.2 ²
Lost Time (secs) ²	0	0	104.9 ²	0
Threshold Headway(secs)	12.21			

a- without pilot car

b- with pilot car

APPENDIX B: USER MANUAL

work - Software for Analyzing One-way Traffic Control Impacts

B.1 Introduction

The computer program "*work*" has been developed to assess the impacts imparted to vehicles as a result of one-way traffic control implementation. The program, which can evaluate both undersaturated and oversaturated operating conditions, exploits the computational procedures previously described in the final report. The reader should refer to the report for procedural details concerning the delay prediction models as well as any technical issues noted in this Appendix (i.e., *User Manual*). As the name implies, the subject appendix addresses use of the software packages itself.

B.2 Installing the *work* Software

The Software can be run on IBM-compatible personal computers. A math co-processor is required where *work* is to be operated on 286-machines (i.e., 80286).

Although the *work* software can be assessed and executed from the diskette, computational speed is enhanced by accessing the program from the "hard disk". Copying the contents of the *work* diskette to the hard disk can be performed using standard DOS commands. The user may wish to first create a unique directory using the commands

md\dirname

where *dirname* represents the user-specified name of the directory. Once changing to this directory using the command

cd\dirname

the contents of the *work* diskette can be transferred to the specified directory with the command

copy *d*:work.exe

where *d* represents the drive where the *work* diskette has been inserted.

B.3 Executing *work* - Program Input

The program is accessed by typing *work*. Once accessing the program, the user is merely required to respond to all prompts by typing in the appropriate information and then hitting *<return/enter>*:

a) name of highway (up to 10 characters)

This information is optional, although such data can aid in "book-keeping" matters.

**b) if the highway is east-west, type 1
if the highway is north-south type 2**

This information is used to "orientate" the analysis to the directional alignment of the subject highway. Typing a numeric character other than 1 or 2 will not effect procedural computations. However, entering a number other than 1 or 2 will mean that subsequent prompts (and print-out) will not display travel directions.

c) hours of analysis

This prompt represents the total number of consecutive hours over which analysis is to occur. Selecting a number for hours of analysis is not particularly important where operation reflects undersaturated conditions given that, under these conditions, operation during a previous hour will not influence the following hour. However, where oversaturated conditions prevail, the

occurrence of residual queueing impacts operation from one hour to the next. The reader may refer to "Example 2" in this appendix for a brief discussion of this issue.

Up to 29 consecutive hours can be specified for evaluation using *work*. Specifying more than 29 hours will eventually result in a "run time error".

d) maximum green time for *northbound* or *eastbound* direction (mins)

This information reflects the assumed maximum time (in minutes) over which flaggers are willing to allocate right-of-way before "cutting-off" a discharging queue of vehicles. This specified value, which should be based upon judgement or existing operating policies, is important only in the context of oversaturated operating conditions. Where a prevailing directional green time calculated by the software exceeds the maximum specified value, oversaturated conditions will occur. The directional green times assumed to prevail during oversaturated conditions are the specified maximum values.

Specified maximum green time values in *work* must be greater than 0 (minutes) and less than 60 (minutes).

e) maximum green time for *southbound* or *westbound* direction (mins)

same as above

f) work zone length (miles)

The physical length of the work zone (in miles) is to be entered here. Any value of length can be specified where work activity is A-C, chip-seal or general construction (i.e., "other") with the use of a pilot car. The somewhat unique operating characteristics of general construction activity without the use of a pilot car dictates that specified work zone lengths should be greater than 0.25 (miles) for avoiding erroneous predictions.

g) vehicle demand rate - *northbound* or *eastbound* (veh/hr)

hour 1

The user is required to enter directional vehicle demand rate for each hour of analysis. The user is sequentially prompted for hourly demand rate up to the hour number previously specified in c). The prompts sequentially request all hourly demand rate entries for the northbound *or* eastbound directions before requesting the equivalent information for the opposing travel direction.

work can accommodate any specified demand rate.

h) speed limit or estimated prevailing speed in the absence of a work zone (mile/hr)

An estimate of the subject highway's "normal" prevailing average speed in the absence of one-way traffic control is required to determine travel time delay through the work zone itself.

work will accommodate any specified value of "normal" speed. However, specified values less than 35 (mph) may result in negative travel time delays as observed work zone vehicle speeds for some job types approached 35 mph.

i) job type

asphalt concrete	= 1
chip seal	= 2
other if pilot car is not used	= 3
other if pilot car is used	= 4

The user is required to specify the type of work activity prevailing at the work zone by selecting options (i.e., keys) 1,2,3 or 4. This is important input information as parameter values such as vehicle queue discharge rates and work zone travel speeds will vary as a function of job type.

The term "other" refers to general construction activity such as shoulder work, cross-drain installation or restriping activity. Where a job type to be analyzed does not fall into one of the four available categories, the user should select the job type option most closely conforming to

the work activity in question.

j) Comment (up to 30 characters)

This prompt provides the user with the option to input relevant characteristics of the subject analysis as a means to assist in "book-keeping". The user can enter up to 30 characters (including spaces between characters.)

k) File name missing or blank - please enter file name

This prompts is merely requesting the user to name the output file which will represent the analysis of the now-specified input conditions. Filenames can consist of up to 8 alpha and/or numeric characters.

l) Do you want to change options ? (Yes = y, No = n)

This prompt represents the *work* program's only editing function. Specifically, the prompt is intended to facilitate sensitivity analyses. By responding "y" to this prompt, the user can change one or more operating parameters (and/or comments) and thereby direct the *work* program to automatically re-analyze operation under modified scenarios.

Parameters which can be directly modified through this prompt are

1. work zone length
2. maximum directional green times
3. "normal" speed in the absence of a work zone
4. job type

The benefits offered by this "editing function" are perhaps obvious. Assume, for example, that a user is interested in identifying a work zone physical length which will result in "acceptable" delays. Assume also that the user wishes to evaluate operation over numerous consecutive hours. Rather than re-entering all required input information (including hourly

demands) and re-executing the *work* program under varying section lengths, the user can *a priori* specify an array of possible work zone lengths for the previously specified input conditions and automatically execute an analysis for each specified length.

The user can specify desired input modifications by appropriately responding to each prompt. Once the user has "cycled through" one sequence of prompts, the software will again display the prompt **Do you want change options ? (Yes = y, No = n)**. In this way, the user can perform virtually unlimited iterations under modified input conditions. Each sequence of prompts will automatically result in a separate analysis reflecting specified changes.

Figure B-1 presents the computer screen reflecting the input information required for Example Problem 1.

B.4 Program Output

Promptly after responding to the editing feature (and hitting <return>), the *work* program will execute all computations. The resulting message display is

Stop - Program terminated

The output file (i.e., the resulting analyses) can be viewed directly from the computer monitor and/or permanent output can be printed using a standard printer device.

To view output directly on the computer, the user can type the DOS command

type *filename*

where *filename* represents the name assigned to the output file described in **k**). This command will cause the entire output to scroll past the monitor, stopping at the end of the file.

```

name of highway (up to 10 characters)
Hwy 49 Down
if the highway is east-west, type 1
if the highway is north-south, type 2
2
hours of analysis
2
maximum green time for northbound direction (mins)
7
maximum green time for southbound direction (mins)
7
work zone length (miles)
3.25
vehicle demand rate-northbound (veh/hr)
hour      1
170
hour      2
160
vehicle demand rate-southbound (veh/hr)
hour      1
140
hour      2
145
speed limit or estimated prevailing speed
in the absence of a work zone (mile/hr)
45
job type
Asphalt Concrete Overlay      = 1
Chip Seal                     = 2
other if pilot car is not used = 3
other if pilot car is used    = 4
2
Comment (up to 30 characters)
Example Problem 1
File name missing or blank - please enter file name
UNIT 2? Test1
Do you want to change options ? (Yes = y , No = n )
n
Stop - Program terminated

```

Figure B-1
Example Input Information

To review the output file on the monitor page by page requires the DOS command

type *filename*more

Each new output page is displayed on the monitor by hitting <return>.

Printing a "hard copy" of the output requires the DOS command

print *filename*

Where the printer has not been previously used to print *work* output, the analyst is required to initialize the printer by hitting <return> in response to the prompt

name of list device [prn]

The prompt *filename* is currently being printed is displayed whenever a print-out is requested by the user.

B.5 Sample Output / Example Problems

The format and the information conveyed on *work* output depend upon whether prevailing operation is undersaturated or oversaturated. These format differences are consistent with the differences in actual computations. The differences are illustrated in three Example Problems.

Example Problem 1 : undersaturated conditions

Required Input Information

Location : Highway 49, Downeville

Orientation : North-South

hours of analysis : 2 (e.g. 8:00 am through 10:00 am)

maximum green time for both directions of travel : 7 minutes

work zone length : 3.25 miles

demand rates (vph) :

	Northbound	Southbound
Hour 1	170	140
Hour 2	160	145

Speed limit / prevailing "normal" speed : 45 mph

job type : chip seal

The input information (displayed on the computer monitor) for Example Problem 1 has been previously presented in Figure B-1. Figure B-2 presents the output generated from the *work* program. Referring to Figure B-2, relevant input information is reproduced on the output file. Both hours of analysis are undersaturated. For each of the two hours, the average delay per vehicle (in minutes) and total delay (in vehicle-hours) is displayed for each travel direction.

If the user so desires, total directional delay can be calculated as the sum of each directional hourly value. Total average delay in both directions is a weighted average of hourly directional delay and hourly directional demand rates. The output also displays initial and residual queue lengths (measured in vehicles) which are zero for undersaturated conditions.

ANALYSIS RESULTS

Highway	Hwy49	Down
Hours of Analysis	2	hour(s)
Job Type	Chip Seal	
Work Zone Length	3.25	mile(s)
Maximum Green Time		
northbound	7.00	min
southbound	7.00	min

Figure B-2

Output - Example Problem 1

Comments : Example Problem 1

	northbound	southbound
hour 1	170.	140.
hour 2	160.	145.

Initial Queue	Residual Queue
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	10
11	11
12	12
13	13
14	14
15	15
16	16
17	17
18	18
19	19
20	20
21	21
22	22
23	23
24	24
25	25
26	26
27	27
28	28
29	29
30	30
31	31
32	32
33	33
34	34
35	35
36	36
37	37
38	38
39	39
40	40
41	41
42	42
43	43
44	44
45	45
46	46
47	47
48	48
49	49
50	50
51	51
52	52
53	53
54	54
55	55
56	56
57	57
58	58
59	59
60	60
61	61
62	62
63	63
64	64
65	65
66	66
67	67
68	68
69	69
70	70
71	71
72	72
73	73
74	74
75	75
76	76
77	77
78	78
79	79
80	80
81	81
82	82
83	83
84	84
85	85
86	86
87	87
88	88
89	89
90	90
91	91
92	92
93	93
94	94
95	95
96	96
97	97
98	98
99	99
100	100

Delay - Average (min/veh)	Total (veh-hr)
northbound 19.1	54.05
southbound 19.5	45.38

Initial Queue	Residual Queue
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	10
11	11
12	12
13	13
14	14
15	15
16	16
17	17
18	18
19	19
20	20
21	21
22	22
23	23
24	24
25	25
26	26
27	27
28	28
29	29
30	30
31	31
32	32
33	33
34	34
35	35
36	36
37	37
38	38
39	39
40	40
41	41
42	42
43	43
44	44
45	45
46	46
47	47
48	48
49	49
50	50
51	51
52	52
53	53
54	54
55	55
56	56
57	57
58	58
59	59
60	60
61	61
62	62
63	63
64	64
65	65
66	66
67	67
68	68
69	69
70	70
71	71
72	72
73	73
74	74
75	75
76	76
77	77
78	78
79	79
80	80
81	81
82	82
83	83
84	84
85	85
86	86
87	87
88	88
89	89
90	90
91	91
92	92
93	93
94	94
95	95
96	96
97	97
98	98
99	99
100	100

Delay -	Average (min/veh)	Total (veh-hr)
northbound	19.1	51.04
southbound	19.3	46.57

	northbound	southbound
hour 1	54.05	45.38
hour 2	51.04	46.57

Output - Example Problem 1

Example Problem 2 : oversaturated conditions

Required Input Information

Location : Highway 28, Tahoe City

Orientation : East-West

hours of analysis : 3 (e.g. 2:00 pm through 5:00 pm)

maximum green time for both directions of travel : 5 minutes

work zone length : 1.25 miles

demand rates (vph) :

	Eastbound	Westbound
Hour 1	440	355
Hour 2	460	375
Hour 3	490	360

speed limit / prevailing "normal" speed : 50 mph

job type : A-C

ANALYSIS RESULTS

```
-----
Highway                               Hwy 28
Hours of Analysis                     3    hour(s)
Job Type                             Asphalt Concrete Overlay
Work Zone Length                     1.25    mile(s)
Maximum Green Time
  eastbound                         5.00    min
  westbound                         5.00    min
Normal Speed                         50.00    mph
Comments      :      Example Problem 2
```

```
Vehicle Demand Rate (veh/hr)
hour 1      eastbound    westbound
            440.         355.
hour 2      460.         375.
```

Figure B-3

Output - Example Problem 2

hour 3 490. 360.

hour 1 --- over-saturated

	Initial Queue	Residual Queue
eastbound	0.	131.
westbound	0.	46.

Delay -	Average (min/veh)	Total (veh-hr)
eastbound	14.6	106.73
westbound	10.9	64.23

hour 2 --- over-saturated

	Initial Queue	Residual Queue
eastbound	131.	282.
westbound	46.	112.

Delay -	Average (min/veh)	Total (veh-hr)
eastbound	25.1	247.51
westbound	17.1	120.01

hour 3 --- over-saturated

	Initial Queue	Residual Queue
eastbound	282.	462.
westbound	112.	162.

Delay -	Average (min/veh)	Total (veh-hr)
eastbound	32.1	413.29
westbound	22.7	178.29

Figure B-3 (con't)
Output - Example Problem 2

	Total Delay (veh-hrs)	
	eastbound	westbound
hour 1	106.73	64.23
hour 2	247.51	120.01
hour 3	413.29	178.29

Figure B-3 (con't)
Output - Example Problem 2

As illustrated in Figure B-3, each of the three analysis hours in Example Problem 2 operate at oversaturated conditions. To further characterize operating conditions during oversaturated conditions, the output displays initial and residual queue lengths (measured in vehicles) prevailing at the beginning and end of each analysis hour.

The inclusion of the "initial queue" at each analysis hour serves to illustrate a rather important point. Computations assume that hours directly preceding selected analysis hours are characterized by undersaturated conditions. Where this assumption is not true, significant discrepancies may exist between actual and computed delay values. To eliminate these errors, specified hours of analysis should include hours at or before the onset of oversaturated conditions.

Example Problem 3 : under- and oversaturated conditions

Required Input Information

Location : Highway 49, Placer County

Orientation : North-South

hours of analysis : 2 (e.g. 3:00 pm through 5:00)

maximum green time for both directions of travel : 5 minutes

work zone length : 0.75 miles

demand rates (vph) :

	Eastbound	Westbound
Hour 1	260	210
Hour 2	495	330

speed limit / prevailing "normal" speed : 50 mph

job type : with pilot car

Referring to the output illustrated in Figure B-4, the first analysis hour in Example Problem 3 results in undersaturated operation. However, a surge in demand rate during the second hour produces oversaturated conditions for that hour. Referring to Figure B-4, a rather large residual queue of 138 vehicles prevails in the northbound direction. Thus, oversaturated conditions will be "carried-over" into the third hour and perhaps beyond.

ANALYSIS RESULTS

Highway	Hwy 49
Hours of Analysis	2 hour(s)
Job Type	Other with Pilot Car
Work Zone Length	.75 mile(s)
Maximum Green Time	
northbound	5.00 min
southbound	5.00 min
Normal Speed	50.00 mph
Comments :	Example Problem 3

Figure B-4
Output - Example Problem 3

Vehicle Demand Rate (veh/hr)		
	northbound	southbound
hour 1	260.	210.
hour 2	495.	330.

hour 1 --- under-saturated		
	Initial Queue	Residual Queue
northbound	0.	0.
southbound	0.	0.

Delay -	Average (min/veh)	Total (veh-hr)
northbound	5.0	21.66
southbound	5.2	18.37

hour 2 --- over-saturated		
	Initial Queue	Residual Queue
northbound	0.	138.
southbound	0.	0.

Delay -	Average (min/veh)	Total (veh-hr)
northbound	12.8	105.47
southbound	6.2	34.36

Total Delay (veh-hrs)		
	northbound	southbound
hour 1	21.66	18.37
hour 2	105.47	34.36

Figure B-4
Output - Example Problem 3

B.6 Final Comments - User Notes

The *work* software program was developed with virtually one objective in mind: To provide an accurate and easy-to-use tool for evaluating one-way traffic control scenarios. To insure that the software would enjoy broad-based implementation, *work* was designed to be straightforward to use. By minimizing execution tasks, the software can be operated with little or no training requirements for the user. As such, *work* represents a very simple software design.

- The program facilitates only limited editing features. (Specifically, the capability to perform sensitivity analyses by responding yes to the prompt " Do you want to change options?") However, the user is not able to move "back and forth" within the input file once data has been entered. Nor can the user re-open (and modify) existing input files. The relatively small input data requirements did not justify the complexities inherent in adding this type of procedural flexibility.
- While the output does provide the most relevant information in a straightforward manner, *work* print-outs are not particularly aesthetic.
- Where the user inputs an *invalid* data entry (e.g. inputting an alpha character where a numeric value is required), the program will immediately terminate (i.e., "bomb"). Again, this was not regarded as a significant deficiency as the limited amount of required input data generally makes re-inputting information simple and timely.
- Where terminating an input file is desirable, the user can type the DOS command
contl - c
- Where the user responds to certain required input data (e.g. work zone length) by hitting <return> without actually entering information, the prompt will persist until data is input.

B.7 Work Source Code

For the purpose of "historical record", the *work* source code is presented on the following pages.

```

      DIMENSION QI(30),QO(30),DI(30),DO(30),AI(30),AO(30)
      real  egi,ego
      real  ila,ild,i1,i2a,i2d,i2,v1,v2
      REAL  TDI(30),TDO(30)
      real  mu,wlength,lsistd,lsostd,vd,lo,li
      character *10, name
      character *10, street(2)
      character *1,opt
      character *1,opt1
      character *30,jobtype,comment
      integer job,sttype
      REAL LSI,LSO,lgi,lgo
      print *, 'name of highway (up to 10 characters)'
      read 897,name
897      format(a10)
71      format(a30)
      print *, 'if the highway is east-west, type 1'
      print *, 'if the highway is north-south, type 2'
      read *,sttype
      if(sttype.eq.1) then
        street(1)='eastbound'
        street(2)='westbound'
      endif
      if(sttype.eq.2) then
        street(1)='northbound'
        street(2)='southbound'
      endif
      print *, 'hours of analysis'
      read *,n
      print *, 'maximum green time for ',street(1),' direction (mins)'
      read *,gmi
      print *, 'maximum green time for ',street(2),' direction (mins)'
      read *,gmo
      gmi=gmi*60.
      gmo=gmo*60.
      print *, 'work zone length (miles)'
      read *,wlength
      wlength=wlength*5280.0
      t=3600.
      if(sttype.eq.1) then
        print *, 'vehicle demand rate-eastbound (veh/hr)'
        do 100 i=1,n
          print *, 'hour',i
          read *,qi(i)
100      continue
        print *, 'vehicle demand rate-westbound (veh/hr)'
        do 101 i=1,n
```

```

        print *, 'hour', i
        read *, go(i)
101      continue
        endif
        if(sttype.eq.2) then
        print *, 'vehicle demand rate-northbound (veh/hr)'
        do 890 i=1,n
        print *, 'hour', i
        read *, qi(i)
890      continue
        print *, 'vehicle demand rate-southbound (veh/hr)'
        do 891 i=1,n
        print *, 'hour', i
        read *, go(i)
891      continue
        endif
        print *, 'speed limit or estimated prevailing speed'
        print *, 'in the absence of a work zone (mile/hr)'
        read *, vd
        vd=vd*5280./3600.
        print *, 'job type'
68      print *, 'Asphalt Concrete Overlay      = 1'
        print *, 'Chip Seal                    = 2'
        print *, 'other if pilot car is not used = 3'
        print *, 'other if pilot car is used   = 4'
        read *, job
        if(job.eq.1) jobtype='Asphalt Concrete Overlay'
        if(job.eq.2) jobtype='Chip Seal'
        if(job.eq.3) jobtype='Other without Pilot Car'
        if(job.eq.4) jobtype='Other with Pilot Car'

67      print *, 'Comment (up to 30 characters)'
        read 71, comment
        write(2,879)
879      format(/// '
*
                        ANALYSIS RESULTS',/,
                        -----',/)

        write(2,72) name,n,jobtype,wlength/5280.,street(1),gmi/60.,
*
        street(2),gmo/60.,vd*3600./5280.,comment
72      format(6x,'Highway',31x,a10,/,6x,'Hours of Analysis',18x,i2,
* 4x,'hour(s)',/,6x,'Job Type',17x,a30,/,6x,'Work Zone Length'
* ,15x,f6.2,4x,'mile(s)',/,6x,'Maximum Green Time',/,10x,a10,
* 18x,f7.2,4x,'min',/,10x,a10,18x,f7.2,4x,'min',/,6x,
* 'Normal Speed',21x,f6.2,4x,'mph',/,6x
* 'Comments      :',10x,a30)

        write(2,374) street(1),street(2)
374      format(////,
*
                        Vehicle Demand Rate (veh/hr)',/,11x,9x,
*
                        a10,5x,a10)

        do 32 kk=1,n
        write(2,351) kk,qi(kk),go(kk)
351      format(6x,'hour',i2,2f15.0)
32      continue

        criteria=12.21
        if(job.eq.1) goto 701
        if(job.eq.2) goto 702
        if(job.eq.3) goto 703
        if(job.eq.4) goto 704

```



```

701      ssi=1083.803
         sso=1083.803
         st=1083.803
         ila=1.0
         i1d=23.19
         i1=i1a+i1d
         i2a=1.0
         i2d=23.19
         i2=i2a+i2d
         v1=0.0
         v2=0.0
         vi=33.74384
         vo=33.74384
         spdi=33.74384
         spdo=33.74384
         spd=33.74384
         lsi=30.1473
         lso=30.1473
         sistd=188.5843
         sostd=188.5843
         vistd=10.49788
         vostd=10.49788
         lsistd=0.0
         lsostd=0.0
         lgi=13.5503
         lgo=13.5503
         spdivar=vistd**2
         spdovar=vostd**2
         ski=ssi/3600
         sko=sso/3600
         li=30.1473
         lo=30.1473
         goto 800

```

```

702      ssi=1018.4893
         sso=1018.4893
         st=1018.4893
         ila=1.0
         i1d=3.89
         i1=i1a+i1d
         i2a=1.0
         i2d=3.89
         i2=i2a+i2d
         v1=0.0
         v2=0.0
         vi=29.076315
         vo=29.076315
         spdi=29.076315
         spdo=29.076315
         spd=29.076315
         lsi=23.32
         lso=23.32
         sistd=302.93275
         sostd=302.93275
         vistd=7.67177
         vostd=7.67177
         lsistd=0.0
         lsostd=0.0
         lgi=6.9618
         lgo=6.9618
         spdivar=vistd**2

```

```

        spdovar=vostd**2
        ski=ssi/3600
        sko=sso/3600
        li=23.32
        lo=23.32
        goto 800

703      ssi=1090.58
        sso=1090.58
        st=1090.58
        ila=1.0
        i1d=15.91
        i1=ila+i1d
        i2a=1.0
        i2d=15.91
        i2=i2a+i2d
        v1=0.0
        v2=0.0
        vi=44.76
        vo=44.76
        spdi=44.76
        spdo=44.76
        spd=44.76
        lsi=34.97136
        lso=34.97136
        sistd=380.6679
        sostd=380.6679
        vistd=10.97534
        vostd=10.97534
        lsistd=104.9463
        lsostd=104.9463
        lgi=6.9618
        lgo=6.9618
        spdivar=vistd**2
        spdovar=vostd**2
        ski=ssi/3600
        sko=sso/3600
        li=34.97136
        lo=34.97136
        goto 800

704      ssi=1047.679
        sso=1047.679
        st=1047.679
        ila=1.0
        i1d=2.10
        i1=ila+i1d
        i2a=1.0
        i2d=2.10
        i2=i2a+i2d
        v1=0.0
        v2=0.0
        vi=29.75
        vo=29.75
        spdi=29.75
        spdo=29.75
        spd=29.75
        lsi=15.37
        lso=15.37
        sistd=160.1344
        sostd=160.1344

```

```

vistd=3.233655
vostd=3.233655
lsistd=0.0
lsostd=0.0
lgi=8.22
lgo=8.22
spdivar=vistd**2
spdo var=vostd**2
ski=ssi/3600
sko=sso/3600
li=15.37
lo=15.37
goto 800

800 DO 16 I=1,N
    QI(I)=QI(I)/3600.
    QO(I)=QO(I)/3600.
16 continue

Tdelay=wlength/spd-wlength/vd
St=St/3600.
C=GMI+GMO+2.*WLENGTH/SPD+LSO+LSI
SI=St*GMI/C
SO=St*GMO/C
I=0
1 IF(I.GE.N) GOTO 9999
AI(I+1)=0.0
AO(I+1)=0.0
I=I+1

GI = QI(I)*(St*(2*WLENGTH/SPD+LSI+LSO+lgo)-QO(I)*(lgo-lgi))/
* (St*(St-(QI(I)+QO(I))))+lgi
GO = QO(I)*(St*(2*WLENGTH/SPD+LSI+LSO+lgi)-QI(I)*(lgi-lgo))/
* (St*(St-(QI(I)+QO(I))))+lgo

IF((GI.LE.GMI.AND.GI.GE.0.0).AND.(GO.LE.GMO.AND.GO.GE.0.0))THEN

c      calculating expected travel time

888      timei = wlength*(spdi**2+spdivar)/spdi**3
          timeo = wlength*(spdo**2+spdo var)/spdo**3

c      calculating variance of travle time

          timeivar=wlength**2*((spdi**2+3*spdivar)/spdi**4
*          -((spdi**2+spdivar)/spdi**3)**2)
          timeovar=wlength**2*((spdo**2+3*spdo var)/spdo**4
*          -((spdo**2+spdo var)/spdo**3)**2)

c      P(headway>C)

          pci=exp(-1.*qi(i)*criteria)
          pco=exp(-1.*qo(i)*criteria)

c      expected extended green time

          egi=(1-exp(-1*qi(i)*criteria))/(exp(-1*qi(i)*criteria))/qi(i)
          ego=(1-exp(-1*qo(i)*criteria))/(exp(-1*qo(i)*criteria))/qo(i)

c      variance of extended green time

```

```

egivar=(1-exp(-1*qi(i)*criteria))/(exp(-1*qi(i)*
*      criteria))/qi(i)**2+(1-exp(-1*qi(i)*criteria))
*      /(exp(-2*qi(i)*criteria))/qi(i)**2

```

```

egovar=(1-exp(-1*go(i)*criteria))/(exp(-1*go(i)*criteria))
*      /go(i)**2+(1-exp(-1*go(i)*criteria))/(exp(-2*go(i)*
*      criteria))/go(i)**2

```

c expected green time

```

gi=qi(i)/ski/(1-qi(i)/ski-go(i)/sko)*(timei+ timeo+go(i)/
*      sko*egi+(1-go(i)/sko)*ego+li+lo)
go=go(i)/sko/(1-go(i)/sko-qi(i)/ski)*(timeo+ timei+qi(i)/
*      ski*ego+(1-qi(i)/ski)*egi+lo+li)

```

c variance of green time

```

xo=i2*go(i)*(timeo+gi+egi+timei+li+lo)/
*      (sko**2*(1-go(i)/sko)**3)
yo=v2/(sko/go(i))**2
zo=go(i)**2/((sko-go(i))**2)
xi=i1*qi(i)*(timei+go+ego+timeo+lo+li)/
*      (ski**2*(1-qi(i)/ski)**3)
yi=v1/(ski/qi(i))**2
zi=qi(i)**2/(ski-qi(i))**2

aoo=xo+yo+zo*(timeovar*(ski+qi(i))/(ski-qi(i))+xi+yi+zi*
*      (timeivar*(sko+go(i))
*      /(sko-go(i))+egovar+timeovar)+egivar+timeivar)
govar=aoo/(1-zi*zo)

aoi=xi+yi+zi*(timeivar*(sko+go(i))/(sko-go(i))+xo+yo+zo
*      *(timeovar*(ski+qi(i))
*      /(ski-qi(i))+egivar+timeivar)+egovar+timeovar)

givar=aoi/(1-zo*zi)

```

c expected red time

```

ri=go+timei+ego+timeo+li+lo
ro=gi+timeo+egi+timei+lo+li

```

c variance of red time

```

rivar=(sko+go(i))/(sko-go(i))*timeivar+govar+egovar+timeovar
rovar=(ski+qi(i))/(ski-qi(i))*timeovar+givar+egivar+timeivar

```

c total delay per cycle

```

totali=qi(i)/(2*(1-qi(i)/ski))*(ri**2+rivar+i1*ri/
*      (ski*(1-qi(i)/ski))+v1/(ski*qi(i)))
totalo=go(i)/(2*(1-go(i)/sko))*(ro**2+rovar+i2*ro/
*      (sko*(1-go(i)/sko))+v2/(sko*go(i)))

```

c average delay

```

avgi=totali/((timei+li+go+ego+timeo+gi+egi+lo)*qi(i))
avgo=totalo/((timei+li+go+ego+timeo+gi+egi+lo)*go(i))
di(i)=avgi+tdelay
do(i)=avgo+tdelay

```

```

c          total delay for the hour

          tdi(i)=di(i)*t*qi(i)
          tdo(i)=do(i)*t*qo(i)

          write(2,199) i
199      format('////////' hour',i2,' --- under-saturated')
899      format('////////' hour',i2,' --- over-saturated')
          write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)
799      format('///' Initial Queue Residual Queue',///,
* 2x,a10,7x,f6.0,10x,f6.0,/,2x,a10,7x,f6.0,10x,f6.0)
          write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
* street(2),do(i)/60.,tdo(i)/3600.
757      format('///,5x,'Delay - Average (min/veh) Total (veh-hr)'
*,///,2x,a10,7x,f6.1,10x,f7.2,/,2x,a10,7x,f6.1,10x,f7.2)
          GOTO 1
          ENDIF

          IF((GI.GT.GMI.OR.GI.LT.0.0).AND.(GO.GT.GMO.OR.GO.LT.0.0)) THEN

          C=GMI+GMO+2*WLENGTH/SPD+LSO+LSI
          SI=St*GMI/C
          SO=St*GMO/C
          AI(I+1)=QI(I)*T-SI*T
          AO(I+1)=QO(I)*T-SO*T

          IF(AI(I+1).LE.0.0 .AND. AO(I+1).LE.0.0) GOTO 21
          IF(AI(I+1).GT.0.0 .AND. AO(I+1).LE.0.0) GOTO 22
          IF(AI(I+1).LE.0.0 .AND. AO(I+1).GT.0.0) GOTO 23

          TDI(I)=AI(I+1)*T*0.5+tdelay*si*t+st*(c-gmi)*0.5*gmi*3600/c
          TDO(I)=AO(I+1)*T*0.5+tdelay*so*t+st*(c-gmo)*0.5*gmo*3600/c
          di(i)=tdi(i)/(ai(i)+qi(i)*t)
          do(i)=tdo(i)/(ao(i)+qo(i)*t)
          write(2,599) i
599      format('////////' hour',i2,' --- over-saturated')
          write(2,299) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)
299      format('///' Initial Queue Residual Queue',///,
* 2x,a10,7x,f6.0,10x,f6.0,/,2x,a10,7x,f6.0,10x,f6.0)
          write(2,257) street(1),di(i)/60.,tdi(i)/3600.,
* street(2),do(i)/60.,tdo(i)/3600.
257      format('///,5x,'Delay - Average (min/veh) Total (veh-hr)'
*,///,2x,a10,7x,f6.1,10x,f7.2,/,2x,a10,7x,f6.1,10x,f7.2)
          GOTO 2

2          IF(I.GE.N) GOTO 9999
          I=I+1

          AI(I+1)=AI(I)+QI(I)*T-SI*T
          AO(I+1)=AO(I)+QO(I)*T-SO*T

          IF(AI(I+1).GT.0.0.AND.AO(I+1).GT.0.0) THEN

          TDI(I)=(AI(I)+AI(I+1))*T*0.5+tdelay*(si*t)
          +st*(c-gmi)*0.5*gmi*3600/c
          TDO(I)=(AO(I)+AO(I+1))*T*0.5+tdelay*(so*t)
          +st*(c-gmo)*0.5*gmo*3600/c
          di(i)=tdi(i)/(ai(i)+qi(i)*t)
          do(i)=tdo(i)/(ao(i)+qo(i)*t)

          write(2,899) i

```

```

write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)
write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
* street(2),do(i)/60.,tdo(i)/3600.

GOTO 2
ENDIF

21 IF(AI(I+1).LE.0.0.AND.AO(I+1).LE.0.0) THEN

ai(i+1)=0.0
ao(i+1)=0.0
TI=AI(I)/(SI-QI(I))
TO=AO(I)/(SO-QO(I))

IF(TI-TO) 3, 4, 5
3 GI1=(QI(I)*(2*WLENGTH/SPD+GMO+LSI+LSO))/(St-QI(I))+lgi
C1=GI1+GMO+2*WLENGTH/SPD+LSO+LSI
C=GMI+GMO+2*WLENGTH/SPD+LSO+LSI
SO1=GMO*St/C1
TO2=(AO(I)-SO*TI+SO1*TI)/(SO1-QO(I))
GI2=QI(I)*(St*(2*WLENGTH/SPD+LSI+LSO+lgo)-QO(I)*(lgo-lgi))
* /(St*(St-(QI(I)+QO(I))))+lgi
GO2=QO(I)*(St*(2*WLENGTH/SPD+LSO+LSI+lgi)-QI(I)*(lgi-lgo))
* /(St*(St-(QO(I)+QI(I))))+lgo
C2=GI2+GO2+2*WLENGTH/SPD+LSO+LSI

TDI(I)=AI(I)*TI*0.5+st*(c-gmi)*0.5*gmi*ti/c
* +0.5*(1-GI1/C1)**2*C1/(1-QI(I)/St)*QI(I)*(TO2-TI)
* +0.5*(1-GI2/C2)**2*C2/(1-QI(I)/St)*QI(I)*(T-TO2)
* +tdelay*(si*ti+qi(i)*(to2-ti)+qi(i)*(t-to2))

TDO(I)=0.5*(AO(I)+AO(I)+QO(I)*TI-SO*TI)*TI
* +0.5*(AO(I)+QO(I)*TI-SO*TI)*(TO2-TI)
* +0.5*(1-GO2/C2)**2*C2/(1-QO(I)/St)*QO(I)*(T-TO2)
* +tdelay*(so*ti+sol*(to2-ti)+qo(i)*(t-to2))
* +st*(c-gmo)*0.5*gmo*ti/c
* +st*(c1-gmo)*0.5*gmo*(to2-ti)/c1
di(i)=tdi(i)/(ai(i)+qi(i)*t)
do(i)=tdo(i)/(ao(i)+qo(i)*t)

write(2,899) i
write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)

write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
* street(2),do(i)/60.,tdo(i)/3600.

GOTO 1

5 GO1=(QO(I)*(2*WLENGTH/SPD+GMI+LSO+LSI))/(St-QO(I))+lgo
C1=GO1+GMI+2*WLENGTH/SPD+LSI+LSO
C=GMO+GMI+2*WLENGTH/SPD+LSI+LSO
SI1=GMI*St/C1
TI2=(AI(I)-SI*TO+SI1*TO)/(SI1-QI(I))
GO2=QO(I)*(St*(2*WLENGTH/SPD+LSO+LSI+lgi)-QI(I)*(lgi-lgo))
* /(St*(St-(QI(I)+QO(I))))+lgo
GI2=QI(I)*(St*(2*WLENGTH/SPD+LSI+LSO+lgo)-QO(I)*(lgo-lgi))
* /(St*(St-(QO(I)+QI(I))))+lgi
C2=GI2+GO2+2*WLENGTH/SPD+LSO+LSI

TDO(I)=AO(I)*TO*0.5+st*(c-gmo)*0.5*gmo*to/c
* +0.5*(1-GO1/C1)**2*C1/(1-QO(I)/St)*QO(I)*(TI2-TO)
* +0.5*(1-GO2/C2)**2*C2/(1-QO(I)/St)*QO(I)*(T-TI2)

```



```

*          +tdelay*(so*to+qo(i)*(ti2-to)+qo(i)*(t-ti2))

      TDI(I)=0.5*(AI(I)+AI(I)+QI(I)*TO-SO*TO)*TO
*          +0.5*(AI(I)+QI(I)*TO-SI*TO)*(TI2-TO)
*          +0.5*(1-GI2/C2)**2*C2/(1-QI(I)/St)*QI(I)*(T-TI2)
*          +tdelay*(si*to+si1*(ti2-to)+qi(i)*(t-ti2))
*          +st*(c-gmi)*0.5*gmi*to/c
*          +st*(c1-gmi)*0.5*gmi*(ti2-to)/c1
      di(i)=tdi(i)/(ai(i)+qi(i)*t)
      do(i)=tdo(i)/(ao(i)+qo(i)*t)

      write(2,899) i
      write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)

      write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
*      street(2),do(i)/60.,tdo(i)/3600.

      GOTO 1

4      C=GMI+GMO+2*WLENGTH/SPD+LSO+LSI
      GI1= QI(I)*(St*(2*WLENGTH/SPD+LSI+LSO+lgo)-QO(I)*(lgo-lgi))
*          /(St*(St-QI(I)+QO(I)))+lgi
      GO1= QO(I)*(St*(2*WLENGTH/SPD+LSI+LSO+lgi)-QI(I)*(lgi-lgo))
*          /(St*(St-QO(I)+QI(I)))+lgo
      C1= GI1+GO1+LSO+LSI+2*WLENGTH/SPD

      TDI(I)=AI(I)*TI*0.5+st*(c-gmi)*0.5*gmi*ti/c
*          +0.5*(1-GI1/C1)**2*C1/(1-QI(I)/St)*QI(I)*(T-TI)
*          +tdelay*(si*ti+qi(i)*(t-ti))
      TDO(I)=AO(I)*TO*0.5+st*(c-gmo)*0.5*gmo*to/c
*          +0.5*(1-GO1/C1)**2*C1/(1-QO(I)/St)*QO(I)*(T-TO)
*          +tdelay*(so*to+qo(i)*(t-to))

      di(i)=tdi(i)/(ai(i)+qi(i)*t)
      do(i)=tdo(i)/(ao(i)+qo(i)*t)

      write(2,899) i
      write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)

      write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
*      street(2),do(i)/60.,tdo(i)/3600.

      GOTO 1

      ENDIF

22      IF(AI(I+1).GT.0.0.AND.AO(I+1).LE.0.0) THEN
          ao(i+1)=0.0
          TO=AO(I)/(SO-QO(I))
          GO1=QO(I)*(2*WLENGTH/SPD+GMI+LSI+LSO)/(St-QO(I))+lgo
          C1=GO1+GMI+2*WLENGTH/SPD+LSO+LSI
          C=GMO+GMI+2*WLENGTH/SPD+LSO+LSI

          SI1=GMI*St/C1
          SI=GMI*St/C
          SO=GMO*St/C

          AI(I+1)=AI(I)+QI(I)*T-SI*TO-SI1*(T-TO)
          IF(AI(I+1).GT.0.0) THEN

```

```

      TDI(I)=(AI(I)+AI(I)+QI(I)*TO-SI*TO)*0.5*TO
      +(AI(I)+QI(I)*TO-SI*TO+AI(I+1))*0.5*(T-TO)
      +tdelay*(si*to+si1*(t-to))
      +st*(c-gmi)*0.5*gmi*to/c
      +st*(c1-gmi)*0.5*gmi*(t-to)/c1
      TDO(I)=AO(I)*TO*0.5
      +0.5*(1-GO1/C1)**2*C1/(1-QO(I)/St)*QO(I)*(T-TO)
      +tdelay*(so*to+qo(i)*(t-to))
      +st*(c-gmo)*0.5*gmo*to/c

      di(i)=tdi(i)/(ai(i)+qi(i)*t)
      do(i)=tdo(i)/(ao(i)+qo(i)*t)
      AO(I+1)=0.0

      write(2,899) i
      write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)
      write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
      * street(2),do(i)/60.,tdo(i)/3600.

```

```

      GOTO 2
      ENDIF
      IF(AI(I+1).LE.0.0) THEN
      ai(i+1)=0.0
      if(ai(i).eq.0.0.and.ao(i).eq.0.0) goto 888
      TO1=(AI(I)-SI*TO+SI1*TO)/(SI1-QI(I))
      GI2=QI(I)*(St*(2*WLENGTH/SPD+LSI+LSO+lgo)-QO(I)*(lgo-lgi))/
      (St*(St-(QI(I)+QO(I))))+lgi
      * GO2=QO(I)*(St*(2*WLENGTH/SPD+LSO+LSI+lgi)-QI(I)*(lgi-lgo))/
      * (St*(St-(QO(I)+QI(I))))+lgo

      C2=GI2+GO2+2*WLENGTH/SPD+LSO+LSI

      TDI(I)=(AI(I)+AI(I)+TO*QI(I)-TO*SI)*0.5*TO
      +(AI(I)+TO*QI(I)-SI*TO)*(TO1-TO)*0.5
      +0.5*(1-GI2/C2)**2*C2/(1-QI(I)/St)*QI(I)*(T-TO1)
      +tdelay*(si*to+si1*(to1-to)+qi(i)*(t-to1))
      +st*(c-gmi)*0.5*gmi*to/c
      +st*(c1-gmi)*0.5*gmi*(to1-to)/c1
      TDO(I)=AO(I)*TO*0.5+st*(c-gmo)*0.5*gmo*to/c
      +0.5*(1-GO1/C1)**2*C1/(1-QO(I)/St)*QO(I)*(TO1-TO)
      +0.5*(1-GO2/C2)**2*C2/(1-QO(I)/St)*QO(I)*(T-TO1)
      +tdelay*(so*to+qo(i)*(to1-to)+qo(i)*(t-to1))

      di(i)=tdi(i)/(ai(i)+qi(i)*t)
      do(i)=tdo(i)/(ao(i)+qo(i)*t)
      write(2,899) i
      write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)
      write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
      * street(2),do(i)/60.,tdo(i)/3600.

```

```

      GOTO 1

```

```

      ENDIF
      ENDIF

```

```

23      IF(AO(I+1).GT.0.0.AND.AI(I+1).LE.0.0) THEN
      ai(i+1)=0.0

```

```

      TI=AI(I)/(SI-QI(I))
      GI1=QI(I)*(2*WLENGTH/SPD+GMO+LSO+LSI)/(St-QI(I))+lgi
      C1=GI1+GMO+2*WLENGTH/SPD+LSI+LSO

```

```

C=GMI+GMO+2*WLENGTH/SPD+LSO+LSI

SO1=GMO*St/C1
SO=GMO*St/C
SI=GMI*St/C

AO(I+1)=AO(I)+QO(I)*T-SO*TI-SO1*(T-TI)
IF(AO(I+1).GT.0.0) THEN

    TDO(I)=(AO(I)+AO(I)+QO(I)*TI-SO*TI)*0.5*TI
    + (AO(I)+QO(I)*TI-SO*TI+AO(I+1))*0.5*(T-TI)
    +tdelay*(so*ti+sol*(t-ti))
    +st*(c-gmo)*0.5*gmo*ti/c
    +st*(c1-gmo)*0.5*gmo*(t-ti)/c
    TDI(I)=AI(I)*TI*0.5+st*(c-gmi)*0.5*gmi*ti/c
    +0.5*(1-GI1/C1)**2*C1/(1-QI(I)/St)*QI(I)*(T-TI)
    +tdelay*(si*ti+qi(i)*(t-ti))
    di(i)=tdi(i)/(ai(i)+qi(i)*t)
    do(i)=tdo(i)/(ao(i)+qo(i)*t)

    AI(I+1)=0.0
    write(2,899) i
    write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)
    write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
* street(2),do(i)/60.,tdo(i)/3600.

    GOTO 2
ENDIF

IF(AO(I+1).LE.0.0) THEN
    ao(i+1)=0.0
if(ai(i).eq.0.0.and.ao(i).eq.0.0) goto 888
    TI1=(AO(I)-SO*TI+SO1*TI)/(SO1-QO(I))
    GO2=QO(I)*(St*(2*WLENGTH/SPD+LSO+LSI+lgi)-QI(I)*(lgi-lgo))/
    (St*(St-(QO(I)+QI(I))))+lgo
*   GI2=QI(I)*(St*(2*WLENGTH/SPD+LSI+LSO+lgo)-QO(I)*(lgo-lgi))/
*   (St*(St-(QI(I)+QO(I))))+lgi

    C2=GO2+GI2+2*WLENGTH/SPD+LSI+LSO

    TDO(I)=(AO(I)+AO(I)+TI*QO(I)-TI*SO)*0.5*TI
*   + (AO(I)+TI*QO(I)-SO*TI)*(TI1-TI)*0.5
*   +0.5*(1-GO2/C2)**2*C2/(1-QO(I)/St)*QO(I)*(T-TI1)
*   +tdelay*(so*ti+sol*(ti1-ti)+qo(i)*(t-ti1))
*   +st*(c-gmo)*0.5*gmo*ti/c
*   +st*(c1-gmo)*0.5*gmo*(ti1-ti)/c
    TDI(I)=AI(I)*TI*0.5+st*(c-gmi)*0.5*gmi*ti/c
*   +0.5*(1-GI1/C1)**2*C1/(1-QI(I)/St)*QI(I)*(TI1-TI)
*   +0.5*(1-GI2/C2)**2*C2/(1-QI(I)/St)*QI(I)*(T-TI1)
*   +tdelay*(si*ti+qi(I)*(ti1-ti)+qi(i)*(t-ti1))

    di(i)=tdi(i)/(ai(i)+qi(i)*t)
    do(i)=tdo(i)/(ao(i)+qo(i)*t)
    write(2,899) i
    write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)
    write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
* street(2),do(i)/60.,tdo(i)/3600.

    GOTO 1
ENDIF

```

```

        ENDIF
    ENDIF
    IF((GI.GT.GMI.OR.GI.LT.0.0).AND.(GO.LE.GMO.AND.GO.GE.0.0)) THEN

        GO=QO(I)*(2*WLENGTH/SPD+GMI+LSI+LSO)/(St-QO(I))+lgo
        C1= GMI+GO+2*WLENGTH/SPD+LSO+LSI
        AI(I+1)=QI(I)*T-St*GMI/C1*T
        AO(I+1)=0.0
        GI=GMI

        IF (AI(I+1).LE.0.0.AND.AO(I+1).LE.0.0) GOTO 888
        IF (AI(I+1).GT.0.0.AND.AO(I+1).LE.0.0) GOTO 22
        DI(I)=0.5*AI(I+1)*T/(QI(I)*T)

        DO(I)=0.5*(1-GO/C1)**2*C1/(1-QO(I)/St)
        write(2,899) i
        write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)
        write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
* street(2),do(i)/60.,tdo(i)/3600.

        GOTO 2
    ENDIF

    IF((GO.GT.GMO.OR.GO.LT.0.0).AND.(GI.LE.GMI.AND.GI.GE.0.0)) THEN

        GI=QI(I)*(2*WLENGTH/SPD+GMO+LSO+LSI)/(St-QI(I))+lgi
        C1= GMO+GI+2*WLENGTH/SPD+LSI+LSO
        AO(I+1)=QO(I)*T-St*GMO/C1*T
        AI(I+1)=0.0
        GO=GMO

        IF(AO(I+1).LE.0.0 .AND. AI(I+1).LE.0.0) GOTO 888
        IF(AO(I+1).GT.0.0 .AND. AI(I+1).LE.0.0) GOTO 23
        DO(I)=0.5*AO(I+1)*T/(QO(I)*T)
        DI(I)=0.5*(1-GI/C1)**2*C1/(1-QI(I)/St)
        write(2,899) i
        write(2,799) street(1),ai(i),ai(i+1),street(2),ao(i),ao(i+1)
        write(2,757) street(1),di(i)/60.,tdi(i)/3600.,
* street(2),do(i)/60.,tdo(i)/3600.

        GOTO 2
    ENDIF
9999    write(2,174) street(1),street(2)
103    format(///,
*      Total Delay (veh-hrs)',///,4x,
*      a10,2x,a10)
803    format(//,
*      Average Delay (min/veh)',///,4x,
*      a10,2x,a10)

174    format(////////,
*      Total Delay (veh-hrs)',///,4x,9x,
*      a10,5x,a10)
        DO 49 I=1,N
        qi(i)=qi(i)*3600.
        qo(i)=qo(i)*3600.

51    WRITE(2,51) i,TDI(I)/3600.,TDO(I)/3600.
        FORMAT('hour',i2,2F15.2)

```

```

49          CONTINUE
          write(2,69)
69          format(////////)
          st=st*3600.

print *, 'Do you want to change options ? (Yes = y , No = n)'
  read 61, opt
  format(a1)
61  if(opt.ne.'y'.and.opt.ne.'n') then
75  print 74, opt
74  format(2x,a1,4x,'incorrect response  ,  Please try again')
  read 61,opt
  if(opt.ne.'y'.and.opt.ne.'n') goto 75
  endif
  if (opt.eq.'n') goto 62
  i=0
  print *, 'Change Work Zone Length ? (Yes = y, No = n)'
  read 61, opt1
  if(opt1.ne.'y'.and.opt1.ne.'n') then
76    print 74, opt1
    read 61,opt1
    if(opt1.ne.'y'.and.opt1.ne.'n') goto 76
    endif
    if (opt1.eq.'y') then
      print *, 'New Work Zone Length (miles)'
      read *, wlength
      wlength=wlength*5280.
    endif
    print *, 'Change Maximum Green Time ? (Yes = y, No = n)'
    read 61,opt1
    if(opt1.ne.'y'.and.opt1.ne.'n') then
77      print 74, opt1
      read 61,opt1
      if(opt1.ne.'y'.and.opt1.ne.'n') goto 77
      endif
      if(opt1.eq.'y') then
        print *, 'New maximum green time for ',
*          street(1), ' direction (mins)'
        read *, gmi
        print *, 'New maximum green time for ',
*          street(2), ' direction (mins)'
        read *, gmo
        gmi=gmi*60.
        gmo=gmo*60.
      endif
      print *, 'Change Speed Limit or Estimated Prevailing Speed'
      print *, 'in the Absence of a Work Zone ? (Yes = y, No = n)'
      read 61, opt1
      if(opt1.ne.'y'.and.opt1.ne.'n') then
78        print 74, opt1
        read 61,opt1
        if(opt1.ne.'y'.and.opt1.ne.'n') goto 78
        endif
        if(opt1.eq.'y') then
          print *, 'New Speed Limit or Estimated Prevailing Speed'
          print *, 'in the Absence of a Work Zone (mile/hr)'
          read *, vd
          vd=vd*5280./3600.
        endif
        print *, 'Change Job Type ? (Yes = y, No = n)'
        read 61,opt1
        if(opt1.ne.'y'.and.opt1.ne.'n') then

```

```
79      print 74, opt1
      read 61,opt1
      if(opt1.ne.'y'.and.opt1.ne.'n') goto 79
      endif
      if (opt1.eq.'y') goto 68
      goto 67
62      STOP
      END
```


COVER DESIGN BY ALDO GIORGINI