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This study addresses the problem of queueing on highway facilities, wherein a large number of computerized methods for the analysis of different queueing situations are available. A three-tier classification system of the methodologies was used with the following categories: dedicated techniques, classical queueing theory, and simulation. A knowledge base for selecting an appropriate technique for a specific facility and problem is provided. The utilization of the video camera to capture queueing data in the field is described and applied to evaluate alternative methods to analyze queueing at signalized intersections. This evaluation revealed three distinct approaches from the respective categories for the evaluation of queueing at signalized intersections: the HCM method, the vacation-server queueing model, and TRAF-NETSIM. It was found that the queueing model and simulation methods offer flexibility over the more structured, dedicated HCM method and should be considered in the analysis of other situations as well as of signalized intersections.

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FINAL REPORT

EVALUATION OF ROADWAY SITES FOR QUEUE MANAGEMENT

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Faculty Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies.)

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ABSTRACT

This study addresses the problem of queueing on highway facilities, wherein a large number of computerized methods for the analysis of different queueing situations are available. A three-tier classification system of the methodologies was used with the following categories: dedicated techniques, classical queueing theory, and simulation. A knowledge base for selecting an appropriate technique for a specific facility and problem is provided. The utilization of the video camera to capture queueing data in the field is described and applied to evaluate alternative methods to analyze queueing at signalized intersections. This evaluation revealed three distinct approaches from the respective categories for the evaluation of queueing at signalized intersections: the 1985 HCM method, the vacation-server queueing model, and TRAF-NETSIM. It was found that the queueing model and simulation methods offer flexibility over the more structured, dedicated 1985 HCM method and should be considered in the analysis of other situations as well as of signalized intersections.

FINAL REPORT

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INTRODUCTION

Waiting lines have become a common occurrence for people and goods moving from one location to another via transportation systems in Virginia, the United States, and the world. These lines, or queues, arise when the demand for a facility or network of facilities approaches and/or exceeds the capacity of the facility or network of facilities.

It is the task of many transportation engineers to analyze queues, delays, and the costs of excess demand and/or insufficient capacity for a variety of situations in order to estimate the quality of service a facility provides. To do this, the analyst must select an analysis procedure appropriate for the problem being considered. In many instances, the engineer/analyst is not completely familiar with the analysis methods available to address the problem of interest, especially computerized methods.

PURPOSE AND SCOPE

This study addressed queue analysis for transportation facilities and the means for evaluating alternative remedial strategies. There were five tasks associated with the study:

1. A literature review was conducted to establish the status of the utilization of queue analysis techniques in the transportation field.

2. A survey of selected personnel in the Virginia Department of Transportation (VDOT) was administered to associate the available methods with VDOT practices.

3. The identified queue analysis methods were classified.

4. Methods developed for specific facility problems were identified using a data base showing techniques of performance/criteria measures provided for typical highway queuing problems.

5. A typical signalized intersection problem was selected for the demonstration of data collection procedures and the evaluation of alternative analysis tools to show the complete process of selecting a queue analysis method(s), collecting appropriate data, and comparing alternative analysis methods.

LITERATURE REVIEW

The following is a categorical summary of queue analysis methods reported in the literature for important types of facilities (also see the bibliography):

- *Highway facilities (general).* The most important document in this category is the 1985 *Highway Capacity Manual* (1985 HCM). However, the 1985 HCM does not specify a queueing analysis procedure for any of the facility types it discusses. Rather, it relates a level of service to density and delay.

- *Arterials.* Sources about queueing phenomena on arterials emphasized coordinated signal control and associated analysis methods, such as bandwidth optimization.

- *Freeway segments.* The analysis methods for freeway segments focused on variants of a supply-demand curve approach to determining delay attributable to queueing.

- *General background information.* The sources included in this section of the bibliography cover the background information for analytic queueing theory models, simulation models, and traffic flow theory.

- *Incidents on freeway segments.* The sources on this topic focused on a supply-demand curve approach. When an incident occurs, the supply (a number of lanes of the freeway) offered to the public is reduced. The demand for those lanes often remains constant, and queueing begins. The analysis methods for this situation focused on determining the difference between the supply offered and the demand in a purely deterministic manner.

- *Networks.* The sources about queueing analysis methods in networks concentrated on simulation models of urban street networks, such as NETSIM and Transyt-7F. A few sources concerned queueing in networks or the impact of queueing on a specific facility on the surrounding network of facilities.

- *Ramps and ramp junctions.* There is a lack of analysis methods for queueing on ramps and ramp junctions. Three computerized analysis methods were found that specifically addressed queueing on ramps. However, it appears that these are simply different implementations of the same approach.

- *Signalized intersections.* There were far more sources for signalized intersections than for any other facility. However, there did not appear to be a consensus on one method. The 1985 HCM method, and earlier versions, were quite popular but did not give a direct measure of queue quantities, such as the average length of the queue or the probability that a queue would develop.
- *Unsignalized intersections.* Little theoretical work has been done on developing queueing analysis methods for unsignalized intersections.
- *Weaving areas.* The only analysis method reported was from the 1985 HCM.
- *Work zones on freeway segments.* The analysis methods for queueing attributable to work zones on freeway segments emphasized simulation models and supply-and-demand models.

VDOT SURVEY

A survey was send to VDOT division heads whose personnel are concerned with analyzing queues (see Appendix A). The divisions surveyed represented many interests of VDOT, including traffic engineering, transportation planning, construction, toll facilities (the Richmond-Petersburg Turnpike), and location and design, in addition to the Transportation Systems Management Center in Northern Virginia. The survey focused on the following:

1. the types of queueing problems of interest
2. the typical measures of congestion
3. the general scope of analysis performed
4. the current analysis methods used
5. the areas where analysis methods are needed.

Not all respondents answered every question. There were 15 total responses. The five queueing problems of most interest were (in order of percentage of total responses indicating the specific answer):

1. signal backups (87%)
2. left-turn storage lane requirements (80%)
3. traffic accidents (67%)
4. unsignalized intersections (60%)
5. short-term work zones, long-term work zones, and freeway ramps (all equally rated at 53%).

The four typical measures of congestion of most interest were:

1. length of queue (80%)
2. average vehicle delay (80%)
3. duration of bottleneck (47%)
4. total vehicle delay (40%).

The focus of the analyses performed was reported as being equally divided between (1) looking at a specific facility alone, and (2) looking at a specific facility and possible impacts on alternate routes when the primary facility is congested. The survey indicated that little or no analysis is currently done at a network level.

CLASSIFICATION OF QUEUEING ANALYSIS METHODS

From the review of the literature, consideration of the survey results, and conversations with individuals concerned with the analysis of queues in transportation systems, it was determined that queueing analysis techniques should be classified by type of method and applications shown for problems associated with different types of facilities.

Although not intended as a rigid classification, the following categories distinguish some of the basic features of available analysis methods:

> The choice of appropriate methods and application procedures depends on the specific problem, the intended use of the results, and on the [data base and other resource requirements]. Limited data, planning budgets, time, staff availability, skills and experience, and access to computers all place restrictions on the methods and procedures that can be applied.[1]

General Techniques

One category of analysis techniques are methods that apply to a wide variety of situations. These queueing analysis methods are, for the most part, not developed specifically for application to transportation systems, but they may be tailored for use in analyzing queueing situations in transportation systems.

Analytic Queueing Theory Models

One subclassification of general techniques is analytic queueing theory models:

> Queueing theory provides a large number of alternative mathematical models for describing a waiting-line situation. . . . The basic

process assumed by most queueing models is the following. Customers requiring service are generated over time by an input source. These customers enter the queueing system and join a queue. At certain times a member of the queue is selected for service by some rule known as the queue discipline (or service discipline). The required service is then performed for the customer by the service mechanism, after which the customer leaves the queueing system. There are many alternative assumptions that can be made about the various elements of the queueing process.[2]

It is various combinations of basic components that distinguish different analytic queueing theory models: "Some fundamental quantities of interest for queueing models are the average number of customers in the system; the average number of customers waiting in queue; the average amount of time that a customer spends in the system; [and] the average amount of time that a customer spends waiting in the queue."[3] These quantities have direct counterparts in transportation systems.

Analytic queueing theory models can therefore be adapted to analyze transportation systems, provided the systems of interest have the fundamental elements of a basic queueing model. Analytic queueing models have been implemented in assorted computer programs such as Microsolve, Queue-2, and Traffen.

Simulation Models

Another subclassification of general techniques is simulation models:

> A simulation is the imitation of the operation of a real-world process or system over time. Whether done by hand or on a computer, simulation involves the generation of an artificial history of a system, and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system. . . .
>
> The behavior of a system as it evolves over time is studied by developing a simulation model. This model usually takes the form of a set of assumptions concerning the operation of the system. These assumptions are expressed in mathematical, logical, and symbolic relationships between the entities, or objects of interest, of the system. Once developed and validated, a model can be used to investigate a wide variety of "what if" questions about the real-world system. Simulation modeling can thus be used both as an analysis tool for predicting the effect of changes to existing systems, and as a design tool to predict the performance of new systems under varying sets of circumstances.[4]

Like analytic queueing theory models, simulation models have a set of basic components, each of which is derived from some aspect of the system the model is meant to emulate:

> An entity is an object of interest in the system. An attribute is a property of an entity. An activity is represented by a time period of

> specified length. The state of a system is defined to be that collection of variables necessary to describe the system at any time, relative to the objectives of the study. An event is defined as an instantaneous occurrence that may change the state of the system. The term endogenous is used to describe activities and events occurring within the system, and the term exogenous is used to describe activities and events in the environment that affect the system.
>
> A complete list [of the components of this system to be simulated] cannot be developed unless the purpose of the study is known. Depending on the purpose, various aspects of the system [would] be of interest, and then the listing of components [could] be completed.[4]

The major simulation models include NETSIM, Texas Model, and Transyt-7F.

Dedicated Techniques

Along with general techniques that can be applied for transportation system analysis, dedicated techniques have been developed for application to specific transportation problems. This category of techniques is organized by the type of facility each is meant to examine, rather than according to analysis approach, as with general techniques.

The following is a list of computerized, dedicated analysis techniques, classified by the type of the facility/situation for which each is dedicated:

- *Basic freeway segments*: Freeway Delay Calculation; Freeway Capacity Analysis; 1985 Highway Capacity Software (1985 HCS); Planning Level Analysis Spreadsheets: Freeway Lane Requirements; Planning Level Analysis Spreadsheets: AADT Thresholds; Rural; and Freeway Operations, Weaving Analysis, Ramps & Ramp Junctions

- *Work zones on freeways*: QUEWZ and Freeway Capacity Analysis

- *Unsignalized intersections:* CINCH, Capcalc 85, 1985 HCS, UNSIG, and UNSIG10

- *Incidents on freeways:* Freeway Traffic Congestion

- *Arterials:* Passer II-87, Maxband-PC, Transyt-7F, and Planning Level Analysis, Spreadsheets: Arterial Level of Service

- *Signalized intersections:* Capcalc 85; CINCH; EZ-POSIT; 1985 HCS; INTCAP; Intersection Analysis; Spreadsheets; Left Turn Analysis Package; Planning Level Analysis Spreadsheets: Intersection Capacity, SOAP 84, SICA, SICAP, SIGCAP, SIGNAL, and SIGPLAN

- *Weaving areas:* FAZWEAVE; Freeway Operations, Weaving Analysis, Ramps & Ramp Junctions; HCMWEAVE; and 1985 HCS

- *Ramps and ramp junctions:* Freeway Operations, Weaving Analysis, Ramps & Ramp Junctions; 1985 HCS; RAMPEN; and RAMPEX
- *Rural highways:* 1985 HCS
- *Rotary intersections*: CIRCAP
- *Diamond interchanges:* Passer III-88.

APPLICATION TO SPECIFIC FACILITY PROBLEMS

As can be seen, there are many methods available to analyze queueing in transportation facilities, varying from formulas and manual techniques to electronic worksheets and computer programs. However, even after these techniques have been identified and classified, without experience, there is no easy, efficient way to determine which method is the most appropriate for the situation at hand.

To aid the practitioner, a simple classification scheme for selecting the most appropriate technique was developed. The concept of classification and evaluation blends quite well with knowledge-based expert system concepts, especially when coupled with other system objectives. As a case in point, in 1987, Edmond Chin-Ping Chang of the Texas Transportation Institute demonstrated an experimental expert system to assist users in selecting computerized software packages supported by the Federal Highway Administration as of 1986.[5] A similar approach is foreseen for queueing analysis techniques as they have been classified here.

A knowledge base like that developed for an expert system was prepared as a means to advise traffic engineers, transportation engineers, and other related professionals in selecting the appropriate analysis techniques to be applied to situations where queuing occurs in transportation systems. Figures 1 through 7 are tabular representations of the current data base that evolved. The information in these figures, thus, serves as a knowledge base for analysts to select queueing models manually in the same manner as an expert system would. This knowledge base can easily be updated to reflect changes in software and practice.

Details concerning the source of the programs shown in Figures 1 through 7, along with their microcomputer hardware requirements, their approximate costs, and their input information where available, are given in Appendix B. The information given in Figures 1 through 7 is reduced to show a summary of queueing situations and appropriate analysis methods in Table 1.

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Facility Type: Basic freeway segment with no other influencing factors

OUTPUTS \ PROGRAMS	Freeway Delay Calculation (P,O)	Freeway Capacity Analysis (O)	1985 Highway Capacity Software	Planning Level Analysis: Freeway Lane Requirements (P)	Planning Level Analysis: Freeway AADT Thresholds (P)	Microsolve	Queue-2	Traffen	Rural	Freeway Operations, Weaving Analysis, Ramps & Ramp Junctions
Total Vehicle Miles Traveled	●									
Recurring Congested Vehicle Miles Traveled	●									
Recurring Delay (Veh-Hr)	●									
Excess Fuel	●									
Typical Incident Delay (Veh-Hr)	●									
Cost for Recurring Delay	●									
Cost for Incident Delay	●									
Cost for Excess Fuel	●									
Total Cost	●									
# of Lanes Needed in Each Direction			●	●						
Directional Design Hour Volume			●	●						
Service Flow Rate			●	●						
Matrix of Threshold AADT Rates for Various Levels of Service and % of Trucks			●		●					
Maximum Queue Length		●								
Time When Queue Starts		●								
Time When Queue Dissipates		●								
Queue Length at End of Observation		●								
# of Lanes Needed to Accommodate Traffic		●								
Total Vehicle Delay		●								
Average Delay per Delayed Vehicle		●								
Average Delay per Approach Vehicle		●								
% of Vehicles Delayed Over Total Time Observed		●								
Typical Capacity		●								

Figure 1. Computerized analysis techniques and outputs for a basic freeway segment with no other influencing factors.

Facility Type: Signalized intersection

OUTPUTS \ PROGRAMS	Capcalc 85 (O,D,P)	CINCH (O,D)	EZ-POSIT (O,D)	1985 Highway Capacity Software	INTCAP (O,P)	Intersection Analysis Spreadsheets	Left Turn Analysis Package (O,P)	Planning Level of Analysis: Intersection Capacity (P)	SOAP 84 (O)	SICA (O,D)	SICAP (D)	SIGCAP (O)	SIGNAL	SIGPLAN	TEXAS Model	TRAF-NETSIM
Average Individual Stopped Delay	●	●	●							●	●					●
Critical Volumes	●															●
V/C Ratio	●	●		●	●											
Capacity	●	●		●	●											●
Green Ratio	●	●		●	●											
Cycle Length	●	●		●	●											
Level of Service	●	●	●	●						●		●				
Utilization Factor	●															
Adjusted Saturation Flow Rate	●	●		●												
Optimal Cycle Length		●	●													
Suggested Timing of Phases		●	●								●					
Left-Turn Bay Warrants							●									
Left-Turn Bay Length							●									●
Excess Fuel Used			●								●					●
Hourly Cost Index											●					
Maximum Queue Length											●					●
Allocated Volumes																●
Flow Rates	●	●			●											●
Loss Time per Cycle		●														
Degree of Saturation			●													●
Left-Turn Warrant			●				●									
Critical Volumes for Each Direction	●							●								
Status of Intersection	●							●								
Storage Lengths												●				●

Figure 2. Computerized analysis techniques and outputs for a signalized intersection.

Facility Type: Basic freeway segment influenced by a work zone

OUTPUTS \ PROGRAMS	QUEWZ (P)	Freeway Capacity Analysis (O)	Microsolve (P)	Queue-2 (P)	Traffen
Maximum Queue Length		●	●		
Time When Queue Starts		●			
Time When Queue Dissipates		●			
Queue Length at End of Observation		●			
Queue Length at End of 1st Hour Observed		●			
Total Vehicle Delay		●			
Average Delay per Delayed Vehicle		●			
Average Delay per Approach Vehicle		●			
% of Vehicles Delayed Over Total Time Observed		●			
Total Capacity		●			
Work Zone Capacity		●			
Average # of Vehicles in the Queue			●	●	
Queue Length for Each Hour of Work Zone Operation	●				
User Costs for Each Hour of Work Zone Operation	●				
Total Work Zone Costs	●				
List of Queues Greater Than 2 Miles and Causing Delay Greater Than 20 Minutes	●				

Figure 3. Computerized analysis techniques and outputs for a basic freeway segment influenced by a work zone.

Facility Type: Unsignaled intersection

PROGRAMS

OUTPUTS	CINCH (O,P)	Capcalc 85 (O)	1985 Highway Capacity Software (O)	UNSIG	UNSIG 10	TRAF-NETSIM
Reverse Capacity		●	●			
Level of Service		●	●			
Delay	●					●
Average Queue Length	●					●

Figure 4. Computerized analysis methods for an unsignalized intersection.

Facility Type: Basic freeway segment influenced by an incident

OUTPUTS \ PROGRAMS	Freeway Traffic Congestion (O)	Microsolve (P)	Queue-2 (P)	Traffen
Total Delay	●			
Average Delay per Incident	●			
Time of Normal Flow	●			
Maximum Queue Length	●	●		
# of Arrivals to System		●		
# of Balks From System		●		
Average Time Between Arrivals or Balks		●		
Average # of Customers in Service		●		
Average Service Time		●		
Average # of Customers in Queue		●	●	
Average # of Customers in System		●	●	
Average Time in Queue		●	●	
Average Time in System		●	●	
% Utilization of Server		●	●	
% Facility Is Idle			●	

Figure 5. Computerized analysis techniques and outputs for a basic freeway segment influenced by an incident.

Facility Type: Arterial with no other influencing factors

OUTPUTS \ PROGRAMS	Passer II-87 (O,D,P)	Maxband-PC (O,D,P)	Transyt-7F (O,D,P)	Planning Level of Analysis: Arterial Level of Service (P)
Optimum Signal Timing		●	●	
Level of Service				●

Figure 6. Computerized analysis techniques and outputs for an arterial with no other influencing factors.

Miscellaneous facilities

OUTPUTS \ PROGRAMS	FAZEWEAVE	Freeway Operations, Weaving Analysis, Ramps and Ramp Junctions	HCMWEAVE	1985 Highway Capacity Software	Rampen & Rampex	Netsim	Transyt-7F	Queue-2	Microsolve	Traffen	Rural	CIRCAP	Passer III-88
Weaving Area	●	●	●	●									
Ramp or Ramp Junction		●		●	●								
Network						●	●						
Toll Plaza								●	●	●			
Garage Entrance or Exit								●	●	●			
Rural Highway				●							●		
Pedestrian Crosswalk				●									
Bikeway or Bikelane				●									
Rotary Intersection												●	
Diamond Interchange													●

Figure 7. Computerized analysis techniques for various facility types.

Table 1

QUEUEING SITUATIONS AND ASSOCIATED ANALYSIS METHODS

	Situation	Analysis Method
1.	Turning and parking movements inhibit traffic flow at signalized intersections.	1985 HCS, CINCH, EZ-POSIT, SICAP
2.	Left-turning vehicles extend beyond the left-turn storage lane and into the through lanes.	EZ-POSIT, Left Turn Analysis Package, SIGCAP, Intersection Analysis Spreadsheets
3.	Excessive queue length on a signalized intersection approach.	1985 HCS, Capcalc 85, CINCH, INTCAP, Soap 84
4.	Insufficient capacity to handle peak traffic volumes at an acceptable level of service on an arterial.	Maxband-PC, Planning Level Analysis Spreadsheets: Arterial Level of Service
5.	Incident on an urban freeway.	Freeway Traffic Congestion, Microsolve, Queue-2, Traffen
6.	Inadequate sight or stopping distances at a signalized intersection.	CINCH, EZ-POSIT
7.	Turning and parking movements inhibit traffic flow on arterials.	Passer II-87, Maxband-PC, Transyt-7F

DEMONSTRATION MODEL

Field Study Method

Available Methods

In order to apply and validate queue analysis methods, field data must be obtained. Because queuing problems have been shown to exhibit many dimensions, the data set must be quite complex. Methods that were considered in this study are shown in Table 2. Each is personnel intensive or relies on video technology. Example queue reduction strategies for the situations given in Table 1 are shown in Appendix C.

The problem of a signalized intersection was selected for the proposes of demonstrating a field data collection effort for queue analysis. The methods, identified

Table 2

OVERVIEW OF DATA COLLECTION METHODS

Method	Description
1. Field crew and clipboards	Vehicle progression through intersection and actual signal cycle recorded by a field crew on paper on a clipboard
2. Automatic traffic counters	Strategically placed automatic traffic counters record intersection activity at regular intervals
3. Field crew and chart recorder	Queue arrival and/or discharge headways recorded by a field crew using one or more chart recorders
4. Field crew and portable personal computers	Vehicle progression through intersection and actual signal cycle recorded by a field crew on portable personal computers
5. Video camera and operator	Vehicle progression through intersection and actual signal cycle recorded continuously using one or more video cameras
6. Still photography	Strategically placed 35 mm cameras record intersection activity at regular intervals
7. Video incident detection systems	All traffic activity through the intersection recorded by an automated video camera and analyzed by a remote-site computer and operator
8. Miscellaneous data reduction methods	All discuss field measurement of delay but do not explicitly describe the mechanics and details of the field measurement technique employed

here, however, can be used to collect queuing data on any facility. Selected comparative measures for these data collection methods are given in Table 3. A complete discussion of each method is provided in Appendix D. The *potential sources of error* are a general guideline to factors that make some of these basic traffic data collection procedures inadequate for the purposes of queue analysis.

Data Collection Method Used

After comparison and consideration of each method and the purposes of this study, the video camera and operator method (method 5 in Table 3) was selected for use. Data were collected for the evaluation and comparison of methods using two video cameras and slow motion frame advance viewing equipment. "The methodology relies on the use of both videotape and personal computer technologies, a

Table 3
COMPARISON OF DATA COLLECTION METHODS

	Method	Staff Required	Training Required	Equipment Required	Potential Sources of Error
1.	Field crew and clipboards	1 to 4 per approach	Minimal	Clipboards, data sheets, and watches	Missed or mis-copied entries with no chance for data recovery
2.	Automatic traffic counters	1	Minimal	4 or more automatic traffic counters	Failure of auto-matic traffic counter, collects only point process data
3.	Field crew and chart recorder	1 to 4 per approach	Operation of chart recorder	Chart recorder	Missed entries with no chance for data recovery
4.	Field crew and portable personal computers	1 or more	Operation of portable personal computer and program	Portable computer	Missed entries with no chance for data recovery
5.	Video camera and operator	1 per pair of approaches	Operation of video camera	Video camera	If camera works, data are collected and accurately preserved
6.	Still photography	1	Placement and operation of 35mm camera	35 mm cameras (also possibly helicopter and coordinate translator)	Missed entries with no chance for data recovery
7.	Video incident detection system	1 for observation center	Operation of entire system video camera, image digitizer, and computer	Automated video cameras, "black box" imagedigitizer, mini or personal computer	Video artifacts, improper digitizing, poor camera placement
8.	Miscellaneous data reduction methods	Not applicable	Not applicable	Not applicable	Not applicable

combination that eliminates the need for a large staff in the data collection process and simplifies data reduction and analysis."[6] It was decided that this technique provided many of the advantages of the more advanced technique described in the video incident detection system method without the prohibitive expense and complexity of the system, which is still being field tested.

Site Selection

Once a field data collection technique was selected, a site was chosen for an evaluation case study of both the data collection technique and analysis methods. The intersection of U.S. Route 29 and Virginia State Route 649 (Airport Road) was selected.

According to a 1987 survey by the Virginia Transportation Research Council, approximately 53% of all signalized intersections in Virginia are isolated. Of these, "essentially all of the Department's signalized intersections are actuated—approximately 20% are operate semi-actuated, 50% operate fully actuated, and 30% operate fully actuated with volume-density timing."[7] Therefore, to be representative of a majority of the signalized intersections that VDOT personnel deal with, the intersection needed to be actuated and isolated from other intersections.

Also, in order to evaluate queueing analysis methods, the traffic using the intersection needed to be heavy enough to experience queueing. Finally, in order to be able to evaluate fully the use of video cameras as a data collection method, the intersection needed to have two locations from which each pair of approaches could be easily viewed.

Figure 8 is a diagram of this intersection with p.m. peak hour volumes. Route 29 Northbound consists of four lanes at the intersection: an exclusive left-turn lane, two through-traffic lanes, and an exclusive right-turn lane. These lanes are governed by three signal heads: one left-turn signal and two through-traffic signals. Route 29 Southbound has the same configuration. Route 649 Westbound consists of a single lane for all traffic movements, which is widened by a paved shoulder at the intersection. In practice, the single lane is most often used as one combined left-turn and through-traffic lane and the paved shoulder is used as an exclusive right-turn lane. The official single lane is governed by two signal heads, each operating identically. Route 649 Eastbound consists of one combined left-turn and through-traffic lane and an exclusive right-turn lane. These lanes are governed by two signal heads, each operating identically.

This intersection is isolated from other signals and is not a part of a signal network. The signal is fully vehicle actuated with volume-density timing. Despite its relative isolation, queueing does occur on all approaches during the peak hours of 7 a.m. to 9 a.m. and 4 p.m. to 6 p.m. Finally, as can be seen in Figure 8, two video camera locations were identified. From each camera location, a pair of approaches could be easily observed and videotaped.

The signal controller at the intersection of Route 29 and Route 649 is fully traffic actuated with a volume-density setting. This means that each phase of the

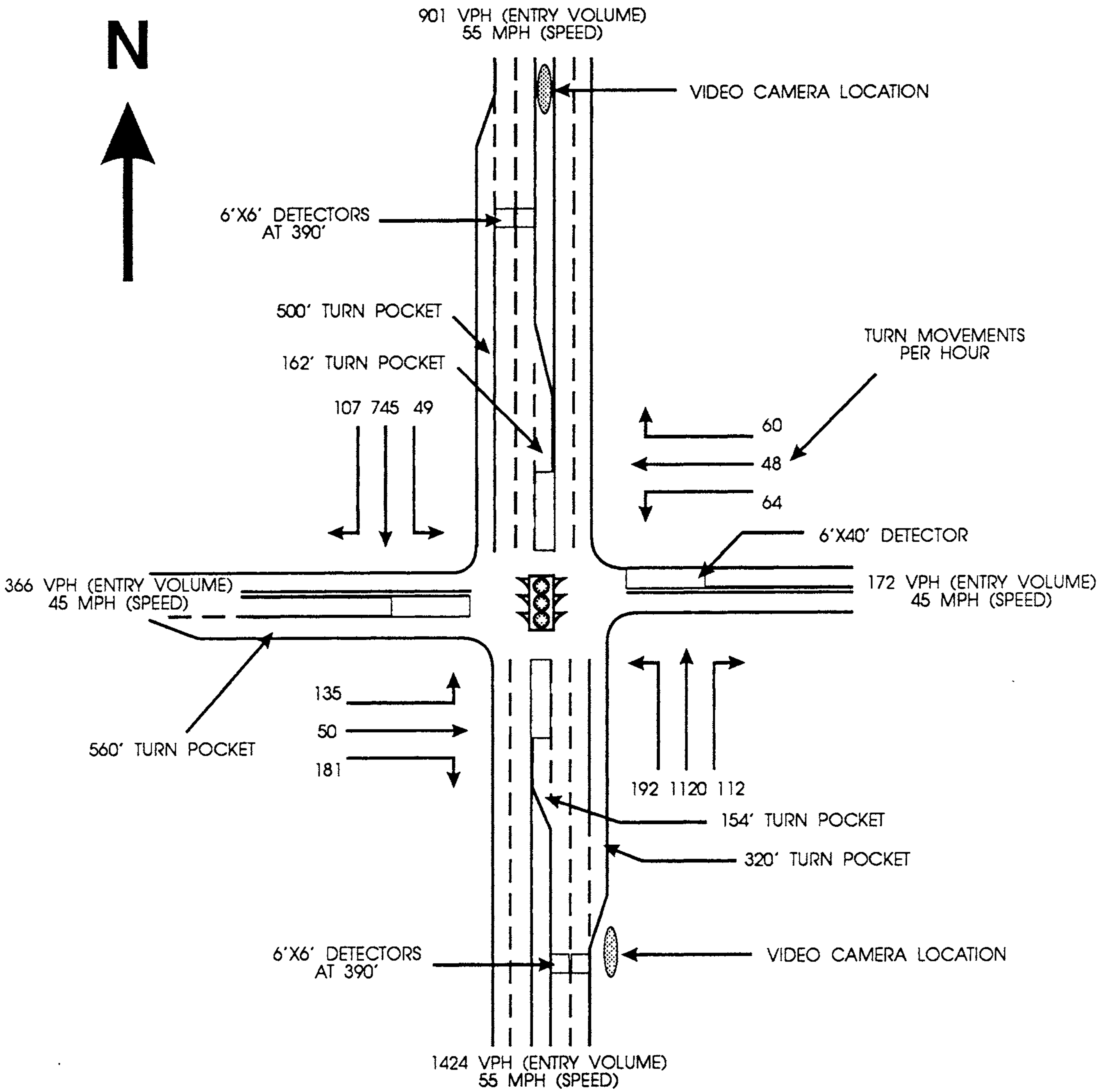

Figure 8. Intersection of U.S. Route 29 and Virginia State Route 649 (Airport Road).

Table 4
SIGNAL TIMINGS—INTERSECTION OF ROUTE 29 AND ROUTE 649

Lane	Signal Head No.	Min. Green	Sec per Actuation	Min. Gap	Max. Green	Yellow Clearance	Red Clearance
29 S Left	1	6	3.0	3.9	25	5.0	2.0
29 N Through	2	15	3.0	3.5	45	5.0	1.5
649 E	4	6	3.0	3.9	30	5.0	2.0
29 N Left	5	6	3.0	3.9	25	5.0	2.0
29 S Through	6	15	3.0	3.5	45	5.0	1.5
649 W	8	6	3.0	3.9	30	5.0	2.0

cycle has a minimum green, a maximum green, a fixed amber clearance time, a fixed red clearance time, and an incremental number of seconds of green allowed per actuation. The intersection has six signals, numbered between 1 and 8. The signal head number refers to its placement in the intersection and the movement(s) it controls. Table 4 gives the timing specifications for each signal.

Figure 9 gives the phasing diagram for the signal. Again, the numerals in the phase designation refer to the signal head number that is given the right of way in the phase. In the first phase (Phase 01-5), the right of way is allocated to Route 29 Northbound left-turning vehicles and to Route 29 Southbound left-turning

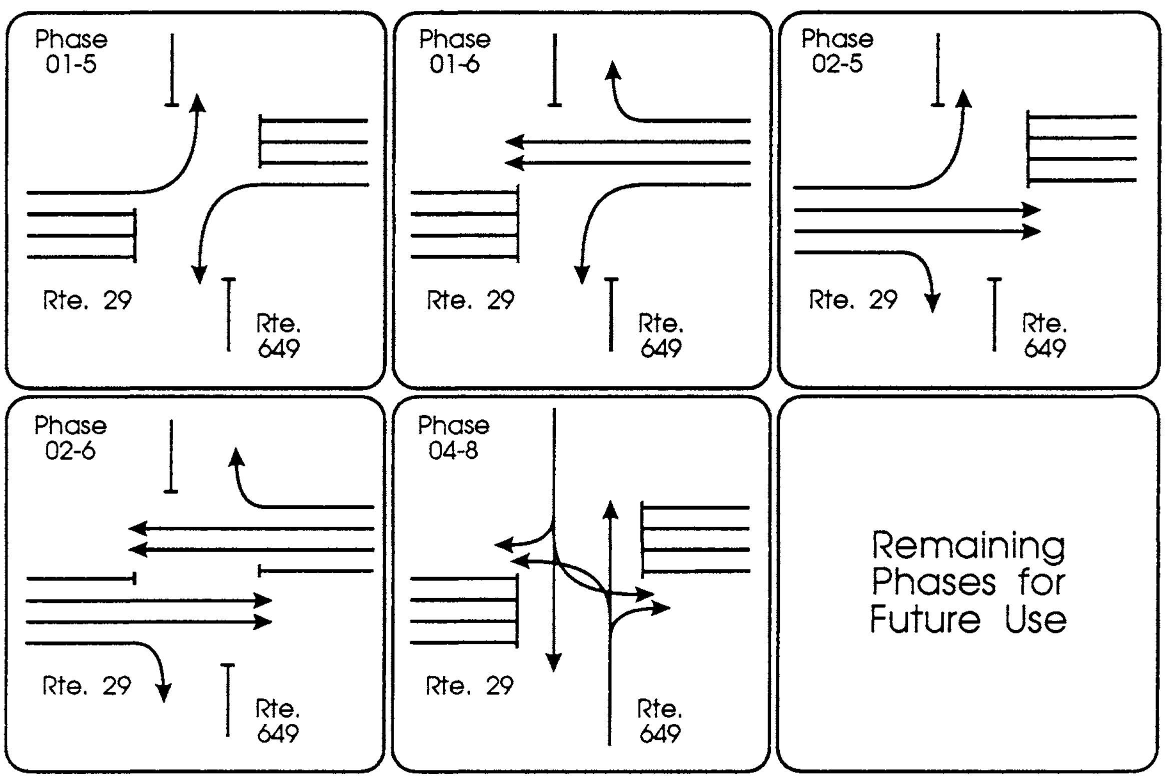

Figure 9. Phasing diagram for Routes 29 and 649.

vehicles. In the second phase (Phase 01-6), all Route 29 Southbound vehicles have the right of way. All Route 29 Northbound vehicles have the right of way in the third phase (Phase 02-5). In the fourth phase (Phase 02-6), through-traffic and right-turning vehicles on both Route 29 Northbound and Southbound are apportioned the right of way. Finally, all movements on Route 649 are given the right of way in the fifth phase (Phase 04-8).

Data Processing

In order to observe the intersection of Route 29 and Route 649 under normal peak hour conditions, the traffic activity at the intersection was videotaped from 4 p.m. to 6 p.m. on Thursday, August 3, 1988. A video camera was set up and operated at each of the locations indicated in Figure 8. The entire data collection effort required two video cameras and tripods, two camera operators, two 2-hour VHS videotapes, two vehicles, and all appropriate safety equipment. This method recorded, in real time, all data necessary to analyze the intersection and determine the level of service being provided to its users. It also recorded information that could be used to validate the results of the analysis.

The data collected for this research were analyzed using a combination of slow-motion, frame-advance videotape viewing technology and microcomputer-based spreadsheets. The two videotapes of the intersection were viewed as often as necessary on a 13-inch Sony Trinitron color monitor/television connected in line to a Convergence Corporation Model 195 videotape editing machine and a Sony U-matic videocassette recorder/player VO-5800 using a 3/4-inch format videotape. A Panasonic video monitor was also connected as another output device to show viewing times and frame counts as the data analysis effort progressed.

From the videotapes it was possible to determine vehicle turning counts; traffic volumes; arrival, service, and departure rates; and arrival, service, and departure probability distributions. For validation of the analysis methods evaluated, it was also possible to record actual queue lengths and stopped delay. Because the viewing equipment allowed the tape to be advanced as slowly as one frame at a time, the exact timing of vehicle arrivals (headways), departures, and destinations through the intersection and time spent in the queue could be recorded.

The similar data points (i.e., all vehicles turning left from the combined left-turn/through-traffic lane on Route 649 [Airport Road]) were entered into an electronic spreadsheet. The analysis spreadsheet was designed to calculate the average headway and the standard deviation of the headways and to determine if the observed arrival distribution was statistically the same as various theoretical distributions. The spreadsheet also provided a count of each group of data points over the time period entered.

Evaluation of Queue Analysis Methods

In this section, the results of the application of four analysis procedures to the intersection are described. The desired output from each method included the level of service, average stopped delay, and average queue length.

The purpose of this evaluation is to demonstrate the variations among the different analysis methods that are available for a specific queuing problem and to impress the need to consider available options carefully and be on the lookout for new tools. Only the results of the evaluation are presented here; the reader is referred to other sources for an in-depth description of the techniques.

Four analysis methods were selected for evaluation: (1) 1985 HCM, (2) CINCH (a potential enhancement of the 1985 HCS software) (3) a vacation-server queueing model, and (4) TRAF-NETSIM (microscopic simulation). The first two methods are dedicated techniques cited by the VDOT survey respondents as the methods available to them at the time of the survey and most often used for analyzing signalized intersections. The third method is a generalized technique, an analytic queueing theory model, which was adapted here to analyze a signalized intersection. No applications of this model to intersection analysis were found in the literature, and a comparison of the different practice-oriented methods with a basic theoretic model is timely. The fourth method is a simulation model that allows the traffic engineer to evaluate different intersection design control strategies on a real-time basis. These methods are representative of the categories of methods that were defined earlier. The first two methods represent the state-of-the-practice, or dedicated, methods; the third investigates the application of a general technique; and the fourth is a simulation model.

The 1985 HCS Approach

The 1985 HCM method was reported by the survey respondents as the method most often used to analyze signalized intersections. This approach is usually implemented through a computer program, the 1985 HCS, which performs calculations in the same manner as directed in the 1985 HCM.

The 1985 HCM method must be used with caution when analyzing traffic activated situations because it is primarily designed to evaluate fixed time signals. In the computer program, the user, however, does indicate a fully actuated signal. The manual recommends using average cycle lengths and green time for the period of analysis. In an attempt to replicate real conditions, the minimum and maximum settings on the signal were used here. A fixed time assumption for establishing the phases and cycle length was also considered, but because the system was traffic actuated, it was eliminated from further consideration because it was unlikely to occur. The application of the 1985 HCS method here is interpreted to show the data it provides for the subject evaluation and comparative analysis with other methods, namely delay and level of service. However, in the 1985 HCM procedure, delay is first calculated and then assigned a level of service based on a table of values (Table 5).

Table 6 shows the comparison of the observed delay measures with those predicted by the 1985 HCM for the minimum and maximum green settings. There is no apparent correlation between the observed values and those given by the 1985 HCM method. In most cases, the observed values fall between those for the respective limits, as would be expected. The value of the 1985 HCM method is to identify problem approaches and compare different intersection control and design strategies using average or limit conditions, as has been shown.

The CINCH Approach

The CINCH program is an improvisation of the 1985 HCM method wherein the basic computational methodology is the same but the input method and output measures differ somewhat. Additional concepts were taken from Hauer, Pagtsas, and Shin[8] and the Institute of Transportation Engineers (ITE) *Handbook.*[9]

LOS (Table 5) and delay (Table 6) are computed as in the 1985 HCM method, but queue length is also calculated using the formula shown in Table 16-23 of the ITE *Handbook.*[9]

Table 7 gives a comparison of the delay estimates from CINCH with observed delay and 1985 HCS estimates. Because there is a wide difference between the

Table 5

HCM LEVEL-OF-SERVICE CRITERIA FOR SIGNALIZED INTERSECTIONS

Level of Service	Stopped Delay per Vehicle (sec)
A	< 5.0
B	5.1 to 15.0
C	15.1 to 25.0
D	25.1 to 40.0
E	40.1 to 60.0
F	>60.0

Source: HCM 1985, Table 9.1.

Table 6

AVERAGED STOPPED DELAY: COMPARISON OF HCM AND OBSERVED (SEC/VEHICLE)

Observation	Observed Values	1985 HCM Min. Green	1985 HCM Max. Green
29 N LT Lane	39.73	16.6	39.4
29 N LT Through Lane	20.73	16.5	36.6
29 N RT Through Lane	14.34	16.5	36.6
29 S LT Lane	46.35	15.1	35.8
29 S LT Through Lane	21.22	11.9	28.5
29 S RT Through Lane	21.22	11.9	28.5

Table 7

AVERAGE STOPPED DELAY: COMPARISON OF CINCH, HCM, AND OBSERVED (SEC/VEHICLE)

Observation	Observed Values	1985 HCM Min. Green	1985 HCM Max. Green	CINCH Min. Green	CINCH Max. Green
29 N LT Lane	39.73	16.6	39.4	23.73	45.45
29 N LT Through Lane	20.73	16.5	36.6	21.33	39.26
29 N RT Through Lane	14.34	16.5	36.6	6.38	12.28
29 S LT Lane	46.35	15.1	35.8	16.9	37.59
29 S LT Through Lane	21.22	11.9	28.5	17.62	33.40
29 S RT Through Lane	21.22	11.9	28.5	8.93	13.94

CINCH values and those given by the 1985 HCS, it is assumed that the improvements in the 1985 HCS give the more correct results.

The CINCH program did not deduct for right turn on red (RTOR) as did the 1985 HCS program. RTOR volumes were therefore subtracted from each approach volume before inputting to CINCH so that the analyses would be comparable. The ranges of values are consistent between the two programs, but there are differences. Both of these software packages are distributed/sold for general use, but they indicate different levels of support. CINCH is not supported by McTrans, its distributor, and the 1985 HCS software is continually being updated as problems arise and are corrected.

Because the purpose of this study is to evaluate the use of available techniques for queue management, the mechanics of the two programs cannot be addressed. Rather, their utility to the user is examined based on the results of an application to an actual intersection.

CINCH adds performance measures, particularly the average queue length and the 95% queue, using formulas from the ITE *Handbook.*[9] Also, CINCH appears to offer some optimization capabilities. The analyst has the option of rerunning the program with new suggested signal settings that improve upon the initial entry. This feature performs like a dynamic program, but in this application, the results were unrealistic. Since CINCH has not been improved to keep up with the newer versions of the 1985 HCS software, it cannot be recommended for practical use. This is a major pitfall to software users where programs such as CINCH are developed for a single study and are abandoned after the original objectives are met. The additional capabilities of CINCH regarding queue analysis are significant but must be considered to be unreliable because of the use of obsolete 1985 HCM programs.

The Vacation-Server Model Approach

Because the 1985 HCS program strictly follows the methodology of the 1985 HCM, its application is limited by the assumptions and structure of the method.

The primary measures given are level of service and delay. As the CINCH method has shown, it is desirable to have measures of queue size as well. It is on this observation that the following investigation was performed into the application of analytic queueing theory to the signalized intersection problem to provide the analyst with a technique to supplement the 1985 HCS output. As discussed earlier, analytic queueing theory models can be adapted to analyze transportation facilities provided the facility of interest has the fundamental elements of a basic queueing model. A signalized intersection has many of the elements of a basic queueing model: an input source—any vehicles traveling on the roadway network; customers—those vehicles wishing to pass through the intersection; a queueing system—a lane group and the controlling signal; a queue—the waiting line of cars in a lane; a service discipline—first come, first served through the intersection for a particular lane; and service mechanism—the signal that controls the right of way for a particular lane.

However, there is one important difference in the operation of a signalized intersection that prevents it from being realistically modeled by a basic analytic queueing theory mode: the availability of the service mechanism to provide service. In the basic model, it is assumed that the service mechanism is continuously available to provide service to customers. This is not the case with a signal, when service is defined as allowing cars on a single lane of an approach to pass through the intersection. In this case, the service mechanism has three states in which it can be, not two (busy and idle). The traffic signal, from the point of view of its customers, is either (1) busy—green and allowing cars to pass through the intersection, (2) idle—green and no cars wish to pass through the intersection from the particular lane, or (3) "on vacation"—red and allowing no cars to pass through the intersection, whether there are any cars desiring to do so or not. An analytic queueing theory model has been developed that incorporates this "vacation" state. This is known as the "vacation-server" queueing model.[10]

Different variations of the vacation-server model have been derived. The one found to be most applicable to the traffic-actuated signalized intersection problem is termed the "limited service queueing model." "This M/G/1 queueing model places an upper bound, say k, on the number of customers that the server will serve per visit to the queue."[10] The variation of this model, in which if the server returns from vacation to find j customers waiting the server gives service to $min(j,k)$ customers before again going on vacation, closely approximates the operation of a fully actuated volume-density signal in which the "default" light is red.

For this research, a limited service vacation-server model was implemented.

> An upper bound, say k, is placed on the number of customers that the server will serve per visit to [the] queue. This is, the server works until either k services have been given or the queue is empty, then departs for the next queue in sequence. . . . This approach yields, in a nearly effortless manner, the mean waiting times $E[W_k]$. . . . For $1 < k < \infty$, simulation results show that this upper bound is fairly tight, typically exceeding $E[W_k]$ by less than 10 percent. Thus this upper bound

also serves as a rather good approximation. For the cases $k = 1$ and k = (exhaustive service), the upper bound is exact.[10]

The mean waiting time is calculated as follows:

$$E[W_k] \leq \frac{1 - \varrho}{1 - \varrho - \frac{\lambda c}{k}} E[W_Q]$$

where:

$E[W_k]$ = Expected waiting time in the queue of an M/G/1 queueing system with vacations and limited service

ϱ = $\lambda E[S]$; server utilization

λ = mean arrival rate

$E[S]$ = mean service rate

$e = \dfrac{\lambda}{E[S]}$

c = $E[V]$; mean vacation duration; first moment of vacation duration distribution

k = upper limit on the number of customers served between vacations

$E[W_Q]$ = expected waiting time in the queue of an M/G/1 queueing system with a dedicated server

$$= E[W_{M/G/1}] + \frac{E[V^2]}{2E[V]}$$

$E[W_{M/G/1}]$ = expected waiting time in the queue of an $M/G/1$ queueing system with a dedicated server

$$= \frac{\lambda E[S^2]}{2(1 - \lambda E[S])}$$

$E[S^2]$ = second moment of service time distribution

$= Var[S] + (E[S])^2$

$Var[S]$ = variance of service time distribution

$E[V^2]$ = second moment of vacation duration distribution

$= Var[V] + (E[V])^2$

$Var[V]$ = variance of vacation duration distribution

L_q = $\lambda E[W_k]$ average queue length.

To apply this model, six parameters must be either estimated or derived from observations. The analyst must know or approximate (1) the arrival rate in units per time, (2) the mean service time, (3) the variance of the service time distribution, (4) the mean red signal/vacation duration, (5) the variance of the red signal/vacation duration distribution, and (6) the number of customers able to be served during the maximum allowable green time [k = (maximum allowable green time + yellow time)/(mean service time)]. Table 8 summarizes the input variables needed to implement the model and the methods suggested to determine appropriate values.

The limited service vacation-server queueing model was implemented with an electronic spreadsheet on a personal computer. This model provides meaningful scientific, but somewhat unconventional, measures for signalized intersection performance. It can be applied to traffic-actuated signals using measures taken from traffic flow observations in a single approach without concern for the other approaches.

Table 8

VACATION-SERVER MODEL: INPUT VARIABLES AND METHOD OF DETERMINATION

Variable	Method of Determination
Mean headway	Calculated from observations
Variance of headways	Calculated from observations
Mean arrival rate	$\dfrac{1}{\text{Mean headway}}$
Mean MPH through the first 25 feet behind the stop line	Estimated from observations
Mean service time	$\dfrac{25 \text{ ft}}{(\text{Mean MPH through})\left(\frac{5280 \text{ ft/mile}}{3600 \text{ sec/hr}}\right)}$
Variance of service time	(Mean service time)^2
Rho	$\dfrac{\text{Mean arrival rate}}{\text{Mean service time}}$
Upper service limit	$\dfrac{\text{Maximum allowable green time + yellow time}}{\text{Mean service time}}$
Mean vacation length	Calculated from observations

Table 9

AVERAGE STOPPED DELAY: COMPARISON OF
HCM, CINCH, AND VACATION-SERVER MODELS (SEC/VEHICLE)

Observation	Observed Values	1985 HCM Min. Green	1985 HCM Max. Green	CINCH Min. Green	CINCH Max. Green	Vacation-Server Model
29 N LT Lane	39.73	16.6	39.4	23.73	45.45	61.86
29 N LT Through Lane	20.73	16.5	36.6	21.33	39.26	26.77
29 N RT Through Lane	14.34	16.5	36.5	6.38	12.28	25.80
29 S LT Lane	46.35	15.1	35.8	16.9	37.59	104.62
29 S LT Through Lane	21.22	11.9	28.5	17.62	33.40	30.08
29 S RT Through Lane	21.22	11.9	28.5	8.93	13.94	30.15

Table 9 compares the essential delay values for the respective methods tested. The queueing model by definition estimates an upper limit, but its results are not always larger than those given for the maximum settings. These values are plotted in Figure 10. This plot shows similar curve shapes between observed delays and those estimated using the vacation-server model. The minimum and maximum signal settings for the 1985 HCM method provide similarly shaped curves. There was no correspondence, however, between the 1985 HCM curves and the others.

The TRAF-NETSIM Approach

TRAF-NETSIM is a microscopic stochastic simulation model (a detailed simulation model that involves the use of probability) used for evaluating urban roadway networks. It is designed to be an operational tool for the purpose of evaluating alternative network control and management strategies. It is particularly appropriate to the analysis of dynamically controlled traffic signal systems based on real-time surveillance of network traffic movements. However, it may also be used to address a variety of other problems, including the effectiveness of conventional traffic engineering measures, bus priority systems, and a full range of standard-fixed time and vehicle-actuated signal control strategies.[11]

Table 10 provides a comparison of TRAF-NETSIM queueing measures with those of the vacation-server model and the observed values. The NETSIM values for delay per vehicle on each approach direction are tabulated in Table 11, along with similar measures from the other models, and plotted in Figure 10. Those values are very close to those given for the vacation-server model except for the Route 29 Southbound left turn. Other differences are readily noted. Table 12 provides the time in seconds that a vehicle spends in the queue and gives a comparison of these values with those observed from the videotape and those given by the vacation-server model.

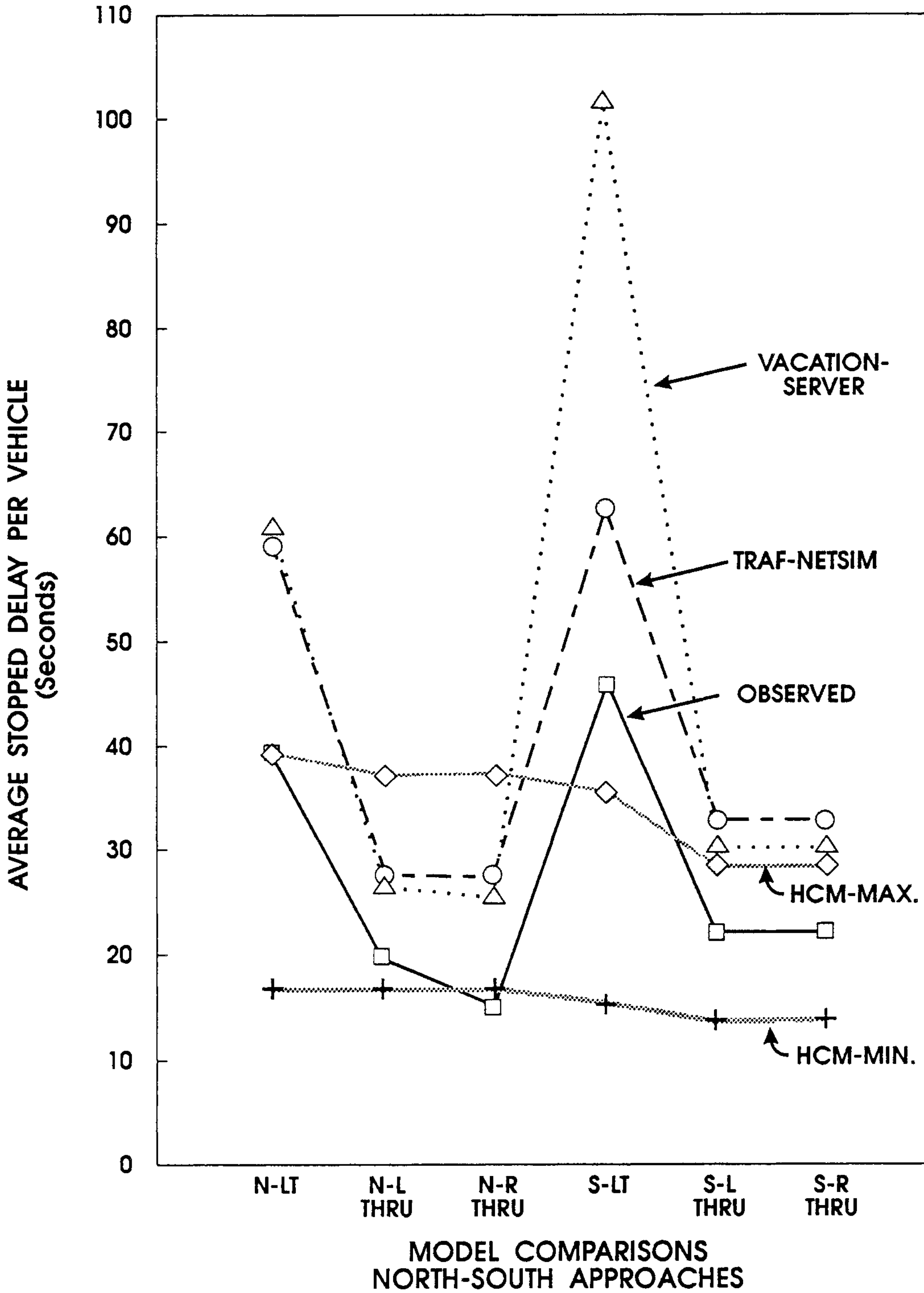

Figure 10. Delay comparisons.

Table 10

QUEUE LENGTH COMPARISONS

Method	29 N LT	29 N L Through	29 N R Through	29 S LT	29 S L Through	29 S R Through
Observed	3.95	10.21	8.33	1.72	6.10	4.71
Vacation-server model	2.8	4.7	3.7	1.1	2.7	2.8
TRAF-NETSIM average	2	2	2	1	2	2
TRAF-NETSIM maximum	8	13	11	4	9	9

Table 11

AVERAGE STOPPED DELAY: COMPARISON OF OBSERVED, HCM, CINCH, VACATION-SERVER, AND NETSIM (SEC/VEHICLE)

Observation	Observed Values	1985 HCM Min. Green	1985 HCM Max. Green	CINCH Min. Green	CINCH Max. Green	Vacation-Server Model	TRAF-NETSIM
29 N LT Lane	39.73	16.6	39.4	23.73	45.45	61.86	58.1
29 N LT Through Lane	20.73	16.5	36.6	21.33	39.26	26.77	27.6
29 N RT Through Lane	14.34	16.5	36.5	6.38	12.28	25.80	27.6
29 S LT Lane	46.35	15.1	35.8	16.9	37.59	104.62	62.9
29 S LT Through Lane	21.22	11.9	28.5	17.62	33.40	30.08	32.3
29 S RT Through Lane	21.22	11.9	28.5	8.93	13.94	30.15	32.3

Table 12

TIME IN QUEUE: COMPARISONS OF OBSERVED, TRAF-NETSIM, AND VACATION-SERVER

Lane	Observed	TRAF-NETSIM	Vacation-Server
29 N Left Turn Lane	39.73	42.1	44.76
29 N Left Through Lane	20.73	12.6	22.90
29 N Right Through Lane	19.18	12.6	22.87
29 S Left Turn Lane	46.35	48.6	93.35
29 S Left Through Lane	21.22	17.9	27.52
29 S Right Through Lane	19.93	17.9	27.52

CONCLUSIONS

A large number of computerized methods are available for the analysis of different queueing situations throughout highway systems. For the most part, dedicated techniques that focus on a particular problem are used by practitioners, as shown in the survey. All of the methods used for the five queueing problems of most interest from the survey were developed for the transportation profession using dedicated methodologies as given, for example, in the *Highway Capacity Manual* and other sources of traditional transportation literature.

Figures 1 through 7 provide a knowledge base for selecting an appropriate tool for a specific facility. This information can serve to initiate the development of a computerized expert system for selecting queue analysis procedures.

The video camera and operator method proved to be an effective way to capture queueing data. The advantage of video is that the situation can be reviewed for precise study of the different parameters. As video incident detection systems become more developed, they will likely become the state-of-the-practice data collection method for queueing. This technology would also encourage more studies on detailed queueing information because of the automation of the staff hours required to view the videotape.

The evaluation of four methods for conducting a queueing analysis of signalized intersections revealed three distinct approaches from the respective categories of dedicated techniques, classical queueing theory, and simulation. Each method indicated a unique merit in itself that lends each to be recommended for specific levels of study. The use of methods from each category can be extended to other situations in highway systems as revealed in this study. The analyst, therefore, has access to different options when facing a study of highway queues.

Overall, the results for the vacation-server model and TRAF-NETSIM were quite consistent, as was expected because the simulation model incorporates the fundamental probabilistic properties inherent in theoretical queueing models. Both of these methods offer improvements to the state of the practice as revealed by the survey.

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APPENDIX A

VDOT Survey of Practitioners: Survey Form and Responses

VIRGINIA TRANSPORTATION RESEARCH COUNCIL

SURVEY OF QUEUE ESTIMATION PROCEDURES

This survey is designed to determine the current uses of and needs for queue analysis procedures in traffic/highway engineering practices. You are asked to assist in identifying (a) specific problems, (b) techniques currently used, and (c) situations where tools are needed. Please answer the following questions as thoroughly as possible.

Please provide your name so we may contact you if further information is needed on a particular problem. Thank you for your cooperation and assistance.

Name ______________________________
Division/Department ____________________
Phone ______________________________

1. In your work, what specific queueing problems are of concern?

Recurrent peak period delays
- signal backups _____
- unsignalized intersections _____
- long-term work zone operations _____
- freeway ramps _____
- toll booths _____
- left-turn storage lane requirements _____
- saturated networks (alternate routes are congested) _____
- special traffic generators (e.g., hospitals) _____
- other (please specify) ______________________________

____

Nonrecurrent (temporary) problems
- traffic accidents _____
- vehicle breakdowns _____
- short-term maintenance work _____
- special events _____
- other (please specify) ______________________________

____

2. For the above problems, what typical measures of congestion do you use to determine the severity of the problem?
- length of queue _____
- average vehicle delay _____
- duration of bottleneck _____
- total vehicle delay _____
- cost of vehicle delay _____
- other (please specify)

3. Does the scope of your analysis of queueing problems focus only on a specific facility (e.g., an interstate highway section) or on a system of alternate routes as well? Please discuss.

4. For the type of queueing problems described above, please identify and describe the analytical methods used, if any, to estimate the dimensions of queues resulting from congestion-inducing events and conditions. For example, the Highway Capacity Manual method could be used to estimate queue length and delay that result from maintenance and construction operations.

Problem/Event	Queueing Analysis Procedure
1. Pavement repair (examples)	1985 *Highway Capacity Manual*
2. Traffic accident	Freeway traffic congestion computer program (FHWA 1986)
3. Signalized intersection	SIGOP computer program

5. Please state those problems that you continue to encounter in your work where a recommended procedure (preferably computerized) would be welcome.

Problem	Measure of Performance
1. Intersection delay (examples)	queue length, maximum delay, average delay
2. Highway work zones	queue length, delay, time duration
3. Traffic accident	queue length, average delay, duration

6. As you are now aware, this study focuses on the analytical techniques used in queueing analysis of highway/traffic congestion problems. Manual and computerized methods will be reviewed relative to practical applications. Consideration will be given to transferring methods to new problem applications. The results will be documented in a technical manual. Please make any comments below that you wish regarding the information requested (or not requested) that will make the resulting product more beneficial to transportation engineers.

SUMMARY OF RESPONSES (Fifteen responses)

1. Specific queueing problems.

Problem	# Responses	%	Comments
Signal backups	13	87	1/3 of largest concern of T.A. Bridewell
Left-turn storage lane req's	12	80	1/3 of largest concern of T.A. Bridewell
Traffic accidents	10	67	in construction zones for C.D. Garver
Unsignalized intersections	9	60	1/3 of largest concern of T.A. Bridewell
Short-term work zones	8	53	
Freeway ramps	8	53	
Long-term work zones	8	53	
Special traffic generators	6	40	
Toll booths	6	40	
Special events	3	20	
Vehicle breakdowns	3	20	in construction zones for C.D. Garver
Saturated networks	3	20	

2. Typical measures of congestion to determine severity.

Problem	# Responses	%	Comments
Length of queue	12	80	used by C.D. Garver to determine need for construction completion incentives
Average vehicle delay	12	80	used by C.D. Garver to determine need for construction completion incentives
Duration of bottleneck	7	47	used by C.D. Garver to determine need for construction completion incentives
Total vehicle delay	6	40	
Cost of vehicle delay	1	7	used by C.D. Garver to determine need for construction completion incentives
Travel time study	1	7	written in by S. Black, District Traffic Engineer
# approach veh./signal cycle (as compared to storage capacity)	1	7	written in by S. Black, District Traffic Engineer

3. Focus of analysis.

Problem	# Responses	%
Specific facility	7	47
Specific facility, maybe alternate routes	7	47
Network	0	0

4. Analysis methods.

4.1 Signalized Intersections	# Responses	%
1985 HCM	5	33
CINCH	4	27
INTERCALC	2	13
SIGOP	1	7
TRANSYT-7F	1	7
Webster's Red Time Formula	1	7
General Observation	1	7

4.2 Left Turns	# Responses	%
1985 HCM	1	7
PASSER-II 84	1	7
SOAP	1	7
Texas DOT Left Turn Analysis	1	7

4.3 Traffic Accidents	# Responses	%
Freeway Congestion	2	13
1985 HCM	1	7

4.4 Unsignalized Intersection	# Responses	%
1985 HCM	3	20
PASSER-II 84	1	7
SOAP	1	7
TRANSYT-7F	1	7
General Observation	1	7

4.5 Work Zones (long and short)	# Responses	%
1985 HCM	2	13
QUEWZ	1	7

4.6 Interchange Entry Ramps	# Responses	%
Aware of nothing available currently	1	7

4.7 Saturated Networks	# Responses	%
1985 HCM	1	7

APPENDIX B

The Software Catalog

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1.0 CAPCALC 85

1.1 **System Requirements**
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives or
5 Mbyte + hard disk and one 5-1/4" DSDD floppy disk drive
80-column printer

1.2 **Operating System**
PC/MS-DOS 2.0+

1.3 **Supporting Software**
None

1.4 **Source**
Roger Creighton Associates, Inc.
274 Delaware Avenue
Delmar, New York 12054
(518) 439-4991

1.5 **Approximate Cost**
Program and documentation: $295

1.6 **Problem Classification**
Facility type: Signalized intersections
Unsignalized intersections
Level of analysis: Planning (signalized intersections only)
Operational
Design

1.7 **Analysis Method**
1985 *Highway Capacity Manual*, Chapters 9 and 10
Formula based, no table look-up

1.8 **Input Required**
For both signalized and unsignalized intersections:
- Intersection name
- Number of approaches (3 or 4)
- Project name
- Street names for each approach
- Day of study or observation
- Hour of study
- Year of study
- Location of intersection (CBD or not)
- Type of intersection (signalized or unsignalized)
- Type of signal (actuated, semiactuated, or pretimed)
- Major street direction (east-west or north-south)

For each approach:
- Percent grade (–6 to 6)
- Percent heavy vehicles (0 to 30)
- Presence of adjacent parking lane
- Number of parking maneuvers per hour (0 to 40)
- Number of buses stopping per hour (0 to 40)
- Peak hour factor for area type (0.1 to 1.0)
- Number of conflicting pedestrians crossing per hour (0 to 2100)
- Presence of a pedestrian button
- Number of seconds allowed for pedestrians (0.0 to 60.0)
- Arrival type (1 to 5)
- Street width (feet)
- Yellow time (seconds)
- Volume of left turns (vehicles per hour)
- Volume of through traffic (vehicles per hour)
- Volume of right turns (vehicles per hour)

For each lane group (numbered from center lane to curb):
- Movement combination that defines group (L, T, R)
- Number of lanes in group (1 to 6)
- Width of lane group

For each phase and approach:
- Phase number (1 to 8)
- First movement of phase (L, T, R)
- Second movement of phase (L, T, R)
- Third movement of phase (L, T, R)
- Protected movements in phase (L, R)
- Permissive movements (L, R) to be deducted from protected movements
- Green time (0 to 240 seconds)

In addition, for unsignalized intersections:
- Seconds of critical gap for each approach and movement

1.9 Output Generated

Planning analysis (signalized intersections):
- Critical volumes for each direction
- Status of the intersection

Operational analysis (signalized intersections):
- For each approach and lane group:
  - Allocated volume
  - Flow rate
  - Utilization factor
  - Proportion of right and left turns
  - Adjusted saturation flow rate
  - V/C ratio
  - Green ratio
  - Cycle length

For each lane group, for each approach, and for entire intersection:
- Delay (seconds per vehicle)
- Level of service

Operational analysis (unsignalized intersections):
- For each approach and lane group:
  - Reserve capacity
  - Level of service

2.0 CINCH

2.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives
80-column printer

2.2 Operating System
PC/MS-DOS 2.0+

2.3 Supporting Software
BASICA

2.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

2.5 Approximate Cost
Program: $15
Documentation: $5

2.6 Problem Classification
Facility type: Signalized intersections
Unsignalized intersections
Turning movements
Level of analysis: Operational
Design

2.7 Analysis Method
1985 *Highway Capacity Manual*, Chapters 9 and 10
Hauer, E.; Pagtsas, E.; and Shin, T. 1981. *Estimation of Turning Flows From Automatic Counts.* Transportation Research Record 795. Washington, D.C.: Transportation Research Board, pp. 1-7.
Institute of Transportation Engineers. 1982. *Transportation and Traffic Engineering Handbook,* 2nd ed. Formulas 16.19 and 16.20 and Table 16-23. Englewood Cliffs, N.J.: Prentice-Hall, Inc.

2.8 Input Required
For signalized intersections:
- Problem main and subtitles
- Location of intersection (CBD or not)
- Number of phases used

For all approaches (north, south, east, and west bound):
- Left-turn volume (vehicles per hour)
- Through volume (vehicles per hour)
- Right-turn volume (vehicles per hour)
- Percent of heavy vehicles
- Peak hour factor
- Number of pedestrians crossing per hour
- Arrival type
- Number of parking moves per hour
- Number of busses stopping per hour
- Pedestrian crosswalk distance (feet)
- Number of exclusive left-turn lanes
- Left-turn lane width (feet)
- Number of through/general purpose lanes
- Through lane width (feet)
- Number of exclusive right-turn lanes
- Right-turn lane width (feet)
- Percent grade
- Presence of parking
- Presence of pedestrian actuation button

For each phase:
- Left-turn movements allowed
- Right-turn movements allowed
- Through movements allowed
- Pedestrian movements allowed
- Green time (seconds)
- Yellow time + red clear (seconds)
- Pretimed or actuated

For each phase, as necessary, percent of green time for that move that opposes the left in question

Minimum allowable cycle length (seconds)

Maximum allowable cycle length (seconds)

For unsignalized intersections:
- Problem main and subtitles
- Urban area size
- For each approach:
  - Name of approach leg
  - Sight distance restrictions for left turns (seconds)
  - Sight distance restrictions for through movements (seconds)
  - Sight distance restrictions for right turns (seconds)
  - Left-turn volume (vehicles per hour)
  - Through volume (vehicles per hour)
  - Right-turn volume (vehicles per hour)
  - Peak hour factor
  - If vehicle mix is known:
    - Percent of cars

Percent of motorcycles
Percent of light trucks
Percent of heavy trucks
For the major street by approach:
Number of general purpose lanes
Number of exclusive right turn lanes
Prevailing speed (miles per hour)
Percent grade
For the minor street by approach:
Number of exclusive right-turn lanes
Number of exclusive left-turn lanes
Presence of a shallow angle or large radius right turn
Presence of an acceleration lane on the major for right turns
Type of sign control
For turning movements:
Problem main and subtitles
Location of intersection (CBD or not)
For each approach:
Identity as arterial or a collector
Volume of existing left turns (vehicles per hour)
Volume of existing straight through (vehicles per hour)
Volume of existing right turns (vehicles per hour)
Volume of future traffic entering (vehicles per hour)
Volume of future traffic exiting (vehicles per hour)

2.9 Output Generated

For signalized intersections:
Cycle length (seconds)
Level of service
Delay (seconds per vehicle)
Optimal cycle length (seconds)
Suggested timing of phases (seconds)
For each approach:
Left-turn flow rate (vehicles per hour)
Through flow rate (vehicles per hour)
Right-turn flow rate (vehicles per hour)
Saturation flow rate (vehicles per hour)
Flow ratio
Green ratio
Capacity (vehicles per hour)
V/C ratio
Critical lane group designation
Cycle length (seconds)
Delay (seconds per vehicle)
Level of service
Loss time per cycle (seconds per cycle)

For unsignalized intersections:

- For each traffic movement allowed:
  - Conflicting flows (vehicles per hour)
  - Critical gap (seconds)
  - Capacity available (vehicles per hour)
  - Capacity used (vehicles per hour)
  - Impedance factor
  - Level of service
  - Reserve capacity
  - Average stopped delay (seconds)
  - Average queue length

3.0 CIRCAP: CAPACITY ANALYSIS FOR ROTARY INTERSECTIONS

3.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

3.2 Operating System
PC/MS-DOS 2.0+

3.3 Supporting Software
BASICA

3.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

3.5 Approximate Cost
Program: $15
Documentation: $5

3.6 Problem Classification
Facility type: Rotary intersections
Level of analysis: Planning
Operational
Design

4.0 EZ-POSIT

4.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

4.2 Operating System
PC/MS-DOS 2.0+

4.3 Supporting Software
None

4.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

4.5 Approximate Cost
Program: $15

4.6 Problem Classification
Facility type: Signalized intersections
Level of analysis: Operational
Design

4.7 Analysis Method
Critical lane movement method

4.8 Input Required
Actual, minimum, or maximum cycle length
Phasing for each approach

4.9 Output Generated
For each phase:
- Percent of phase
- Duration of phase

Left-turn warrant indication
For each movement and for the entire intersection:
- Level of service
- Degree of saturation
- Stops
- Delays
- Fuel consumption

4.10 General Comments

EZ-POSIT is an interactive, window oriented program for traffic engineers. With a minimum amount of required input data, the program can produce an optimal signal setting, including cycle time an phase pattern, that can minimize fuel consumption for a given intersection.

No new techniques were used in developing the technical aspects of the program, however a great deal of concepts and methods described in the Critical Lane Movement Analysis documented in the TRB Interim Materials on Highway Capacity were adopted. This feature makes EZ-POSIT quite applicable to U.S. conditions [from the *User's Manual* by Hobih Chen, University of Kansas].

5.0 FAZWEAVE VERSION 2.0

- Four Weaving Operational Analysis and Design Procedures

5.1 System Requirements

IBM PC, XT, AT, or compatible
64k RAM
One 5-1/4" DSDD floppy disk drive

5.2 Operating System

PC/MS-DOS 2.0+

5.3 Supporting Software

BASICA

5.4 Sources

McTrans
Center for Microcomputers
in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

Mr. Joseph Fazio
Urban Transportation Center (M/C 357)
University of Illinois at Chicago
Box 4348
Chicago, Illinois 60680
(312) 996-4820

5.5 Approximate Cost

Program: $15
Documentation: $10

5.6 Problem Classification

Facility type: Weaving areas
Level of analysis: Operational
Design

5.7 Analysis Method

(1) Jack E. Leisch (March 1985)
(2) JHK & Associates (November 1985)
(3) Joe Fazio (August 1985)
(4) 1985 *Highway Capacity Manual* (January 1986)

6.0 FREEWAY CAPACITY ANALYSIS

6.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

6.2 Operating System
PC/MS-DOS 2.0+

6.3 Supporting Software
BASICA

6.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

6.5 Approximate Cost
Program (including SIGNAL): $15
Documentation (including SIGNAL): $5

6.6 Problem Classification
Facility type: Freeways
Work zones on freeways
Level of analysis: Operational

6.7 Input Required
Number of lanes (one direction only) (for work zones, no more than 6)
Length of grade (miles) (4 miles or less)
Percent grade (7% or less)
Percent trucks (20% or less)
Percent busses (7% or less)
Width of each lane (feet) (12 ft or less)
Number of sides in which obstruction exists (0, 1, or 3)
Distance to obstruction from edge of lane (feet)
Assumed value of typical capacity
Assumed value of work zone capacity
    Number of lanes closed (one direction only) (not more than available, and one must remain open)

Percent of time the input capacity will be exceeded
Time that the work starts (hours, minutes, seconds of a 24-hour clock)
Time that the work ends (hours minutes, seconds of a 24-hour clock)
Time that the volume collection data started (hours, minutes, seconds of a 24-hour clock) (work zone time cannot exceed the total time observed)
Time that the volume collection data ended (hours, minutes, seconds of a 24-hour (work zone time cannot exceed the total time observed)
Data collection interval (seconds) (the beginning and end of time of the work zone must begin and end exactly on an interval time—user can reassign or let program reassign)
Assumed demand volume, all lanes open (vehicles per hour), in one direction, all lanes inclusive
Actual demand observed (vehicles per interval) for each interval

6.8 Output Generated

Maximum queue length (miles per lane)
Maximum queue length (vehicles)
Time when queue starts (minutes after beginning of work)
Time when queue dissipates (minutes after beginning of work)
Queue length at end of observed time (miles per lane)
Queue length at end of observed time (vehicles)
Queue length at end of first hour (miles per lane)
Queue length at end of first hour (vehicles)
Total vehicle delay (vehicle-hours)
Average delay per delayed vehicle (vehicle-minutes)
Average delay per approach vehicle (minutes per vehicle)
Percent of vehicles delayed over the total time data was taken
Typical capacity
Work zone capacity

7.0 FREEWAY DELAY CALCULATION

7.1 **System Requirements**
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

7.2 **Operating System**
PC/MS-DOS 2.0+

7.3 **Supporting Software**
None

7.4 **Source**
McTrans Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

7.5 **Approximate Cost**
Program: $15
Documentation: $5

7.6 **Problem Classification**
Facility type: Freeways
Level of analysis: Planning
Operational

7.7 **Analysis Method**
Lindley, Jeffery A. 1986. *Quantification of Urban Freeway Congestion and Analysis of Remedial Measures.* FHWA Report No. RD-87-052. Washington, D.C.: FHWA.

7.8 **Input Required**
Route name
Section length
Total number of lanes
Right shoulder width
Left shoulder width
Annual average daily traffic
K factor
Peak hour directional factor
Lane width (feet)
Percent of trucks

Value of travel time ($ per vehicle-hour)
Fuel costs ($ per gallon)

7.9 Output Generated

Total vehicle miles traveled (vehicle-miles)
Recurring congested vehicle miles traveled (vehicle-miles)
Recurring delay (vehicle-hours)
Excess fuel (gallons)
Incident delay (vehicle-hours)
Cost for recurring delay ($)
Cost for incident delay ($)
Cost for excess fuel ($)
Total cost ($)

8.0 FREEWAY OPERATIONS, WEAVING ANALYSIS, RAMPS & RAMP JUNCTIONS

8.1 System Requirements

IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

8.2 Operating System

PC/MS-DOS 2.0+

8.3 Supporting Software

BASICA

8.4 Source

Kenneth Hausman
c/o Bellomo-McGee, Inc.
901 Follin Lane
Suite 220
Vienna, Virginia 22180

8.5 Approximate Cost

Program and documentation: $5 to cover diskette and shipping

8.6 Problem Classification

Facility type: Freeways
Weaving areas
Ramps and ramp junctions
Level of analysis: Operational
Design

8.7 Analysis Method

1985 *Highway Capacity Manual*, Chapters 3, 4, and 5

8.8 Output Generated

Capacity
Level of service

9.0 FREEWAY TRAFFIC CONGESTION

9.1 **System Requirements**
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives
Color monitor

9.2 **Operating System**
PC/MS-DOS 2.0+

9.3 **Supporting Software**
Lotus 1-2-3 Version 1

9.4 **Source**
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

9.5 **Approximate Cost**
Program: $15

9.6 **Problem Classification**
Facility type: Incidents on freeways
Level of analysis: Operational

9.7 **Analysis Method**
Supply-demand curves
Morales, Juan M. 1986. "Analytical Procedures for Estimating Freeway Traffic Congestion." *Public Roads*, 50:2, pp. 55–61.

9.8 **Input Required**
Name of facility
Number of lanes
Capacity flow rate (vehicles per hour)
Initial demand flow rate (vehicles per hour)
Initial bottleneck flow rate (vehicles per hour)
Adjusted flow rate (vehicles per hour)
Revised demand flow rate (vehicles per hour)
Incident duration until first change (minutes)
Duration of total closure (minutes)

Incident duration under adjusted flow (minutes)
Elapsed time under initial demand (minutes)

9.9 Output Generated

Total delay (vehicle hours)
Average delay per incident (vehicle hours)
Time to normal flow (minutes)
Maximum queue length (vehicles) and (miles)

10.0 HCMWEAVE

10.1 System Requirements

IBM PC, XT, AT, or compatible
512k RAM
Two 5-1/4" DSDD floppy disk drives

10.2 Operating System

PC/MS-DOS 2.0+

10.3 Supporting Software

Lotus 1-2-3 Version 2.0

10.4 Source

Harold N. Estes, Jr., P.E.
Watt & Estes, Inc.
4926 Adams Road
Chattanooga, Tennessee 37343
(615) 842-3335

10.5 Approximate Cost

Program and documentation: Basic version: $10; enhanced version: $50

10.6 Problem Classification

Facility type: Weaving areas
Level of analysis: Operational
Design

10.7 Analysis Method

1985 *Highway Capacity Manual*

11.0 1985 HIGHWAY CAPACITY SOFTWARE

11.1 System Requirements

IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

11.2 Operating System

PC/MS-DOS 2.0+

11.3 Supporting Software

None

11.4 Source

McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

11.5 Approximate Cost

Program: $115
Documentation: $20

11.6 Problem Classification

Facility type: Freeways
Weaving areas
Ramps and ramp junctions
Rural highways
Signalized intersections
Unsignalized intersections
Arterials

Level of analysis: Planning
Operational
Design

11.7 Analysis Method

1985 *Highway Capacity Manual,* Chapters 3, 4, 5, 7, 8, 9, 10, 11, 12, and 13

11.8 Output Generated

For basic freeway segments: Level of service (density)
For weaving areas: Level of service (average travel speed)
For ramps and ramp junctions: Level of service (flow rate)
For rural highways (multi-lane and two lane): Level of service (density, percent time delay, and average travel speed)

For signalized intersections: Level of service (average individual stopped delay)
For unsignalized intersections: Level of service (reserve capacity)
For arterials: Level of service (average travel speed)

12.0 INTCAP

12.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

12.2 Operating System
PC/MS-DOS 2.0+

12.3 Supporting Software
Lotus 1-2-3 Version 1

12.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

12.5 Approximate Cost
Program (including LINKFLO): $15
Documentation (including LINKFLO): $5

12.6 Problem Classification
Facility type: Signalized intersections
Level of analysis: Operational

12.7 Analysis Method
FHWA Circular 212—to calculate V/C ratios of an isolated intersection

12.8 Input Required
Title and other identifying information
Adjusted capacity
For each approach:
- Volume of left-turn vehicles (vehicles per hour)
- Number of exclusive left-turn lanes
- Number of through-left turn lanes
- Volume of through traffic (vehicles per hour)
- Number of through lanes
- Volume of right turns (vehicles per hour)
- Number of exclusive right-turn lanes
- Number of through-right turn lanes
- Signal phase
- Approach code (see *User's Manual* for coding)

12.9 Output Generated

Total critical volume (vehicles per hour)
Number of phases used
Intersection capacity
V/C ratio
Critical volume comparison
For each approach:
- Total left volume (vehicles per hour)
- Left volume per lane (vehicles per lane-hour)
- Critical exclusive left-turn volume (vehicles per hour)
- Total through volume (vehicles per hour)
- Through volume per lane (vehicles per lane-hour)
- Critical through-right turn volume (vehicles per hour)
- Total right-turn volume (vehicles per hour)
- Right-turn volume per lane (vehicles per lane-hour)
- Volume in (vehicles per hour)
- Volume out (vehicles per hour)
- Green ratio
- Shared left
- Through-left maximum
- Through-right maximum
- Shared right
- Approach phasing

13.0 INTERSECTION ANALYSIS SPREADSHEETS

- Peak Hour Intersection Turning Movement Survey
- Peak Hour Turning Movement Projections—Iterative Process
- Signalized Intersection Capacity Analysis

13.1 System Requirements
IBM PC, XT, AT, or compatible
512k RAM
Two 5-1/4" DSDD floppy disk drives

13.2 Operating System
PC/MS-DOS 3.0+

13.3 Supporting Software
None

13.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

13.5 Approximate Cost
Program: $15
Documentation: $5

13.6 Problem Classification
Facility type: Signalized intersections
Level of analysis: Planning

14.0 LEFT TURN ANALYSIS PACKAGE

14.1 System Requirements
IBM PC, XT, AT, or compatible with 256k RAM
Two 5-1/4" DSDD floppy disk drives

14.2 Operating System
PC/MS-DOS 2.0+

14.3 Supporting Software
None

14.4 Source
McTrans Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

14.5 Approximate Cost
Program: $15

14.6 Problem Classification
Facility type: Signalized intersections
Level of analysis: Operational and design

14.7 Input Required
Problem title
Volume of opposing straight-through and right-turn traffic (vehicles per hour)
Number of opposing straight-through lanes
Percent of vehicles in heaviest opposing lane
Percent of trucks in opposing traffic
Cycle length (seconds)
Green time of opposing through phase (seconds)
Definite use of a bay or evaluate option of with or without a bay
Flow in median lane from which left turns will be executed (not including left turns) (vehicles per hour)
Left-turn demand (vehicles per hour)
Percent of left turns that are trucks
Time headway of discharging vehicles (seconds)
Space taken by queued car (feet)
Space taken by queued truck (feet)

14.8 Output Generated
Left-turn capacity without bay (vehicles per hour)
Warranting volume for left-turn bay (vehicles per hour)

520

Recommendation of bay warrant or not
Left-turn capacity with bay (vehicles per hour)
Required bay length (if warranted) (feet)
Warranting volume for separate left-turn phase (vehicles per hour)
Recommendation of separate left-turn phase with and without bay

15.0 MAXBAND-PC (MAXIMAL BANDWIDTH SIGNAL SETTING OPTIMIZATION PROGRAM FOR MICROCOMPUTERS)

15.1 System Requirements

IBM PC, XT, AT, or compatible
448k RAM
Two 5-1/4" DSDD floppy disk drives

15.2 Operating System

PC/MS-DOS 2.0+

15.3 Supporting Software

None

15.4 Source

Carl Thor
PC-TRANS
University of Kansas Transportation Center
2011 Learned Hall
University of Kansas
Lawrence, Kansas 66045
(913) 864-5658

15.5 Approximate Cost

Program and documentation: $25

15.6 Problem Classification

Facility type: Arterials
Level of analysis: Planning
Operational
Design

15.7 Input Required

Range of cycle lengths
Network geometry
Traffic flows
Saturation flows
Left-turn patterns
Queue clearance times
Range of speeds

15.8 Output Generated

Optimum signal timing patterns for up to 20 signalized intersections along an arterial street
Data field manual
Cycle times
Bandwidths

Selected phase sequencing splits, splits, and travel times on links
Speeds on links

15.9 General Comments

The major advantage of MAXBAND is the freedom to provide a range for the cycle time and speed. The disadvantage in using MAXBAND lies in the use of bandwidth as optimization criterion, limited experience with field testing, and lack of incorporated bus flows in the optimization [from Arnold, E. D., Jr. 1985. *An Evaluation of Signal Timing and Coordination Procedures, Volume I: Technical Report*. Charlottesville: Virginia Transportation Research Council].

16.0 MICROSOLVE

16.1 System Requirements
IBM PC, XT, AT, or compatible
128k RAM
One 5-1/4" DSDD floppy disk drive

16.2 Operating System
PC/MS-DOS 2.0+

16.3 Supporting Software
None

16.4 Source
Holden-Day, Inc.
4432 Telegraph Avenue
Oakland, California 94609

16.5 Problem Classification
Facility type: Multichannel, single-phase facilities.
For example: parking gates, cashiers, toll booths, garage entrances/exits, intersection approaches
Level of analysis: Planning

16.6 Analysis Method
Classical queuing theory: multichannel, finite queue

16.7 Input Required
Maximum allowable queue length
Random number seed
Initial number of customers in the system
Simulation run time
Mean interarrival time (and standard deviation, if necessary)
Interarrival time distribution (exponential, constant, normal)
Mean service time (and standard deviation, if necessary)
Service time distribution (exponential, constant, normal)
Number of servers (less than 5)

16.8 Output Generated
Total simulation run time
Number of arrivals to the system
Number of balks from the system
Maximum queue length
Average time between arrivals or balks
Average number of customers in the queue
Average number of customers in service
Average number of customers in the system

Average time in the queue
Average service time
Average time in the system
Percent utilization of the server(s)

16.9 General Comments

Designed mainly to solve "textbook" type problems accompanying an introduction to operations research course.

17.0 NETSIM

17.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

17.2 Operating System
PC/MS-DOS 2.0+

17.3 Supporting Software
None

17.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

17.5 Approximate Cost
Program: $35
Documentation: $50

17.6 Problem Classification
Facility type: Networks
Level of analysis: Operational

17.7 Analysis Method
Microscopic simulation

18.0 PASSER II-87 Version 1.0

18.1 System Requirements
IBM PC, XT, AT, or compatible
512k RAM
Two 5-1/4" DSDD floppy disk drives
Graphics capabilities

18.2 Operating System
PC/MS-DOS 2.0+

18.3 Supporting Software
None

18.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

18.5 Approximate Cost
Program: $30
Documentation: $10

18.6 Problem Classification
Facility type: Arterials
Signalized intersections
Level of analysis: Operational
Design

19.0 PASSER III-88

19.1 System Requirements

IBM PC, XT, AT, or compatible
512k RAM
Two 5-1/4" DSDD floppy disk drives
Graphics capabilities

19.2 Operating System

PC/MS-DOS 2.0+

19.3 Supporting Software

None

19.4 Source

McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

19.5 Approximate Cost

Program: $25
Documentation: $5

19.6 Problem Classification

Facility type: Diamond interchanges
Level of analysis: Operational
Design

20.0 PLANNING LEVEL ANALYSIS SPREADSHEETS

- Arterial Level of Service ARTERIAL.WK1
- Freeway Lane Requirements FREELANE.WK1
- Intersection Capacity INTERSEC.WK1
- Freeway AADT Thresholds for Variable Conditions LOSCAP.WK1

20.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

20.2 Operating System
PC/MS-DOS 2.0+

20.3 Supporting Software
Lotus 1-2-3 Version 2.0 or Lotus Symphony

20.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

20.5 Approximate Cost
Program and documentation: $15

20.6 Problem Classification
Facility type: Arterials
Freeways
Signalized intersections
Level of analysis: Planning

20.7 Analysis Method
1985 *Highway Capacity Manual*

20.8 Input Required
For ARTERIAL.WK1
- Length of arterial (miles)
- Average delay per intersection
- Number of intersections

For FREELANE.WK1
- Annual average daily traffic
- Percent of daily traffic occurring during peak hour

Percent of traffic in peak direction
Percent of trucks
Peak hour factor
Terrain
Level of service desired

For LOSCAP.WK1

Peak hour factor
Number of lanes in one direction
K factor
Density

20.9 Output Generated

For ARTERIAL.WK1

Average segment length
Number of intersections per mile
Speed
Level of service

For FREELANE.WK1

Number of lanes needed in each direction
Directional design hour volume
Service flow rate

For LOSCAP.WK1

Matrix of threshold AADT rates for various levels of service and percent of trucks

21.0 QUEUE-2 Version 2: General Purpose Queuing Model

21.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

21.2 Operating System
PC/MS-DOS 2.0+

21.3 Supporting Software
None

21.4 Source
Rick Kuner, President
New Alternatives, Inc.
8 South Michigan Avenue, Suite 610
Chicago, Illinois 60603
(312) 263-2808

21.5 Problem Classification
Facility type: Single-channel, single-phase facilities
For example: freeways, work zones on freeways, incidents on freeways, parking gates, cashiers, toll booths, garage entrances/exits, intersection approaches
Level of analysis: Planning

21.6 Analysis Method
Classical queuing theory: Single-channel, single-phase queue

21.7 Input Required
Mean arrival rate
Mean service time

21.8 Output Generated
Mean number of units in the system
Mean queue length
Mean time in the system
Mean waiting time
Percent the facility is used
Percent the facility is idle

22.0 QUEWZ

22.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

22.2 Operating System
PC/MS-DOS 2.0+

22.3 Supporting Software
None

22.4 Source
Texas Transportation Institute

22.5 Problem Classification
Facility type: Work zones on freeways
Level of analysis: Operational

22.6 Input Required
Problem title
Highway or freeway name
Free flow speed
Level of service D/E break point speed
Capacity speed after queue formation
Closure strategy (crossover or single lane)
Time that traffic control setup is begun (military time)
Time that traffic control setup is removed (military time)
Time that actual work begins (military time)
Time that actual work ends (military time)
Percent of 1981 dollars used to estimate current worth
Total number of inbound lanes
Number of open inbound lanes
Total number of outbound lanes
Number of open outbound lanes
Percent of inbound trucks
Percent of outbound trucks
Length of work zone from beginning of taper to end (miles)
Hourly capacity flow per inbound lane before work activity (vehicles per hour per lane)
Hourly capacity flow per outbound lane before work activity (vehicles per hour per lane)
Level of service D/E breakpoint volume per inbound lane (vehicles per hour per lane)
Level of service D/E breakpoint volume per outbound lane (vehicles per hour per lane)

Estimated inbound work zone capacity (vehicles per hour per lane)*
Estimated outbound work zone capacity (vehicles per hour per lane)*
ADT or hourly volume based inbound volumes
ADT of inbound traffic
Hourly volumes for hours 0-1, 1-2, . . . , 22-23, 23-24 for inbound lanes
ADT or hourly volume based outbound volumes
ADT of outbound traffic
Hourly volumes for hours 0-1, 1-2, . . . , 22-23, 23-24 for outbound lanes
**Note:* given a range of values and a median value from field data for sake of comparison.

22.7 Output Generated

Queue length in inbound lanes for each hour of work zone operation
Queue length in outbound lanes for each hour of work zone operation
User costs for each hour of work zone operation in inbound lanes
User costs for each hour of work zones operation in outbound lanes
Total inbound lane work zones costs
Total outbound lane work zone costs
List of queues greater than 2.0 miles long and causing delay greater than 20 minutes

23.0 RAMPEN and RAMPEX

23.1 System Requirements
IBM PC, XT, AT, or compatible
512k RAM
Two 5-1/4" DSDD floppy disk drives

23.2 Operating System
PC/MS-DOS 2.0+

23.3 Supporting Software
Lotus 1-2-3 Version 2.0

23.4 Source
Harold N. Estes, Jr., P.E.
Watt & Estes, Inc.
4926 Adams Road
Chattanooga, Tennessee 37343
(615) 842-3335

23.5 Approximate Cost
Program and documentation: Basic version; $50; enhanced version: $200
Note: Sample output reports and user instructions are free.

23.6 Problem Classification
Facility type: Ramps and ramp junctions
Level of analysis: Planning
Operational
Design

23.7 Analysis Method
1985 *Highway Capacity Manual*

23.8 General Comments
Capacity analysis for entrance ramps and exit ramps by the 1985 HCM procedures

24.0 SOAP 84

24.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives
80-column Epson-compatible, parallel printer

24.2 Operating System
PC/MS-DOS 2.0+

24.3 Supporting Software
None

24.4 Source
STEAM Support Center, DTS-74
Transportation Systems Center
Kendall Square
Cambridge, Massachusetts 02142

24.5 Approximate Cost
To cover the cost of copying and diskettes

24.6 Problem Classification
Facility type: Signalized intersections
Level of analysis: Operational
Design

24.7 Input Required
Observation period length (minutes)
Beginning time of study (military time)
Ending time of study (military time)
Step size for cycle optimization (seconds)
Saturation level for actuated control
Minimum improvement for split optimization

24.8 General Comments

Soap is based on a microscopic analysis technique with the primary objective of developing signal control plans for individual intersections. However, Soap is unable to analyze closed loops. It has not been widely tested nor has the platoon dispersion algorithm been adequately validated [from Arnold, E. D., Jr. 1985. *An Evaluation of Signal Timing and Coordination Procedures, Volume I: Technical Report.* Charlottesville: Virginia Transportation Research Council].

25.0 SICA: SIGNALIZED INTERSECTION CAPACITY ANALYSIS

25.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

25.2 Operating System
PC/MS-DOS 2.0+

25.3 Supporting Software
BASICA

25.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392- 0378

25.5 Approximate Cost
Program: $15
Documentation: $5

25.6 Problem Classification
Facility type: Signalized intersections
Level of analysis: Operational
Design

25.7 Analysis Method
1985 *Highway Capacity Manual*, Chapter 9

25.8 Input Required
Actual or estimated signal timing

25.9 Output Generated
Average stopped delay
Level of service

26.0 SICAP: SIGNALIZED INTERSECTION CAPACITY ANALYSIS PROGRAM

26.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
One 5-1/4" DSDD floppy disk drive

26.2 Operating System
PC/MS DOS 2.0+

26.3 Supporting Software
None

26.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

26.5 Approximate Cost
Program and documentation: $95 plus shipping and handling

26.6 Problem Classification
Facility type: Signalized intersections
Level of analysis: Planning
Operational
Design

26.7 Analysis Method
1985 *Highway Capacity Manual*, Chapter 9

26.8 Output Generated
Excess fuel
Stops
Delays
Hourly cost index
Maximum queue length

26.9 General Comments
Can evaluate existing or calculate practical phase timings.

27.0 SIGCAP: SIGNALIZED INTERSECTION CAPACITY ANALYSIS PROGRAM

27.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

27.2 Operating System
PC/MS-DOS 1.0+

27.3 Supporting Software
None

27.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

27.5 Approximate Cost
Program: $15
Documentation: $5

27.6 Problem Classification
Facility type: Signalized intersections
Level of analysis: Planning
Operational

27.7 Analysis Method
1985 *Highway Capacity Manual,* critical V/C values and traffic demand method

27.8 Input Required
Traffic demands

27.9 Output Generated
Level of service
Storage lengths
Service volumes at level of service C
Green time requirements

27.10 General Comments
More detailed than 1985 HCM planning procedures, but not as detailed as 1985 HCM operational procedures.

28.0 SIGNAL

28.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

28.2 Operating System
PC/MS-DOS 2.0+

28.3 Supporting Software
BASICA

28.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

28.5 Approximate Cost
Program (including Freeway Capacity Analysis): $15
Documentation (including Freeway Capacity Analysis): $5

28.6 Problem Classification
Facility type: Signalized intersections
Level of analysis: Operational

29.0 TEXAS MODEL

29.1 System Requirements
IBM PC, XT, AT, or compatible
512k RAM
One 5-1/4" DSDD floppy disk drive
5 Mbyte + hard disk
Math coprocessor
CGA or EGA graphics capability

29.2 Operating System
PC/MS-DOS 3.1+

29.3 Supporting Software
None

29.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

29.5 Approximate Cost
Program: $45
Documentation: $20

29.6 Problem Classification
Facility type: Signalized intersections
Level of analysis: Planning
Operational
Design

29.7 Analysis Method
Microscopic simulation

30.0 TRAFFEN: A TRAFFIC ANALYSIS, ENGINEERING AND CAPACITY PROGRAM

30.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives
Math coprocessor

30.2 Operating System
PC/MS-DOS 2.1+

30.3 Supporting Software
None

30.4 Source
Bellcore—Bell Communications Research, Inc.
290 West Mount Pleasant Avenue
Livingston, New Jersey 07039-2729
1-800-521-CORE

30.5 Problem Classification
Facility type: Multiple-channel, single-phase facilities
For example: freeways, work zones on freeways, incidents on freeways, parking gates, toll booths, garage entrances/exits, intersection approaches
Level of analysis: Planning

30.6 Analysis Method
Classical queueing theory
M/M/s queues: Poission-distributed customer arrivals/negatively exponentially distributed service times/arbitrary number of servers

30.7 Input Required
Offered traffic
Number of servers
Choice of traffic model (Erlang B [loss], Erlang C [delay], Poisson [delayed calls held], Palm J [delayed with queue abandonment])
Choice of objective function

30.8 Output Generated
Probability of blocking or delay
Carried load
Mean queue length

Mean delay
Carried load/offered load ratio
Mean server occupancy
Probability that mean delay sill exceed a fraction or multiple of the mean service time
Probability of finite queue overflow

30.9 General Comments

TRAFFEN is a traffic program handling M/M/s queues. It supports loss, delay, delay with defections, and a mix of loss with delay models. Queues can be finite or unbounded. The program also supports retrials for customers who are not served. TRAFFEN has three capabilities: traffic analysis, which computes the congestion parameters, given the offered load and server group size; traffic engineering and traffic capacity, which respectively compute the number of servers and offered load to satisfy a choice of one of six possible objective functions [from the *User's Manual*].

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31.0 TRANSYT-7F: TRAFFIC NETWORK STUDY TOOL, VERSION 7F

31.1 System Requirements
IBM PC, XT, AT, or compatible
512k RAM
Two 5-1/4" DSDD floppy disk drives
Math coprocessor
Epson M/X series printer

31.2 Operating System
PC/MS-DOS 2.0+

31.3 Supporting Software
None

31.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

31.5 Approximate Cost
Program: $40
Documentation: $50

31.6 Problem Classification
Facility type: Networks
Arterials
Level of analysis: Operational
Design

32.0 UNSIG, SIGPLAN, RURAL

- Unsignalized Intersection Analysis
- Signalized Intersections Analysis (Planning Method)
- Rural Highways Analysis (including 2-lane and multilane highways and basic freeway sections)

32.1 System Requirements

IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

32.2 Operating System

PC/MS-DOS 2.0+

32.3 Supporting Software

None

32.4 Source

ITS Systems Unit
107 McLaughlin Hall
University of California
Berkeley, California 94720
(415) 642-1008

32.5 Approximate Cost

Program and documentation: $25 to cover copying and handling

32.6 Problem Classification

Facility type: Freeways
Signalized intersections (planning only)
Unsignalized intersections
Rural highways
Level of analysis: Planning
Operational
Design

33.0 UNSIG10: UNSIGNALIZED INTERSECTION CAPACITY ANALYSIS PROGRAM

33.1 System Requirements
IBM PC, XT, AT, or compatible
256k RAM
Two 5-1/4" DSDD floppy disk drives

33.2 Operating System
PC/MS DOS 1.0+

33.3 Supporting Software
None

33.4 Source
McTrans
Center for Microcomputers in Transportation
University of Florida
512 Weil Hall
Gainesville, Florida 32611
(904) 392-0378

33.5 Approximate Cost
Program: $15
Documentation: $5

33.6 Problem Classification
Facility type: Unsignalized intersections (2-way stop, 4-way stop, and yield intersections)
Level of analysis: Operational

33.7 Analysis Method
1985 *Highway Capacity Manual*, Chapter 10

33.8 Output Generated
Approach level of service by movement for controlled legs
Approach level of service for left turns for uncontrolled legs

APPENDIX C

Example Queue Reduction Strategies

SITUATION 1: Turning and parking movements inhibit traffic flow at signalized intersections.

Analysis Methods: 1985 HCS, CINCH, EZ-POSIT, SICAP

Possible Solutions:

- Many queue length problems can be solved by simply retiming the signal by using standard methods and up-to-date traffic demand data. Attempts to eliminate damaging queues should always start with a check of the actual signal operation against a timing plan calculated from current data.[1]
- "Keep the intersection clear" signs; turn restrictions such as "No Turn," "No Right Turn on Red," or " No Right Turn"; and/or pavement markings should be tried. However, in general, pavement markings (such as stop bars and lateral lines) unaccompanied by associated signs have proved more confusing than beneficial to motorists. Motorists seem to perceive that a stop bar without any accompanying signing is an advisory message having no regulatory meaning. Nonetheless, certain pavement markings are beneficial, even without accompanying signing. One such exception is the provision of lateral lines to define heavily used noncommercial driveways. Provision of lane lines through intersections where driver disorientation causes reduced speeds is also effective.[1]
- Reduce delays and conflicts by separating flows with new signals, turn lanes, striping, traffic police, and/or islands.[2]

SITUATION 2: Left-turning vehicles extend beyond the left-turn storage lane and into the through lanes.

Analysis Methods: EZ-POSIT, Left Turn Analysis Package, Intersection Analysis Spreadsheets, SIGCAP

Possible Solutions:

- Use lead-lag or lag-lead left-turn phasing.[1]
- Implement intersection improvements following the 11 principles established by the Institute of Transportation Engineers[1]:
  1. *Reduce the number of conflict points among vehicular movements.*
  2. *Control the relative speeds of vehicles both entering and leaving an intersection.*
  3. *Coordinate the type of traffic control devices used (such as stop signs or traffic signals) with the volume of traffic using an intersection.*
  4. *Select the proper type of intersection to serve the volume of traffic being served.* Low volumes can be served with no control, whereas high levels of traffic may require more expensive and sophisticated treatments such as turning lanes or even at grade separation structures.

5. *When traffic volumes are high, separate right-turn and/or left-turn lanes may be required.*

6. *Avoid multiple or compound merging and diverging maneuvers.* Multiple merging or diverging requires driver decisions and creates additional conflicts.

7. *Separate conflict points.* Intersection hazards and delays are increased when intersection maneuver areas are too close together or they overlap. These conflicts may be separated to provide drivers with sufficient time (and distance) between successive maneuvers to cope with the traffic situation.

8. *Favor the heaviest and fastest flows.* The heaviest and fastest flows should be given preference in intersection design to minimize hazard and delay.

9. *Reduce areas of conflict.* Excessive intersection area causes driver confusion and inefficient operations. When intersections have excessive areas of conflict, channelization should be employed.

10. *Segregate nonhomogeneous flows.* Separate lanes should be provided at intersections where there are appreciable volumes of traffic traveling at different speeds. For example, separate turning lanes should be provided for turning vehicles.

11. *Consider the needs of pedestrians and bicyclists.* For example, when there are pedestrians crossing wide streets, refuge islands should be provided so that more than five lanes do not have to be crossed at one time.

SITUATION 3: Excessive queue length on a signalized intersection approach.

Analysis Methods: 1985 HCS, Capcalc 85, CINCH, INTCAP, Soap 84,

Possible Solutions:

- *Increase the green-to-cycle-length ratio (G/C).* In coordinated systems, it is not generally practicable to change the cycle length for an individual signal, but the G/C ratio can often be changed by shifting the green time from one approach to another.[1]

- *Make more efficient use of green time; reduce pedestrian conflicts, increase turning radii; improve lane delineation;* etc.[1]

- *Improve the rate of discharge from the head of the queue; widen the intersection, improve the geometrics, remove bus stops,* etc.[1]

- *Reduce the rate at which vehicles arrive at the tail end of the queue;* a slight reduction in the upstream through green phase. However, "reduction of upstream arrivals to a queue by reducing upstream green means upstream capacity will be reduced to less than demand on at least one approach. This technique inevitably produces a standing queue on that approach. The traffic engineer should carefully consider whether such a shift is acceptable."[1]

- *Reducing cycle length is the single most effective way to control vehicular queues at signals not experiencing cycle failure.* This is because the maximum length of the standing queue is proportional to the length of the red interval experienced on an approach and has nothing to directly to do with G/C ratio or capacity. As long as enough capacity is provided to service the demand, the shorter the cycle length, the shorter the queue.[1]

SITUATION 4: Insufficient capacity to handle peak traffic volumes at an acceptable service level on an arterial.

Analysis Methods: Maxband-PC, Planning Level Analysis Spreadsheets: Arterial Level of Service

Possible Solutions:

- *Coordinate signals.* "One reviewer has suggested that all effective queue management techniques require signal coordination. Signal coordination can be ensured only by the use of interconnected signals or the incorporation of very accurate clocks within the controller cabinets."[1]
- *Implement reverse progression* where the green interval progresses from downstream to upstream at the speed of the starting wave or adjust the offset so that the queue stands in the intersection during the through green but not during the cross-street green.[1]
- *Reduce travel delays* by adding capacity through new lanes reserved for buses and car pools, new reversible lanes, and/or extended ramps and merge zones.[2]
- *Reduce travel delays* through more effective use of existing capacity by implementing ramp metering, contra-flow or reversible lanes, ramp closures, and/or travel in breakdown lane during the peak period.[2] Reversible lanes may be feasible if the flow is strongly directional and the direction of flow during the morning peak period is opposite that of the evening peak. If a lane can be removed from the secondary flow direction, reversible lanes should be considered.[1]
- *Reduce travel delays* by encouraging travelers to use transit and car pools by implementing bus and car pool lanes, and ramp metering bypasses, establishing park/ride or park/pool lots, adding express buses, and/or extending feeder bus routes.[2]
- *Shift queues to more manageable locations.* However, be aware that this technique is unacceptable if there is no queue storage space at the upstream signal or if such a new queue would itself cause damage.[1]

SITUATION 5: Incident on an urban freeway.

Analysis Methods: Freeway Traffic Congestion, Microsolve, Queue-2, Traffen

Possible Solutions:

- *Use a freeway incident detection and management system:* roving tow or service vehicles, motorist call boxes, citizen band radios and cellular phones, incident teams, detectors in mainline lanes to monitor volume, traffic diversion, alternate route identification[3]
- *Use integrated freeway and arterial network surveillance and control.*[3]
- *Use motorist information systems* (future technologies): changeable message signs.[3]
- *Use ramp metering devices.*[3]
- *Provide additional lanes without widening the freeway.* Use one or more shoulders as travel lanes only during peak hours and in peak direction.[3]
- *Use high occupancy vehicle (HOV) facilities.*[3] However, preferential treatment for HOVs have little direct effect on queue management. However, the provision for preferential treatment for HOVs can substantially increase the person-throughput of a traffic stream. It is generally assumed that if high-occupancy vehicles are perceived as providing superior service an eventual mode shift will reduce general congestion problems.[1]

SITUATION 6: Inadequate sight or stopping distances at a signalized intersection.

Analysis Methods: CINCH, EZ-POSIT

Possible Solutions:

- *Reduce delays and conflicts* by diverting movements using left-turn prohibitions (restrictions may be limited to hours of peak traffic flow), jug-handles, and/or on-street parking restrictions near the intersection (restrictions may be limited to hours of peak traffic flow).[2]
- *Increase the time available for driver reaction* using new signals or stop signs, signal phasing and timing changes (changes should include an all-red phase or extended amber), and/or warning devices.[2]

SITUATION 7: Turning and parking movements inhibit traffic flow on arterials.

Analysis Methods: Passer II-87, Maxband-PC, Transyt-7F

Possible Solutions:

- *Reduce delays and conflicts* by separating flows using two-way left-turn lanes, expanded off-street parking or loading areas, and/or removal or restriction of on-street parking (restrictions may be limited to hours of peak traffic flow).[2]
- *Reduce delays and conflicts* by diverting movements using medians and/or side street and curb cut closures.[2]

REFERENCES

1. ITE Technical Council Committee 4A-24. 1988. *Management of Damaging Traffic Queues: An Informational Report.* Washington, D.C.: Institute of Transportation Engineers.
2. NCHRP. 1983. *Simplified Procedures for Evaluating Low-Cost ISM Projects: User's Manual.* Report 263. Washington, D.C.: Transportation Research Board.
3. Institute of Transportation Engineers. 1989. *A Toolbox for Alleviating Traffic Congestion.* Washington, D.C.

APPENDIX D

Data Collection Methods for Queueing

1. **Field Crew and Clipboards** (vehicle progression through intersection and actual signal cycle recorded by a field crew on paper on a clipboard)

"To manually measure stopped delay, one must at regular intervals, typically 15–20 seconds, observe the number of stopped vehicles. The procedure is straightforward and described in detail in Appendix III of Chapter 9 of the *Highway Capacity Manual*. The net result is one measure of approach delay per observer. Thus an intersection with four approaches would require a labor-intensive team of four observers to obtain simultaneous estimates of delay on all approaches."[1]

Robertson and Berger[2] described their method for measuring intersection delay as a manual procedure in which "the total time period of interest (e.g., cycle length) [is divided] into sufficiently small number of equal intervals (e.g., 5s). The vehicles that stop in each interval are tallied separately, and the midpoint of the interval is assumed to represent the average arrivals of the vehicles in the interval. The number of previously stopped vehicles departing (clearing the intersection) is also tallied by interval. Again, the departure of these vehicles is assumed to be randomly distributed in the interval. A clipboard and tally sheet are required. Having an interval timer with an auditory tone is helpful for signaling the onset of each interval."[2]

2. **Automatic Traffic Counters** (strategically placed automatic traffic counters record intersection activity at regular intervals)

The data collection technique discussed by Hauer et al.[3] uses automatic counting machines to estimate turning movements in an intersection. Two automatic traffic counters are placed on each leg of the intersection, one to count entering traffic and one to count traffic leaving the intersection. The data collected by the traffic counters may then be used by an algorithm to estimate turning flows. This method was determined to be inappropriate for this research as it did not provide a large enough proportion of the data required by the different analysis methods to be evaluated. However, this method and estimation algorithm may be entirely appropriate for analyses that are mainly interested in traffic flow and turning estimations.

3. **Field Crew and Chart Recorder** (queue arrival and/or discharge headways recorded by a field crew using one or more chart recorders)

The focus of research by King and Wilkinson[4] is the relationship of signal design to discharge headway, approach capacity, and delay, and, therefore, queue dissipation characteristics. However, their data collection method could be adapted to gain information concerning queue arrivals and delay. They describe a data collection technique in which "queue discharge headway data were recorded by manual input to a chart recorder. The observer pressed a button when the signal changed to green and when a vehicle passed the stop line (or a screen line established as the location of the front wheels of the first car in queue)."[4]

4. **Field Crew and Portable Personal Computers** (vehicle progression through intersection and actual signal cycle recorded by a field crew on portable personal computers)

The data collection method described by Henry[5] utilizes a laptop personal computer to implement a variation of the method described in the 1985 HCM for computing stopped delay at a signalized intersection. "The principal idea behind the program is the sequential polling of each approach in turn at frequent, but not necessarily equal intervals. The laptop approach allows for simultaneous observations of all approaches to the intersection. In practice, the procedure requires two persons: one to key in the number of stopped vehicles, the other to do a turning movement count."[5] This data collection method has obvious advantages over a manual measure of stopped delay. However, for the purposes of this research, this method was deemed inadequate because more information for the intersection was required than could be easily collected by a single laptop computer and operator. One laptop per approach would be required, and resource limitations were of concern.

5. **Video Camera and Operator** (vehicle progression through intersection and actual signal cycle recorded continuously using one or more video cameras)

The data collection technique discussed by Kyte and Marek[6] uses a video camera and operator to collect comprehensive data about traffic flow through an intersection. "The instructions to the video camera operator are straightforward. First, the camera field of view must include an unobstructed view of the intersection so that all approaches and turning movements can be observed. Second, the view must include all queue formation and dissipation activity for at least one of the approaches. The procedure yields optimum results when the video camera is located 150 to 200 ft downstream and faces the approach on which queue formation is to be studied."[6] "With data in real-time videotape format, intersection operation can be reviewed as often as needed to record additional data or to observe traffic dynamics. This technique has been used to collect data in Moscow, Idaho; Lewiston, Idaho; Beaverton, Oregon; Portland, Oregon; and Iowa City, Iowa. Future data collection sites include Spokane, Washington; Boise, Idaho; and other sites in Idaho."[6] This collection technique seemed the most appropriate for this research as it collected the most data about the intersection with the smallest field crew; provided a lasting, real-time record of the intersection activity that could be used to validate the analysis results, and demonstrated the feasibility and advantages of using more advanced technologies for data collection of complex queueing situations.

6. **Still Photography** (strategically placed 35 mm cameras record intersection activity at regular intervals)

The data collection technique discussed by Mountain and Garner "involves the collection of data in digital form by the use of small-format photography taken from a hovering helicopter. The data are obtained in this form by means of a coordinate reader and processed by means of a computer that, using a two-dimensional coordinate transformation system, transforms the data to ground data and outputs information on a range of traffic flow parameters. These parameters include approach volumes, the origins and destinations of all vehicles followed through the intersection, and the mean journey time and speed for each route."[7] This method, too, was determined to be inappropriate for this research, due to resource limitations. However, if the resource limitations were to be removed, "it was found that, where comprehensive traffic data are required, the technique can provide a simple, accurate, and economical method of traffic data collection and could be a workable alternative to conventional ground-survey methods."[7]

Buehler, Hicks, and Berry also described a time-lapse photography data collection method "that is used to validate other field methods that utilize observers."[8] This method uses as many as three cameras simultaneously from different positions to identify queue positions accurately. Automatic timers regulate the interval between each picture. This method is a much more simple than the implementation of still photography discussed by Mountain and Garner.[7] As such, it might be more appropriate for collecting data about queueing activity. However, camera placement is crucial, and manual analysis of the resulting photographs is difficult and time-consuming.

7. **Video Incident Detection Systems** (all traffic activity through the intersection is recorded by an automated video camera and analyzed by a remote-site computer and operator)

Video incident detection systems have been developed under a variety of names: for example, CCATS (Camera and Computer Aided Traffic Sensor),[9] WADS (Wide Area Detection System), UMITS (University of Manchester Institute of Technology System), and TULIP (Traffic Analysis Using Low-Cost Image-Processing). In the most generic form, this type of a system "uses video camera sensors coupled to electronic units that undertake image processing in numeric mode."[9] In the WADS configuration, a visual light video camera is mounted above the traffic stream at the site of interest and aimed to view a wide area of the site. The camera is connected to a "black box," either on site or at a remote location, that digitizes the image from the camera for data analysis. The digitized images are transferred to an optical video disk from which they are accessed and analyzed by the data analysis algorithms. The data reduction algorithms eliminate undesirable artifacts that would cause false positives, such as shadows and reflections, and then determine the desired traffic flow characteristics. These flow characteristics are then input into traffic control algorithms and simulations that determine signal timing plans for critical intersections fed by the traffic stream sampled by the video camera.

The WADS approach "has two advantages over current point detection systems: 1. relatively low installation cost, 2. the ability to measure spatial traffic flow parameters such as queues."[2] These systems also provide technological benefits for addressing congestion and real-time traffic control, as well as data collection for analysis of queueing situations. "Indeed, the major advantages of this machine vision system lie in the multispot, multilane wireless detection capabilities which, along with recent advances in image understanding, should essentially transform it to an 'electronic eye' for computerized surveillance and control or for automating time-consuming and expensive functions (performance evaluation, derivation of measures of effectiveness, etc.)."[10] The multiple functions offered by this technology include incident detection, control, surveillance, counting, classification, traffic parameter and MOE extraction, and bus and special vehicle recognition. Various systems are being field tested currently. It appears that video incident detection systems will be the most appropriate data collection method in the future for queueing situations.

8. **Miscellaneous Data Reduction Methods** (all discuss field measurement of delay but do not explicitly describe the mechanics and details of the field measurement technique employed)

Buehler, Hicks, and Berry[8] documented five methods for field measurement of delay. The first was "the Berry-Van Til method in which stopped-time delay is periodically sampled."[8] The second was "the Sagi-Campbell method for determining TIQD [Time-in-Queue Delay], in which queue lengths are observed at specified times in each cycle."[8] The third method was "the delay meter method, in which vehicles are input as they stop and output as they enter the intersection and the meter accumulates TIQD."[8] The fourth method was "the volume density method for determining TTD [Travel-Time Delay], in which observers count the number of vehicles occupying the section of the approach under study at successive time intervals such as 15 s."[8] The fifth method was "the time-lapse photography method that is used to validate other field methods that utilize observers."[8]

Berry[9] did not explicitly describe a data collection technique. He did, however, describe a method to identify the 15-minute period having the highest volume for use in the 1985 HCM method for computing delay. Berry stated that "the ideal data collection system should include cycle-by-cycle counts of discharge volumes for each lane group, so that the peak 15-minute period can be selected more accurately than with 15 minute counts."[9] The cycle-by-cycle counts are then viewed graphically, in which form the peak 15-minutes are easily identifiable.

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