



URBAN CONGESTION REDUCTION FOR ENERGY CONSERVATION
CONTROL STRATEGIES FOR URBAN STREET SYSTEMS
A STATE OF THE ART

Final Report

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SUMMARY

The primary objective of this study is to acquire an understanding of the current state-of-the-art of traffic signal control strategies at urban street systems.

Control of traffic signals is by far the most common type of control at heavily trafficked intersections in urban areas. Inefficient use of the transportation system results when traffic signals are set without the aim of optimizing them. The byproducts of such situations include greater fuel consumption, increased vehicle emissions, increased travel time, higher accident rate, and less reliable services.

Signalized intersections can be classified into three types: (a) an isolated intersection (b) an arterial street and (c) a network. For the analysis of isolated intersection capacity and performance, many analytical methods have been developed. The commonly used methods include the U.S. highway capacity manual (HCM); Webster's method; and the Australian method.

Investigation of traffic signal upgrading strategies in the field can be expensive and time consuming. Unexpected and unnecessary congestion may result and cause negative citizen reaction. Thus, many efforts have been directed towards the development and use of software computer models to evaluate the impacts of various strategies for upgrading traffic signals in different operating

environments. The two most widely used packages that were developed to analyze and evaluate traffic operation at isolated intersections are the signal operations analysis package (SOAP) and the traffic experimental and analytical simulation package (TEXAS).

For arterial streets, the methods that are commonly used in the timing design of fixed-time arterial systems include conventional methods, the maximal bandwidth method, and the delay/difference of offsets method. The two commonly used packages in the design and evaluation of signal operations at arterials are the progression analysis and signal system evaluation routine (PASSER II(80)), and the arterial analysis package (AAP).

For a network that is comprised of a number of signalized intersections, the coordination of traffic signals along the route is regarded as one of the most efficient ways to improve total system performance by reducing delay, stops, fuel consumption, and vehicle emissions. Cycle length, splits, and offsets need to be evaluated and made optimum to improve total system performance. Since the manual work involved in designing the timing plans for a network is quite cumbersome and at times unmanageable, many efforts have been made to develop and use software packages that can assist traffic engineers in solving traffic and transportation management problems on grid networks. The two most widely used packages are TRANSYT and NETSIM.

In response to the need to develop advanced operational control programs which would result in a marked improvement in traffic flow, extensive research and development efforts have been directed towards traffic-responsive control strategies of urban street systems. This area represent one of the leading edges of the traffic

control field. The methods that showed good promise to reach the desired goal are: the urban transportation systems analysis, UTCS, methods; the splits, cycle and offset optimization technique (SCOOT); and the Toronto methods. These methods represent new concepts which could enhance the state of the art in online control techniques.

1. INTRODUCTION

The importance of energy efficiency in the transportation sector cannot be overemphasized. Transportation accounts for one-fourth of all the United States' energy use, but more than one-half of its oil consumption. Automobile fuel consumption constitutes 30% of the United States' total. Urban automobile travel alone accounts for more than one-sixth of the total oil consumption of the United States, making this sector one of the most important in which to seek greater energy efficiency.

Traffic signal control systems dominate the operation of urban highway networks on surface streets and roads. In typical urban areas, approximately two-thirds of all vehicle miles of travel and an even higher percent of vehicle hours of travel are on facilities controlled by traffic signals. Hence, traffic signal operation quality is the major determinant of areawide vehicular traffic flow quality and, in turn, plays a vital role in determining urban transportation energy consumption. During the past two decades, the street systems in the Nation's urban areas have been increasingly plagued with traffic congestion especially during peak periods. The delays experienced are a result of poor signal timing - signals are either inadequate or improperly operated for assigning green time and coordinating traffic movements through a network of intersections. This in turn leads to increased travel time for motorists, as well as frayed nerves caused by the frustration of unnecessary stops and delays.

Another very important consequence is that precious fuel is wasted as engines idle unproductively. Thus many efforts have been directed towards the development of traffic signal control strategies that would upgrade the service quality and energy efficiency on urban street systems.

Significant advances have been made in traffic control equipment, traffic surveillance techniques, and traffic monitoring techniques. In order to keep pace with the rapid progress in control hardware capabilities more sophisticated urban traffic control systems have been developed. Moreover, technical advances in the state-of-the-art included the use of computer modeling which has proven to be a useful, and in many cases, necessary means of optimizing and evaluating traffic control strategies. The offline software packages that are most commonly used are summarized in the Appendix.

In response to the need to develop advanced operational control programs which would result in a marked improvement in traffic flow, extensive research and development efforts have been directed towards online computer control of urban street networks. This area represents one of the leading edges of the traffic control field.

The objective of this study is to evaluate existing and new traffic signal control strategies, including both offline signal control techniques and real-time computer traffic responsive control techniques. The results would provide the traffic

engineer with decision oriented material related to offline signal optimization techniques, viability of computer traffic control, and real-time traffic responsive control strategies, thus enabling him/her to select the more significant models which would be most beneficial considering the capability of available personnel and equipment.

2. CONTROL STRATEGIES FOR ISOLATED INTERSECTIONS

Traffic signal control concepts for isolated intersections fall into two basic categories.

1. pretimed signal control in which it is necessary to determine the cycle length, the phase lengths (or cycle splits), and the number and sequence of phases. This timing must be related to the characteristics of traffic flow at the intersection.
2. traffic-actuated signal control in which the timing plan will be continuously adjusted and will be responsive to traffic demand registered at the intersection. One might expect that delay will thus be minimized and the maximum capacity of the intersection will be obtained. This may not be the case, however, unless careful attention is given to the type of equipment installed, the mode of operation, the location of detector, and the timing settings that are established.

Because of the relative complexity of the problem and the rapid changes in the state-of-the-art, there has been no universal "best" method for determining the optimal type of control for a given intersection. The prominent methods that are in use for designing the timing plans for isolated intersections are discussed herein.

2.1 Highway Capacity Manual (HCM) Method

The methods as documented in Chapter 9 of the 1982 Highway Capacity Manual are perhaps the most widely used by traffic engineers in determining the adequacy of individual signal timing design. Generally speaking the HCM method is based on a level-of-service concept, which is qualitative measure of operating conditions at an intersection approach. There are six levels of service, A through F, which cover the range of excellent to intolerable traffic conditions. Each level of service is associated with a service volume or design capacity. The different levels of service may be expressed in quantifiable terms through the use of load factors, (defined as the ratio of the number of green signal intervals that are fully utilized by traffic during the design hour to the total number of green intervals for that approach during the same period).

The HCM method involves a large amount of arithmetical manipulations. While it is reasonable for the purpose of checking the capacity provided by an existing set of timings, trial-and-error efforts are necessary for the redesign of existing signal timing or design of new signal timing. To simplify the computational procedures of the HCM method, a series of nomograms were developed. With these nomograms, the calculation of capacity at signalized intersections is reduced to a simple graph inspection procedure. Alternatively for those who have access to electronic computers, intersection capacity computer programs based on the HCM method have been developed.

It is recognized that the Highway Capacity Manual requires a monumental effort in assembling the data into its present form; however, there are a number of limitations with the existing Highway Capacity Manual method. These limitations are listed below.

- a. The HCM method is basically a procedure for evaluating existing signal operation, but it is not an optimization technique.
- b. It has argued that the capacity should be calculated on the basis of number of lanes at an approach instead of the approach width.
- c. The HCM method for calculating delay at the intersection does not account for all possible conditions. The influences of such characteristics of specific curb-corner radii, intersection angle, combination of grades on various approaches, odd geometric features (offset intersections, narrowing on the departure lanes, etc.), and other unusual site-specific conditions are not addressed in the methodology.

2.2 Webster Method

Webster of the British Road Research Laboratory used computer

simulation and extensive field observations to provide an excellent study of isolated intersection operation. This work is applicable to either regular unchannelized or high-type fully channelized intersections. In considering the vital element of vehicle delay, Webster developed the classic equation shown as follows:

$$d = \frac{C(1-\lambda)^2}{2(1-\lambda X)} + \frac{X^2}{2q(1-X)} - 0.65 \left(\frac{C}{q^2} \right)^{1/4} X^{(2+5/4)}$$

Where:

d = Average delay per vehicle on the intersection approach under consideration

C = Cycle length

$\hat{\lambda}$ = Proportion of the cycle which is effectively green for the phase under consideration

q = Flow rate

S = Saturation rate (1800 vph)

X = The degree of saturation, (X = q/S).

A fundamental assumption of Webster's work is that the random vehicle arrivals and that saturation does not occur.

Webster shows that a critical lane can be designated and defined as the one with the highest ratio of flow to saturation flow.

This ratio is denoted by the symbol Y, where $Y = \max (q/S)$ for a given phase.

An optimum cycle-length formula was developed by Webster for pretimed application. This formula, yields the cycle length that will produce minimum total vehicle delay. A second formula was developed for similar cycle length calculations for actuated applications.

From Webster's delay model, which calculates average delay, formulae were also derived for estimating queue lengths, number of stops and the effect of parked vehicles on delay.

The main disadvantages of Webster's method are listed below.

- a. The saturation flow values are based on approach widths rather than number of approach lanes. It has been found that lane-by-lane saturation flow analysis is more appropriate in areas where the roadway is spacious and well delineated, and where there is strong lane-following discipline. The Australian Road Research Board developed a similar signal timing design in which the saturation flow is analyzed based on the number of lanes rather than the approach width, which is considered to be an improvement over Webster's method.
- b. Webster's delay model is not applicable for saturation levels greater or equal to 1; which is the case during peak hours.

2.3 Available Computer Software

In the United States there are over 240,000 signalized intersections with more being installed each day. Most drivers regard these as obstacles to their free movement on their way to their destination. Inefficient operation of an intersection can lead to excessive fuel consumption.

Manual design techniques for intersection signal timing do not permit comprehensive analysis and evaluation of the alternative timing plans for a given set of geometrics and traffic conditions.

Therefore, considerable effort was made to develop computer programs that would provide accurate and quantifiable estimates for assessing proposed improvements at intersections. Most of these models had become old and had not been maintained. Thus they became outdated. Table 1 summarizes the software packages that were developed to analyze and evaluate traffic operations at intersections. Two of these packages are relatively new and potentially useful. These are the SOAP and the TEXAS models.

2.3.1 SOAP

2.3.1.a Features

SOAP is a design and analysis tool which enables the user to design the signalization for any two- to four-legged

Table 1 - Summary of Intersection Models

Number	Name	Date	Application	Modeling Approach	Program Language	Computer
1-1	TEXAS	1977	Traffic Performance	Mic., Det., TS, Sim.	Fortran IV	CDC 6600 IBM 370
1-2	SOAP	1977	Signal Timing (Cycle, splits & phasing)	Mac., Det., TS, Opt.	Fortran IV	IBM 360/ * 370
1-3	SIGCAP	1977	Signal Intersection Capacity	Mac., Det., TS, Opt.	Fortran	IBM 360/ 370
1-4	SPLIT	1976	Signal Timing (Splits only)	Mac., Det., TS, Opt.	Fortran	IBM 360 CDC 74
1-5	CYCLE	1976	Signal Timing (Cycle only)	Mac., Det., TS, Opt.	Fortran	IBM 360 CDC 74
1-6	HARPST	1975	Pedestrian Effects	Mac., Det., TS, Sim.	GPSS	IBM
1-7	UTCS-IS	1973	Traffic Performance	Mic., Stoc., Sim.	Fortran IV	IBM 360
1-8	BLY	1973	Bus Priority Lanes	Mic., Sim.	Fortran	Unknown
1-9	SIGSET	1973	Signal Timing (Cycle & Splits)	Mac., Det., TS, Opt.	Fortran	IBM 360/ 370
1-10	BRADFORD	1968	Gap Acceptance	Mic., Stoc., TS, Sim.	ALGOL	ICL 1909
1-11	TEC	1968	Traffic Performance	Mic., Det., TS, Sim.	GPSS	IBM 7094 IBM 360
1-12	JONES	1968	Left Turn Storage	Mic., Stoc., TS, Sim.	Fortran	IBM 1130
1-13	DARE	1968	Advisory Speed Signals	Mic., Det., TS, Sim.	GPSS	IBM 360
1-14	WRIGHT	1967	Stop Control Delays	Mic., Stoc., TS, Sim.	ALGOL (Ext.)	Unknown
1-15	BOTTGER	1965	Four Way Stop	Mic., TS, Sim.	Unknown	Unknown
1-16	MILLER	1965	Effect of Turns	Mic., Stoc., Sim.	Unknown	Unknown
1-17	NCHRP	1964	Traffic Performance	Mic., Stoc., TS, Sim.	Fortran II, FAP	IBM 1094
1-18	AUSTRALIAN	1964	Capacity and Controls	Mic., Stoc., TS, Sim.	Fortran	IBM 7090
1-19	BLEYL	1964	Traffic Performance	Mic., Stoc., TS, Sim.	Fortran II	IBM 7094
1-20	EVANS	1963	Queueing at Stop Signs	Mic., Stoc., TS, Sim.	Unknown	IBM 7090
1-21	AITKEN	1963	Queueing at "T" Junction	Sim.	Unknown	Ferrenti Sirius
1-22	KELL	1962	Vehicular Delay	Mic., Stoc., TS, Sim.	FAP	IBM 701 & 7094
1-23	LEWIS	1962	Traffic Control	Mic., Stoc., TS, Sim.	Fortran II/FAP	IBM 7094
1-24	NPL	1962	Traffic Performance	Mac, Det., Sim.	Unknown	Ferrenti Pegasus
1-25	CHEUNG		Delay	Mac., Det., TS, Sim.	Fortran	ICL 1907
1-26	GOODE	1956	Delay	Mic., Det., TS, Sim.	Unknown	M10AC IBM 704

Abbreviations: Mic. - Microscopic
Det. - Deterministic
TS - Time Scan
Sim. - Simulation

Mac. - Macroscopic
Stoc. - Stochastic
ES - Event Scan
Opt. - Optimization

*Also available in hand-held calculator and micro computer versions.

intersection. A wide range of control alternatives can be evaluated, including pretimed or multiphase-actuated control. To summarize, the following options are available in SOAP: analysis and design, existing preset timing and optimization, pretimed and actuated, protected and unprotected left-turns, isolated runs and multiple runs with comparisons, preset and optimal phase sequencing, preset and optimal dial assignments, numerous input data and default options, isolated and coordinated control, and data check without execution. Furthermore, SOAP takes into consideration the effect of adjacent coordinated signals on the subject signal (i.e. platooned arrivals).

2.3.1.b Data Requirement and Outputs

The developers of the SOAP program have provided a program which can be run with only the information gathered routinely by typical traffic engineering agencies. Provisions have been made for the user to modify the default values built into the program to reflect local conditions.

Three types of inputs are required.

Type 1 - Instruction cards which tell SOAP what to do

Type 2 - Parameter cards which tell SOAP how to
conduct an analysis

Type 3 - Data cards which supply the input variables
for the intersection under study

Five primary types of outputs are available. Each of these
provide useful information to the user.

1. Input report : echoes the input data and prints
warning and error messages as appropriate

2. MOE's report : for each run a table of the numerical
results of the current run is produced. General and
control strategy information is found above the table.
Within the table are the current values of the MOE's,
namely:
 - Delay in veh-hr
 - Percent saturation (v/c)
 - Maximum queue length in vehicles
 - Percentage of stops
 - Excess fuel consumed due to stops and delay
 - Left-turn conflicts

3. Design Recommendations : SOAP develops recommended
designs based on optimal flow as constrained by
input parameters. There are two types of outputs for
recommended designs, phasing patterns and timing design.

4. Intermediate Calculations Reports.

5. Comparison Summaries : SOAP may be used to examine
several control strategies at an intersection.

2.3.1.c Computational Algorithms

In this section we will focus on the prominent MOE's that directly influence the energy problem. These are

- Delay
- Stops
- Excess fuel consumption

Delay

Delay is calculated using Webster's method for unsaturated flow under fixed-timed operations. The drawbacks of using Webster's model are stated in 2.2.

Webster's delay increases infinitely as the V/C ratio approaches 1.0; therefore Webster's model is only practical to use up to $V/C = 0.975$. For saturations in excess of capacity the following is used:

$$Q_r = T(V - S)$$

where

Q_r = no. of vehicles not accommodated during the green
 T = time period (sec)
 S = saturation flow (veh/sec) and the rest as before

N.B. The above algorithm may be realistic for short periods of mild oversaturation, but during long periods of oversaturation, the program will build and retain unrealistic queues which will

overestimate the delay.

The queue length at the end of the phase, Q_e , is,

$$Q_e = Q_b + Q_r$$

where

Q_b = queue length at the beginning of the period.

Given these values the total delay, D , is,

$$D = \frac{T}{2} (Q_b + Q_e)$$

For the region where saturation is between 0.975 and 1.0 no model existed. Since the region is small, the assumption that delay is constant was used, which was the Webster's delay at $V/C = 0.975$, or 2 minutes, whichever was less.

For actuated control, no reliable delay model exists and this problem is extremely complex. SOAP addresses this problem by modifying Webster's model. The actuated control strategy is assumed to

1. distribute the available green time in proportion to the demand on the critical approaches, and
2. minimize "wasted " time by terminating each green interval as soon as the queue has been dissipated.

This approximation simulates a "well timed" actuated controller. To achieve the results calculated by SOAP, it is therefore necessary to avoid excessively long initial and extension

intervals.

As the intersection approaches saturation, actuated control approaches fixed time control. The estimate of delay must account for the various sources of delay as expressed in Webster's component models.

Stops

The proportion of vehicles required to stop, P_s , is equal to the number of vehicles joining the queue while it is still discharging, all divided by the number of arrivals per cycle, or:

$$P_s = \frac{rs}{c(s-v)}$$

where r = length of red (sec)
 s = saturation flow during green (sec) and the rest as before,

In the case of actuated signals, the number of stops will be higher than in fixed-timing signals because the latter switch from one phase to another as soon as the end of the queue is detected and do not allow for slack time between phases. The proportion of vehicles required to stops, P_s , for actuated signals is expressed as

$$P_s = \frac{1 - \lambda}{1 - \lambda x}$$

Excess Fuel Consumption

Excess fuel consumption is computed from the percentage of stops as follows:

$$E_s = \alpha v P_s$$

where E_s = gallons of fuel consumed due to stop (gal/hr)

α = fuel consumption rate (gal/stop)
 v = volume (veh/hr)
 P_s = percent of stops

The excess fuel consumption due to delay, E_d , is,

$$E_d = \beta v d/3600$$

where β = fuel consumption rate per veh-hr of idling
 d = average vehicle delay (sec/veh)

Total consumption, $E = E_s + E_d$

The fuel consumption rates, α and β are based on studies compiled by Claffey.

2.3.1.d Limitations

- SOAP does not differentiate between through vehicles and right-turning vehicles. It does not treat right-turning vehicles on-red.

- It does not estimate delay under coordinated operations.

- Detector placement is not specified as a variable in the input deck for traffic actuated control.

2.3.2 TEXAS

2.3.2.a Features

The TEXAS model is designed to perform detailed evaluations of traffic performance at isolated intersections. The TEXAS model does not recommend design decisions; rather, it provides a rigorous analysis of the particular set of input conditions. The TEXAS model produces a realistic simulation of intersection operations. A review of the available program options are presented below.

- Geometry - any feasible design of a single intersection including divided highways which operate under a single signal controller, parking lanes, turn bays and channels.
- Driver-vehicle units - extremely flexible classifications, all randomly assigned.
- Turning - lane changes, right and left-on-red, U-turns, protected, permissive and unprotected.
- traffic control - no control; stop or yield sign control; and/or fixed time, semi-actuated or full-actuated signal control. The latter may be based on detector calls set in the pulse or presence modes.

2.3.2.b Data Requirement and Outputs

The necessary inputs for the TEXAS model were designed to be user oriented and minimal. There are two basic formats for the three processors in the model. Since the pre-simulation processors, the Geometry Processor (GEOPRO) and the Driver-Vehicle Processor (DVPRO), use the same input data, only one input format is required for the two processors. The simulation processor (SIMPRO) has its own separate input format. Both formats include alphanumeric coding.

Four basic types of information must be provided for the pre-simulation processors.

1. Geometric information about the intersection including number of approaches, number of lanes, etc.
2. Traffic data such as volumes, speeds, etc.
3. Types of vehicles to be included in the simulation, and
4. Types of drivers.

Inputs for the simulation processor consists of control parameters for the simulation itself and specifications regarding the traffic control devices at the study intersection.

Outputs include printed input data, intermediate results and summary statistics of traffic MOE's; line plots of geometrics, turning movements and sight-distance restrictions; and

interactive graph displays. Additionally, punched card outputs can be obtained for use in evaluating alternative designs or control strategies using other computer programs.

2.3.2.c Operational Summary

TEXAS is a microscopic, deterministic and time-scan simulation model. It contains three major subprograms which run independently. The geometry processor, GEOPRO, translates the user input data into the required geometry information. These geometry input data are straightforward and comprehensive. The driver-vehicle processor, DVPRO, randomly generates the individual driver-vehicle units based on a variety of user data and program default values. The particular driver characteristics and the vehicle generation are treated stochastically. The main subprogram is the simulation processor, SIMPRO, which microscopically processes each driver-vehicle unit through the intersection in a fixed, discrete time increment, and accumulates data on the vehicle performance and traffic interactions.

2.3.2.d Limitations

- No estimates of fuel consumption or vehicle exhaust emissions are included.

- External preemption of traffic cannot be modelled (e.g., bridge, RR or fire preemption).

- The model does not take into consideration any effect by pedestrians. All-red signal phases can be modeled for pedestrian intervals at signalized intersections, but the interference to traffic by pedestrians moving simultaneously cannot be simulated.

- There is no provision for coordinated signals, or even the effect of adjacent signals. Nearby signals will clearly affect the arrival patterns, tending to establish platoons. This type of effect cannot be simulated except by direct user input (special vehicles) of driver-vehicle units to the driver-vehicle processor, DVPRO.

- Approaches must be straight and at zero grade. In reality, many intersections have approaches on grades, which affect acceleration and deceleration. This can be compensated by using different headway distributions or parameters for the affected approaches, but automatic adjustments would be more convenient.

This model is useful in developing and evaluating alternative geometric or control improvements and it would be an efficient well-developed tool if its limitations were overcome.

3. CONTROL STRATEGIES FOR ARTERIAL STREETS

In an urban arterial system, especially where signals are closely spaced, it is desirable to coordinate the traffic signals to provide uninterrupted vehicular flow. Arterial street control is namely, controlling signals along an arterial street so as to give major consideration to the progression of traffic along the arterial. While designing the timing plans for the arterial, consideration must be given to the operation of the signals as a system. During this process the cycle length and splits may have to be adjusted for optimum system operation. The following is a discussion of some of the methods that are commonly used in the timing design of fixed-time arterial signal systems.

3.1 Conventional Methods

Signals are usually co-ordinated by setting the difference of offsets equal to the vehicular travel time between the signals. In a one-way street the difference of offsets θ_{ij} between two signals i and j is given by:

$$\theta_{ij} = D / V_{ij}$$

where D = distance between signals i and j

V_{ij} = assumed vehicular speed between i and j (speed of leading vehicle or average speed of entire

platoon may be used)

To allow for an initial queue at signal j due to vehicles unable to clear from the previous cycle and due to turning movements from signal i, the above equation now becomes:

$$\theta_{ij} = D / V_{ij} - [q_j / S_j + l_j]$$

where q_j = average initial queue at signal j

S_j = queue release rate or saturation flow

l_j = lost time due to starting up of initial queue

For a two-way street; θ_{ij} is given as above and θ_{ji} , the difference of offsets for traffic moving from j to i, is calculated in a similar way as θ_{ij} , and subject to the constraint that

$$\text{Cycle length, } C = \theta_{ij} + \theta_{ji}$$

In most cases, the above constraint cannot be met and a compromise has to be reached by adjusting θ_{ij} and θ_{ji} . It is common practice to favour the direction of travel with the heavier volume at the expense of the other direction.

The conventional method does provide an offset design for uninterrupted traffic flows along an arterial at least in the favoured direction of travel, but it does not take into account effects of platoon spreading, interruptions due to buses and

side-street traffic, and variations in progression speeds. Furthermore, this method is not based on any quantitative control criteria such as delay and number of stops, and the choice of offset timings is often reduced to either local policy or an arbitrary decision. Nevertheless, the conventional method is both simple to understand and easy to use, although its application to an arterial with a large number of signals could become difficult and unwieldy.

3.2 Maximal Bandwidth Method

Little et al developed a computational algorithm for optimizing signal offsets for maximum bandwidth along an arterial, given the cycle length, splits, signal spacing and progression speeds. For efficient execution of this algorithm, a computer program was developed which tries to arrange bandwidths so that vehicular platoons traveling in both directions along an arterial fit into their respective green progression band.

The Maximal Bandwidth Model optimizes progression bandwidth which is only a geometrical quantity on the time-space diagram and does not necessarily relate to any actual traffic characteristics. In other words, the model does not necessarily minimize travel time, delay or stops. The effectiveness of the model is therefore dependent on the type of traffic conditions existing in the system and on how well the bandwidth is utilized. Where signals are closely spaced and vehicle platoons remain intact throughout the system, the model will provide efficient signal operation.

The same is true if the traffic is light and the bandwidth is wide enough to allow for platoon dispersion. In cases where the bandwidth is barely adequate for the platoon at the start of the progression, platoon dispersion and interruption along the route will cause vehicles at the end of the platoon to stop at the critical intersections.

3.3 Difference-of-Offsets Method

The British Road Research Laboratory developed a technique for optimizing offsets in a fixed-time signal timing plan for an arterial or network based on the minimization of vehicular delay. Given the traffic flows, the common cycle length and the splits, the vehicular delay along a traffic link connecting a pair of signal depends on the departure and arrival patterns at the downstream signal and hence on the difference of offsets between the two signals. That is:

$$D_{ij} = f(\theta_{ij})$$

where D_{ij} = total delay along link ij connecting signals i and

j

f = a function of ...

θ_{ij} = difference of offsets between i and j

From a knowledge of arrival and departure rates throughout the cycle at signal j , D_{ij} can be computed for different values of

θ_{ij} . For a one-way street section the best set of offsets for link ij corresponding to the minimum value of D_{ij} can be obtained from the computed delay/difference-of-offsets relationship.

For a two-way street section, the offset settings producing minimum delay for one direction (link ij) may not be appropriate for the opposing direction (link ji). To find the optimum offset settings for both link ij and ji , the delay values D_{ij} and D_{ji} for each θ_{ij} are first weighted by their respective arrivals, A_{ij} and A_{ji} and then combined to form an overall delay value (D) as follows:

$$D = A_{ij} + A_{ji} \cdot [D_{ij}/A_{ij} + D_{ji}/A_{ji}]$$

where $D_{ij} = f(\theta_{ij})$

$D_{ji} = f(\theta_{ji})$

$= f(C - \theta_{ij})$ since $\theta_{ij} + \theta_{ji} = C$, the cycle length

In the early version of the delay/difference-of-offsets method, the delay is calculated assuming that the pattern of traffic arriving at the end of the link is identical with that entering the link except for a displacement in time corresponding to the assumed speed along the link. The method was later refined to account for the effect of traffic behaviour on traffic arrivals at the downstream signal.

The delay/difference-of-offsets method has perhaps the soundest

logical base among the various offset optimization techniques because a quantitative traffic measure, delay, is taken under direct consideration and systematically minimized. It should be noted, however, that while delay is minimized, the method does not necessarily minimize the number of stops or provide uninterrupted progression. In fact, to obtain minimum-delay offsets, traffic platoons have to be re-bunched at critical intersections in order that the green time will be fully utilized. Frequent re-bunching can be irritating to the motorists. This problem can be overcome by introducing a stop penalty into the method to allow for the undesirable effect of stoppages due to platoon re-bunching. Another drawback of the delay/difference-of-offsets method is that it is based on average arrival data and the random fluctuations in the arrivals are ignored.

In spite of these criticisms, the effectiveness of the delay/difference-of-offsets technique has been demonstrated by various investigators. It was found that this method ranked consistently the highest among the various off-line arterial signal optimization techniques in providing improvement on a test arterial system.

3.4 Available Offline Computer Software

Many arterial highways are now congested. Engineers have a wide range of alternatives that can be applied to reduce congestion.

These alternatives such as geometric improvements, coordination improvements, and parking restrictions can be expensive and the traffic engineer will need an extremely strong case before funds will be allocated. A variety of arterial signal coordination programs have been developed to help traffic engineer design a more effective signal system (i.e., minimizing overall delay and maximizing the width of the progression band). Table 2 summarizes the arterial software packages being developed. Two of these packages are discussed here. These are the PASSER-II(80) and AAP models.

3.4.1 PASSER-II(80)

3.4.1.a Features

PASSER-II, (Progression Analysis and Signal System Evaluation Routine), was developed to determine optimal traffic signal timings for progression along an arterial street considering varied multiphase sequences. PASSER-II can handle up to 20 signalized intersections along a single arterial, with up to four phase sequences (with or without overlap) per intersection. The model permits the user to examine some traffic engineering improvements, such as installing median refuge zones to reduce pedestrian clearances or alterations in parking policies. The model can also be used to analyze single intersections.

The program was designed to calculate all of the signal timing

Table 2 - Summary of Arterial Models

Number	Name	Date	Application	Modeling Approach	Program Language	Computer
A-0	MAXBAND	UD	Signal Progression	Mac., Det., TS, Opt.	Fortran IV	IBM 370
A-1	TWOMIC-2CL	1980	Two-Lane Rural Roads	Mic., Stoc., TS, Sim.	Fortran IV	CDC 6400
A-2	MRI	1980	Traffic Flow in Mts.	Mic., Stoc., TS, Opt.	Fortran IV /Assembly	CDC 6900
A-3	NO STOP I	1979	Signal Progression	Mac., Det., TS, Opt.	Fortran IV	IBM 360
A-4	PASSER II	1978	Signal Progression	Mac., Det., TS, Opt.	Fortran IV	IBM 360/ 370
A-5	PASSER III	1976	Signal Timing Diamond Ramps	Mac., Det., TS, Opt.	ANSI/ Fortran IV	IBM 360/ 370
A-6	SIMTOL	1976	Grades & Trucks	Mic., Stoc., TS, Sim.	Fortran IV	CDC 6400
A-7	SUB	1973	Urban Bus Operations	Mic., Stoc., ES, (buses), TS (others)	Fortran IV	IBM 360/ 370
A-8	NCSU	1973	Passing Sight Distance Requirement	Mac., Det., TS, Opt.	Fortran IV	Unknown
A-9	YU/VANDYKE	1973	Parking Effects on Capacity	Mic., Det., Sim.	Unknown	Unknown
A-10	VECELLIO	1973	Platoon Dispersion	Mac., Det., Sim.	GPSS	IBM 360/ 165
A-11	TSUMB	1971	Intersection Operations	Mic., Stoc., Sim.	Machine Code	Elliott 920 NB
A-12	MACCLEN- AHAN	1969	Vehicle Lengths	Mic., Det., TS, Sim.	Fortran IV	Unknown
A-13	DELAY/ DIFFERENCE	1969	Signal Progression	Mac., Det., TS, Sim.	Fortran IV	IBM 7094
A-14	SIGPROG	1967	Signal Progression	Mac., Det., TS, Opt.	Fortran	IBM 360
A-15	FIRL	1967	Passing Maneuvers	Mic., Det., TS, Sim.	Fortran IV	IBM 360
A-16	WARNSHIUS	1967	Traffic Flow - Rural Roads	Mic., Det., TS, Sim.	Fortran IV	IBM 7094
A-17	SIGART	1965	Signal Progression	Mac., Det., TS, Opt.	Fortran IV	IBM 360 CDC 74
A-18	NEWARK	1965	Car Following Man.	Mic., Stoc., Sim.	Unknown	Unknown
A-19	LITTLE & MORGAN	1964	Signal Progression	Mac., Det., TS, Opt.	Fortran IV	IBM 7094 & 1620
A-20	YARDENI	1964	Signal Progression	Mac., Det., TS, Opt.	Fortran IV	IBM 7090 & 7040
A-21	FISHER	1964	Lateral Restrictions	Mic., Stoc., TS, Sim.	Unknown	IBM 650
A-22	PRETTY	1964	Traffic Flow Signal- ized Arterial	Sim.	Unknown	Unknown
A-23	ARNOLD/ RESZ	1964	Traffic Flow on Two- Lane Roads	Mic., Det., ES, Sim.	Unknown	Unknown
A-24	MANCHESTER	1963	Traffic Performance	Mac, Stoc., TS, Sim.	Atlas Autocode	Atlas ICT
A-25	RHEE	1963	Traffic Control Pol.	Mac., Det., TS, Sim.	Unknown	Unknown
A-26	NBS	1961	Traffic Flow	Mac., Sim.	Assembly	IBM 704

Abbreviations: Mic. - Microscopic Sim. - Simulation Stoc. - Stochastic
 Det. - Deterministic UD. - Under Development ES - Event Scan
 TS - Time Scan Mac. - Macroscopic Opt. - Optimization

information needed for plan development and field implementation. The program calculates degree of saturation, delay and probability of queue clearance for all movements.

The optimization algorithm of PASSER-II (80) identifies the best cycle length, phasing sequence and offsets- best being defined as that combination which results in the greatest bandwidths in both directions of travel. Phase delays are calculated to minimize delay at each intersection.

3.4.1.b Data Requirement and Outputs

Inputs to PASSER-II involve three type of data cards: (1) arterial header card that specifies the global system parameters; (2) intersection header cards, each of which specifies the operating parameters for one of the intersections in the system; and (3) intersection data cards that each separately provide the traffic volume, saturation flow, and minimum green time for each approach to every intersection.

Three types of outputs are available from PASSER-II. These are (1) input data report, which gives all input data in a structured format; (2) design recommendation, which includes cycle length, offsets, phase sequences and splits, and MOE values for bandwidth efficiency and degree of saturation; and (3) time space diagrams.

3.4.1.c Computational Algorithms

The PASSER-II model is a macroscopic, deterministic, time-scan, optimization model. It combines Brook's Interference Algorithm with Little's Optimized Unequal Bandwidth Equation, and extends them to multiphase arterial signal operations.

The program first determines the optimal demand/capacity relationships and from these green splits are determined. Trial cycle lengths, phase, patterns and offsets are varied to determine the "best" set of timings, i.e. that which maximizes the bandwidths.

The salient computational expressions include the following:

Determine Maximum Bandwidth (B_{\max}) by Direction

$$B_{\max} = G_{o_{\min}} + G_{i_{\min}} - li_{\min}$$

where

$G_{o_{\min}}$ = minimum outbound progressive green

$G_{i_{\min}}$ = minimum inbound progressive green

li_{\min} = minimum possible inbound band interference

subject to upper and lower limits

Determine Green Time (g)

Green times (including clearances) are determined by a gradient

search technique which minimizes delay at the intersection (subject to specified minimum greens). The algorithm shifts the phase change times in small increments until the least calculation of delay is obtained.

The last relationship (the objective function) is the basis of the most significant algorithm used. Some earlier models required that the bandwidths be equal. This is not the case for PASSER-II (80), in fact neither direction is automatically favored.

Estimate of Delay

The delay estimate is based on a modification to Webster's delay equation because, when signals are coordinated the arrival rate on green and the arrival rate on red are not equal. The modification takes into account the differences in arrival rates between green and red. Therefore, the equation used is as follows:

$$D = \frac{VR C(1-g/c)^2}{2V(1+(VR/(S-VG)))} + \frac{x^2}{2(V/3600)(1-x)}$$

$$-0.65(C/(V/3600))^{1/3} x^{(2+5gk)}$$

where VR = traffic arrivals on red
 VG = traffic arrivals on green
 V = traffic volume
 C = cycle length
 g = effective green time
 S = saturation flow rate
 X = signalized volume to capacity ratio on the approach

3.4.1.d Limitations

- The major limitation is the narrow range of cycle lengths that can be tried in a given run.
- While phase sequencing is automatically "optimized", selection of the best sequences depends on many factors requiring engineering judgement.
- Maximum number of intersections that can be analyzed during one run is 20 and the minimum number of intersections is 2.
- For a progressive system, the maximum number of arterial phasing patterns that can be analyzed at a single intersection is 4.
- For an isolated intersection, the maximum number of arterial phasing patterns is 1.
- The maximum number of cross-street phasing patterns that can be analyzed at a single intersection is 1.
- Program output does not illustrate multiple solutions.
- Estimates of fuel consumption or vehicle exhaust emissions are not included.

- The degree of saturation must not exceed 0.95. This condition is considered as a limitation because during peak hours over saturation is always the case.

3.4.2 AAP

The Arterial Analysis Package, AAP, is a collection of existing signal design and analysis programs, most of which are described in previous texts. The TRANSYT-7F model optimizes signal offsets for a given cycle length by minimizing a performance index which is a linear function of stops and delays. The SOAP model determines optimum signal timing at an individual signalized intersection with either pretimed or actuated control. It also provides dial assignments for multiple time periods. The PASSER II model calculates cycle lengths, phase sequences, offsets, and splits so that the band width along an arterial street is maximized.

The AAP model package uses a common data base, and input and output formats (some interactive) for all component models to facilitate the use of these models as an integrated system. It provides traffic engineers with a set of easy-to-use analysis programs.

4. CONTROL STRATEGIES FOR NETWORKS

The efficient movement of traffic through a grid network of signalized intersections can improve the capacity of the system and reduce adverse effects of traffic, such as stops and delays.

Efforts to improve traffic flow, such as signal interconnection, signal timing improvement, parking prohibition, one-way streets, reversible lane operations and other changes, frequently meet with opposition from local businesses and residents.

Engineers need a rather inexpensive method of developing and evaluating various alternatives in order to select the ones most beneficial to the network as a whole and persuading council, business, and residents of the potential benefits. Since the manual work involved in designing the control plans for a network is quite cumbersome and at times unmanageable, many efforts have been made to develop software packages that assist traffic engineers in solving traffic and transportation management problems on grid networks. Table 3 summarizes the computer packages that can assist the traffic engineer in analyzing and evaluating alternative network control systems. TRANSYT and NETSIM are the two most widely used network packages.

Table 3 - Summary of Arterial Network Models

Number	Name	Date	Application	Modeling Approach	Program Language	Computer
N-0	NETFLO	1982	Eval. TSM Strategies	Mac., Stoc, TS, Sim.	Fortran	IBM, CDC, BURROUGH
N-1	TRANSYT-7F	1981	Opt. Signal Timing	Mac., Det., TS, Opt.	Fortran IV	IBM, CDS, BURROUGH, HONEYWELL
N-2	SIGOP III	1980	Opt. Signal Timing	Mac., Det., TS, Opt.	Fortran	CDC 660 IBM 360/370
N-3	TRANSYT-7	1978	Opt. Signal Timing	Mac., Det., TS, Opt.	Fortran IV	ICL 4-70 IBM 360/370
N-4	NETSIM	1977	Evaluate Signal Control Systems	Mic., Stoc, TS, Sim.	Fortran IV	IBM 360/370 CDC 6600
N-5	TRANSYT-6C	1977	Opt. Signal Timing	Mac., Det., TS, Opt.	Fortran	CDC 6600 IBM 360/370
N-6	SIGRID	1977	Opt. Signal Timing	Mac., Det., TS, Opt.	Fortran	CDC 74/172
N-7	TRASOM	1976	Opt. Signal Timing	Mac., Det., TS, Opt.	Fortran IV	Unknown
N-8	BRITISH COMBIN.	1974	Opt. Signal Timing	Mac., Det., TS, Opt.	Fortran IV	IBM 360/50
N-9	MITROP	1974	Opt. Signal Timing	Mac., Det., TS, Opt.	MPSX/MIP	IBM 370/165
N-10	SIGOP I	1974	Opt. Signal Timing	Mac., Det., TS, Opt.	Fortran IV	IBM 370/165
N-11	ERIKSEN	1973	Eval. Bus Movement	Mic., ES, Sim.	Unknown	Unknown
N-12	SIGNET	1972	Eval. Sig. Timing	Mic., Stoc., TS, Opt.	Fortran IV	CDC 6500
N-13	UTS-1	1971	Eval. Traffic Flow	Mic., Stoc., TS, Sim.	Unknown	Unknown
N-14	BIRMINGHAM	1970	Evaluate Signal Timing	Mic., Det., TS, Sim.	Egtran 3	Atlas ICL
N-15	DYNET	1969	Eval. Traffic Flow	Mic., Stoc., TS, Sim.	Fortran	IBM 360
N-16	SAKAI/NAGAO	1969	Eval. Traffic Flow	Mac., Det., TS, Sim.	Machine Language	Mini-Computer
N-17	SCHALK-WIJK	1968	Eval. Traffic Flow	Mac., Sim.	SimScript	CDC
N-18	LONGLEY	1968	Eval. Traffic Flow	Mic., Det., TS, Sim.	Fortran	Elliott 4100
N-19	MILLER & SCHWARTZ	1966	Eval. Sig. Timing	Mac., Sim.	GPSS	IBM 7094
N-20	VETRAS	1966	Eval. Traffic Flow	Mic., Stoc., TS, Sim.	GPSS	IBM 360
N-21	TRRL	1965	Eval. Sig. Timing	Mac., Stoc., TS, Sim.	Unknown	Ferranti Pegasus
N-22	VTS	1964	Eval. Traffic Flow	Mic., Stoc., TS, Sim.	GPSS/FAP	IBM 7090
N-23	TRANS	1963	Eval. Sig. Timing	Mac., Stoc., TS, Sim.	SAP/FAP	IBM 709
N-24	TRAUTMAN	1954	Eval. Traffic Flow	Mac., Stoc., TS, Sim.	Unknown	SWAC

Abbreviations: Mic. - Microscopic Mac. - Macroscopic
 Det. - Deterministic Stoc. - Stochastic
 TS - Time Scan ES - Event Scan
 Sim. - Simulation Opt. - Optimization

4.1 TRANSYT-7F

4.1.1 Features

The TRANSYT model is a macroscopic, deterministic, time-scan optimization model. It is used to optimize signal timing on coordinated arterials and grid networks. The mode of signal control considered by TRANSYT-7F is pretimed with 2 to 7 phases and time sequence. It also incorporates environmental impacts and demand responses.

TRANSYT-7F has a number of options which can be controlled by the user. These options include the following

- Large networks can be subdivided into sections that can be handled by the program (i.e., 50 nodes and 250 links). The boundary nodes are fixed from section to section so that their timings are not changed in the subsequent analysis. Another alternative is the expansion of program dimensional arrays to accommodate the large network.
- RT/LT delays caused by pedestrians can be reflected.
- Unsignalized intersections controlled by stop signs on the cross-streets and bottle necks can be modeled.

4.1.2 Data Requirement and Outputs

There are up to 20 major types of input cards for TRANSYT (depending on the version); some are single cards and others multiple cards. The inputs fall into five functional categories, namely data that

1. Are common to the entire network,
2. Control the optimization process,
3. Specify traffic data,
4. Specify signal timing, and
5. specify plots.

Since TRANSYT is a network optimization program, the input data are based on a link-node structure. This structure is considerably more complicated conceptually than the single intersection orientation of the non-network models. User training is therefore a significant problem with TRANSYT.

Six outputs are available from TRANSYT-7F

1. Input data report - a structured echo of input data, including any errors or warning conditions detected.
2. Performance table - a listing of significant data and MOE's including (by link) volume, saturation flow, degree of saturation, total travel and travel time, delay, stops, fuel consumption, maximum back of queue, and green times

(subtotals are given by intersection and aggregated for the entire network).

3. Signal timing tables - for each intersection the offset (or yield point) is given along with the signal timing in terms of individual interval lengths.
4. Flow profiles - graphically show the arrival and departure flow patterns.
5. Time-space diagrams - available for any number of routes desired.
6. Cycle length evaluation summary - if more than one cycle length was input, a summary table is printed with pertinent MOE's for each cycle length evaluated.

4.1.3 Computational Algorithms

The TRANSYT-7F package contains two models.

- Optimization model; and
- Simulation model

Optimization Model

The optimization technique used in TRANSYT-7F is referred to as "hill climbing" technique. This is an iterative, gradient search technique where the signal timings (offsets and splits) are varied in small, medium or large steps and the resulting flow and

travel characteristics are recalculated. Optimization is achieved by minimizing an objective function called the "performance index", or "PI", and it is defined as follows:

$$\text{Minimize PI} = \sum_i^n [W(D)_i \cdot d_i + K \cdot W(S)_i \cdot S_i]$$

where

- d_i = delay on the i^{th} link of network (veh-hr/hr)
- S_i = average number of stops per second on link i ,
- K = the weighting factor for stops entered on Card Type 1, and
- W = weighting factors for delay (D) and stops (S) for link i .

Traffic Flow Model or Simulation Model

The traffic flow simulation model is the dispersion of platoons of traffic between adjoining signalized intersections. It will also produce estimates of the amount of traffic delays experienced on each link and the the number of stops due to traffic signal timing in the network. TRANSYT-7F has the capability of calculating the fuel consumption based on the MOE's produced by the simulation model.

The average delay is calculated in two parts which are added together. The first is the average queue length over the cycle (times the cycle length) and the second is the delay due to random variations of arrivals and saturation. The second component for each link is found by

$$d_{rs} = \left[\left(\frac{B_n}{B_d} \right)^2 + \frac{x^2}{B_d} \right]^{1/2} - \frac{B_n}{B_d}$$

where

d_{rs} = random and saturation delay;
 B_n = $2(1-X) = ZX$;
 B_d = $4Z - Z^2$;
 Z = $2X/V * 60/T$;
 X = degree of saturation;
 V = volume on the link; and
 T = simulation time.

The expression of random delay used in TRANSYT tends to exaggerate the random delay at high saturation levels. This aspect is considered an advantage over the Webster's random delay component since it tends to prevent the TRANSYT optimization process from selecting phase lengths which lead to saturation or oversaturation.

TRANSYT treats the vehicles in a queue as a stack. It does not consider the effect of spillover on the upstream intersection

The number of stops is simply equal to the number of vehicles delayed. Since some delays may be only slow downs and not full stops, the calculation of stops may be adjusted by entering the appropriate parameters on Card Type 5. The recommended values found to be valid in England are as follows:

Seconds of
 Delay: 1 2 3 4 5 6 7 8 9 10 >10

% of
 Stops: 20 50 65 76 83 88 93 95 97 99 100

The network traffic flow is simulated to estimate fuel consumption and exhaust emissions for each link. Fuel consumptions are computed based on total travel, stops, and delay. The fuel consumption value includes fuel consumed at cruise, idle, and

acceleration or deceleration. Fuel estimates are calculated for each link and then summed for the entire network.

4.1.4 Limitations

- TRANSYT-7F does not explicitly optimize the cycle length or phase sequences; however, these can be optimized by multiple runs with varying values of the cycle length input in Card Type 1 or phase sequences on Cards Types 2X.
- TRANSYT does not test the offsets to determine if it conflicts with with a pin setting on electro-mechanical controllers, nor does it test if the offset falls within a clearance interval. The user should check for this and manually adjust the offsets if necessary.
- The fuel model parameters were determined from studies conducted with only one test vehicle. The fuel consumption rate differs from one vehicle type to another.
- In calculating the fuel consumption, no explicit consideration is given to factors such as vehicle-type-mix (e.g. trucks and diesel engines) or geometrics and environmental factors such as road gradient, curvature, surface quality, temperature and other factors.
- All major intersections in the network have traffic signals,

although sign-controlled intersections and other mid-block bottlenecks can be modeled.

- Traffic entering the network from the outside does so at a constant uniform rate on each approach. This is not realistic over a long period such as an hour.
- The volumes and proportions of turns remain constant at each approach for the entire period of analysis.
- Traffic dispersion is assumed to be uniform for the period of analysis.

4.2 NETSIM

4.2.1 Features

The Network Simulation model is a microscopic, stochastic, time-scan, simulation model. It is designed primarily to provide the traffic engineer with a powerful tool for analyzing and evaluating a wide range of urban traffic control and surveillance concepts for complex street networks. NETSIM does not perform design tasks; rather, it evaluates the effectiveness of different alternative designs as specified by the user's input. Several runs may be evaluated by the user to determine which is "best," thus the evaluation function is, to a certain extent, a design

tool, but it must be emphasized that the "best" solution is only among those alternatives tested. There is no assurance that the "best" solution is an optimal solution.

NETSIM treats the street network as a series of interconnected links and nodes, along which vehicles are processed in a time-scan format subject to the imposition of traffic control systems. It is particularly applicable to evaluation of dynamically controlled signal systems which use real-time traffic surveillance information. A wide variety of simple problems can also be addressed. The model can investigate a wide mix of traffic control and traffic management strategies including fixed or actuated signal control, and sign control; special-use (i.e., turns) and general-use lanes; and standard or channelized geometrics. NETSIM modular structure incorporates detailed treatment of

- Car Following Behavior
- Network Geometry
- Grades
- Bus Traffic
- Queue Formation
- Intersection Discharge
- Intra-Link Friction and Mid-Block Blockage
- Pedestrian-Vehicular Conflicts

The model contains two major modules

- Preprocessor - reads and checks input data

- Simulator - the main simulation model

In regards to testing, NETSIM has been applied to a fairly wide range of problems with satisfactory results.

4.2.2 Data Requirement and Outputs

Inputs of NETSIM include network geometry, traffic flow rates, saturation flow rates, turning movements and counts, traffic composition, type of signal controller, mode of operation, and timing settings. In addition to the normal data on vehicle performance (speed, delay, vehicle-miles, etc.) output data includes estimates of fuel consumption and vehicle emissions.

4.2.3 Operational Summary

NETSIM is a microscopic, stochastic, simulation model with fixed time-scan updating.

Traffic demand is initially input to the network via "entry" links on the periphery of the system or "source" nodes within the network. Upon reaching the periphery or internal sinks, vehicles are processed out via "exit" links and "sink" nodes, respectively.

Within the network, vehicles are propagated through the system along the various links every second, with their time-space trajectories being recorded at 0.1 second resolution. The internal simulation is extremely complex and vehicle motion is governed by a series of car-following, queue discharge and lane changing algorithms.

Within any sub-interval, all conditions (e.g., input flow rates, turning movements rates, signal timing, etc.) are constant. To allow for variation in such variables, several sub-intervals, which may be as short as one minute, or as long as desired, are input.

In order to predict the performance of individual vehicles within the network, each vehicle is randomly assigned various characteristics, such as vehicle type, average discharge headway, acceptable gap, etc.

Nodes are operated according to the type of traffic control specified. Nodes may be yield or stop sign controlled or signalized with fixed-time, actuated (both isolated or coordinated) or volume-density controlled. The latter two may involve detectors in either pulse or presence modes.

Depending on the control status and queue length, vehicles are either queued, discharged or processed through the node. Turning movements occur randomly - that is, based on the input

proportions of turns, individual vehicles are selected to execute left or right turns. Turns may be protected or unprotected, as specified by the user. In the case of signalized control, up to nine phases may be programmed for any given signal controller.

4.2.4 Limitations and Problems

The model is expensive to operate. High computer costs are attributed to the large core memory requirements of the program.

The model limits the input volumes on entry links at 999 vehicles per hour. As physical constraints, 99 nodes, 160 links and 1600 vehicles are allowed in the system at any time. NETSIM allows a maximum of only five input lanes at intersection, and limits the storage in right-turn pockets to nine vehicles. The application of NETSIM does not allow for dual turns, it cannot simulate four-way stop conditions with moderate to high volumes, and right- and left-hand merges from lane drops are unrealistically simulated. The model does not adequately accommodate fully-actuated signal controllers nor correctly balance lanes of queued vehicles at signalized intersections.

Freeway facilities cannot be modeled in NETSIM. A rough estimate of the effect of freeways on the street systems is possible, by making the ramps "sink/source" nodes. The freeway effects must be estimated separately.

NETSIM model generates vehicles based on a uniform statistical distribution and not according to the shifted exponential distribution. The findings of a study conducted by Hurley and others () shows that delay and fuel consumption output is significantly different when the shifted negative exponential distribution is used to generate vehicles rather than the uniform distribution.

In a non-research application of NETSIM , operation of a four-intersection coordinated network in York County, Virginia, was evaluated. One of the controllers in the system was a dual-ring actuated controller. The average delay value for the intersection was estimated to be an obviously incorrect 372 s/vehicle by NETSIM. A similar estimate for the intersection assuming pretimed control was "only" 109 s/ vehicle. The dual-ring logic is obviously faulty.

Hurley and others () conducted a study to ascertain whether or not significant differences existed in fuel consumption output between the Claffey-based fuel model (Claffey's data are the result of field testing of fuel consumption of highway vehicles under various operating conditions) and that embedded in NETSIM. Also studied was the sensitivity of fuel consumption and delay to saturation headway (or saturation flow rate). The effect of grade on fuel consumption and delay was investigated, although only in part because the NETSIM fuel consumption logic does not consider grade effects. That is, the effect of grade on saturation headway was considered, but the direct effect of grade on fuel

consumption was not.

Most of the study conclusions were based on data generated for an isolated intersection under pretimed control. Conclusions reached from the study were

1. NETSIM's embedded fuel consumption data produced significantly lower estimates than did the Claffey's-based tables.
2. NETSIM fuel consumption and delay outputs are sensitive to saturation headways greater than 2.2 sec.
3. Within the limits of the investigation, grade effects appear to significantly affect fuel consumption and delay only at high volumes.

4.3 COMPARISON

The simulation model adopted in TRANSYT represents an abstract type of simulation model, one that attempts to emulate rather than to simulate the traffic flows in a network. Unlike NETSIM, which attempts to simulate the details of individual vehicles dynamics, TRANSYT is based on platoon dispersion. It considers the distribution of traffic over time at each single location of interest in the TRANSYT network.

In an evaluation effort conducted by many agencies and local jurisdictions, TRANSYT was found to be easier to work with than NETSIM, as it requires less-detailed data and employs a simpler form of data input. TRANSYT performance evaluation procedure also requires much less computer time than NETSIM's. TRANSYT needs a quick evaluative procedure because it employs an iterative "optimization" model that has to perform many evaluations in optimizing the aggregated operation of the traffic signals in a network. Therefore, it has to be selective in choosing the aspects of a traffic network that it will model. Many studies show that TRANSYT evaluation capabilities are commensurate with those of NETSIM.

TRANSYT has been demonstrated to be reliable and effective both as a design and as an evaluation tool. In a study carried out by the British Road Research Laboratory, it was found that TRANSYT accurately predicted network delay.

From all the evidence available to-date, TRANSYT seems to be the most promising fixed-time signal system optimization technique. However, further tests and experience with the program are necessary before it can be adopted as a standard design procedure.

The above discussion does not advocate TRANSYT as a replacement for NETSIM. It is noted that TRANSYT can only be considered as an alternative to NETSIM for certain types of applications. For

example, TRANSYT cannot treat networks with more than one cycle length in a single application.

5. ONLINE CONTROL STRATEGIES

With the advent of computers into the field of traffic signal control, the goal of traffic engineers has been to develop a completely demand-responsive system. While many efforts have been directed towards this goal, the restraints placed by "real-world" conditions have limited real-time control effectiveness to-date. This chapter is a brief description of the current real-time control strategies in use or in the development stage together with general comments pertinent to the particular strengths and weaknesses of each approach.

5.1 UTCS Control Techniques

5.1.1 First-Generation Control (1-GC)

These programs are basically of the table look-up type. A number of essentially fixed timing patterns have been precomputed and stored. Timing patterns for 1-GC can be calculated using one of the offline computer software described earlier. Control plans are selected based on time-of-day or on sensing certain demand parameters at strategically located detectors. As threshold positions are reached, alternative predeveloped and stored control plans are implemented. This procedure is used in most of the presently operational digital computers.

Further, Critical Intersection control is provided, where a critical intersection is one that frequently oversaturates. When

critical intersection control is necessary, the splits at a critical intersection is set proportional to the smoothed queue length ratio. Bus priority control is also implemented at certain critical intersections. The decision whether to grant additional green time for a particular phase depends on the queue ratio as well as on the detection of a bus on the approach to the intersection.

5.1.2 UTCS 1½-Generation Control

To overcome the problems resulting from an inadequate number of improperly maintained timing plans, it was necessary to develop a simple procedure for generating and maintaining an adequate library of appropriate plans. One way to accomplish this objective is to use an online timing plan generator with automated loading of the generated plans into the traffic control system. This concept is referred to as 1½-generation control.

5.1.3 Second-Generation Control (2-GC)

This type of control program is still based on a background cycle, but provides for on-line, real-time computation of control plans and strategies. It utilizes a prediction model to predict near-term (e.g., 15-minutes) changes in traffic demand. Current conditions and these predictions are then used in an on-line optimization program to compute splits and offsets.

5.1.4 Third-Generation Control (3-GC)

Third generation philosophy differs from second generation in that it does not require a common background cycle. The cycle length of each controller is permitted to vary (within limits) to respond to local demands.

5.1.5 Comparison

The FHWA sponsored extensive research in evaluating the three generations of control under the Urban Traffic Control Systems (UTCS) program. The general features of the three generations are summarized in table 4. The abstract of the Executive Summary of the Evaluation Study (Ref.) states:

" The First Generation... was found to be operationally effective, was the least expensive to apply, and should be given primary consideration for implementation. Second Generation proved effective on arterials, was only slightly more costly to implement than [first generation], and should be given consideration for areas with substantial arterial development. Third Generation did not prove effective, and requires further development."

5.2 The SCOOT model

SCOOT is an acronym for Splits, Cycle and Offset Optimizing Technique. The Transportation Road Research Laboratory has developed a traffic-responsive method of coordinating traffic

Table 4 Features of UTCS Strategies

Feature	First Generation	Second Generation	Third Generation
Optimization	Off-line	On-line	On-line
Frequency of update	15 min.	5 min.	2.0–3.5 min.
Number of timing patterns	Up to 40 (7 used)	Unlimited	Unlimited
Traffic prediction	No	Yes	Yes
Critical intersection control	Adjusts split	Adjusts split and offset	Adjusts split, offset, and cycle
Hierarchies of control	Pattern Selection	Pattern computation	Congested, medium flow
Fixed cycle length	Within each section	Within variable groups of intersections	No fixed cycle length

Source: Adapted from Ref.

signals. It is described as follows:

"SCOOT operates groups of adjacent junctions on a common cycle time. At any instant the cycle time, green durations, and offsets between signals are controlled by timings held in computer store. The traffic model uses information from vehicle detectors on the approaches to each junction to predict the total delay and stops caused by the signal timings; the signal optimiser adjusts the timings to reduce this total. Frequent small alterations adapt the signals to short term fluctuations in the traffic demand. Longer term trends are satisfied by the accumulation of small changes over several minutes. Thus, there are no large sudden alterations in timings that might disrupt traffic flow. Special procedures deal with congestion."

The implementation phase of SCOOT started in 1979 where it was used to control a network of 40 signals in Glasgow's CBD. The results of SCOOT were compared with a new prepared TRANSYT fixed-time system. Averaged over the day, there was a 6 percent reduction in journey time. The benefits obtained by SCOOT varied considerably during the day. The SCOOT model was most effective when congestion was worst.

5.3 The Toronto Methods

During the inception of the Toronto Traffic Control System, two real-time modes were developed by the Traffic Research Corporation for use in the system. These are Traffic Responsive

Control Mode 1 (TR1) for critical intersection control, and Mode 2 (TR2) for both area and critical intersection control. TR1 control in effect was never extensively used on the grounds of limited application and as a result it was ultimately abandoned. On the other hand TR2 was ultimately put into operation by the staff of the Metropolitan Toronto Roads and Traffic Department, though on a limited scale.

5.3.1 TR1 Control Mode

The TR1 Control Mode is analogous to a volume-density approach in that the the green time of each phase at a critical intersection is extended or terminated depending on current traffic conditions on all approaches and subject to prescribed maximum and minimum values.

5.3.2 TR2 Intersection Control Mode

The TR2 control routine for an individual intersection is basically a split-variation technique based on current traffic flow information. The cycle length is kept constant to maintain system coordination and the split is calculated at the end of each cycle.

It was found that TR2 Intersection Control Mode provides very little improvements over an efficient fixed-time design method when traffic does not fluctuate widely throughout the control period. Furthermore, by keeping the cycle length constant, a

restriction on the effectiveness of this control method is placed especially when the total traffic demand at the intersection exceeds the overall capacity provided by the existing cycle length.

5.3.3 TR2 Area Control

The TR2 area control routine facilitates real-time control of a group of signals along an arterial or in a network. However, it is not truly traffic responsive control routine since control decisions are based on a table look-up procedure. In this routine, the computer collects the necessary traffic data from detectors at an area master intersection, and selects an appropriate combination of cycle length, splits and offsets for the control area (called a control subplan) to suit the current traffic conditions. The main disadvantages of TR2 area control is that it only takes the main street traffic into account and no allowance is made for side-street traffic conditions except at locations where TR2 intersection control is also in effect. This tends to limit the use of this area routine to an arterial-oriented system where side-street traffic operation is not critical.

6. CONCLUSIONS

Since traffic signal timing improvements rank as one of the most cost-effective urban transportation energy conservation actions, a review of the recent state-of-the-art was conducted to promote the utilization of modern traffic control and computer technology to generate traffic signal timing plans that reduce fuel consumption and improve traffic performance.

Offline and online control techniques have proved to be useful and important means of optimizing urban traffic operations. Furthermore, they consistently provide good results in terms of fuel savings. Thus, the increased availability and ease of use will continue to expand the application and acceptance of these models. These two factors will benefit the user, and, ultimately, the public through improved operations and cost effective use of manpower and funds.

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APPENDIX

This section contains a compendium of the offline computer software packages described earlier in the previous sections.

General Description

SOAP	<p>The Signal Operation Analysis Package is a computer model for developing signal timing plans for up to 4 legged isolated intersections with or without left turns.</p>
TEXAS	<p>The Traffic Experimental and Analytical Simulation model is a simulation tool dealing with signal timing. The model does not recommend design decision; however, it provides rigorous analysis of the particular input data. The user can evaluate alternative designs by performing several simulations with various input data. It is a microscopic model.</p>
PASSER-II	<p>This model was developed to analyze individual signalized intersection equations or to determine optimum progression along an arterial street considering varied multiphase sequences. The PASSER-II model combines Brook's Interference Algorithm with Little's Optimized Unequal Bandwidth Equation, and extends them to multiphase arterial signal operation. It can handle up to 20 signalized intersections along a single arterial street, with up to four phase sequences per approach.</p>
AAP	<p>It is a collection of existing design and analysis programs; TRANSYT-7F, PASSER-II, and SOAP. The AAP model package uses a common data base, and input and output formats (some interactive) for all component models to facilitate the use of these models as an integrated system.</p>
TRANSYT-7F	<p>Traffic Network Study Tool, version 7F. It is a traffic simulation and signal timing optimization program. It was developed to optimize the coordinated traffic signal systems to reduce delay, stops, and most significantly fuel consumption. It is a macroscopic model. Its advantages are: buses can be modeled separately, pedestrian RT/LT delay can be reflected, and it is capable of handling up to 50 nodes and 250 links.</p>
NETSIM	<p>It is designed primarily to provide the traffic engineer with a powerful tool for analyzing and evaluating a wide range of urban traffic control and surveillance concepts for complex street networks. It is particularly applicable to evaluation of dynamically controlled signal systems which use real-time traffic surveillance information. It treats the street networks as a series of interconnected links and nodes, along which vehicles are processed in a time-scan format subject to the imposition of traffic control systems.</p>

	TYPE OF SYSTEM	TYPE OF CONTROL	MODELING APPROACH
SOAP	Isolated Intersection	Traffic actuated and pretimed control	Macroscopic, deterministic, time-scan, optimization
TEXAS	Isolated Intersection	NA	Microscopic, stochastic, time-scan, simulation
PASSER-II	Arterial streets		Macroscopic, deterministic, time-scan, optimization
AAP	Arterial Street	NA	NA
TRANSYT-7F	Closed Network	Fixed-time signal; stop, yield signs	Macroscopic, deterministic, time-scan, optimization
NETSIM	Networks	Fixed or actuated signal control, sign control, special-use (i.e., turns) and general-use lanes, and standard or channelized geometrics.	Microscopic, stochastic, time-scan, simulation.

	INPUTS	DEFAULT VALUE	OUTPUT
SOAP	Input cards are: begin, capacity, compare control, dense, diagram, end, growth, headway, left turn, min green, plot, run, sequence, table, timing, truck, volume.	Yes	Input data report, MOE'S are: delay, stops, v/c ratio ex fuel consumption ex left turns, max queue.
TEXAS	NA	Yes	NA
PASSER-II	Basic inputs include turning movements, saturation capacity flow rates, min green times for each movement at each intersection. For progression analysis: distance between inter- sections, average link speed, queue clearance intervals and permissible phasing sequences.	No	Echo copy, progression values (optimum cycle length and bandwidth in sec.) and average speed in both directions as well as 2 MOE's, band- width efficiency and percent of min. arterial green time included in the band. Also included is signal timing inform- ation on phase sequence, offset and v/c ratios. Printed or digital time- space diagrams.
AAP	NA	Yes	NA
TRANSYT-7F	All normal TRANSYT-7F inputs are required (as applicable). It also requires data on the roadway and traffic composition (for fuel consumption) and para- meters for the demand responses.	No	Input data report, traffic performance table, stopline flow profile plot, TRANSYT-7F signal control setting table, time-space diagram, cycle length evaluation summary, MOE's : degree of saturation, TT, TTT, delay, uniform stop, max back of queue and queue capacity, performance index.

	INPUTS	DEFAULT VALUE	OUTPUT
NETSIM	Network geometry, traffic flow rates, saturation flow rates, turning movements and counts traffic composition, type of signal controller, mode of operation and timing settings.	No	In addition to the normal data on vehicle performance (speed, delay, veh-mi, etc.) output data includes estimates of fuel consumption and vehicle emissions.

	PROGRAM, MANUAL TYPE	PROGRAM LANGUAGE	TYPE OF MACHINE
SOAP	User friendly, Interactive program	Fortran	16/32 byte mainframe, minicomputers with Fortran compilers, and IBM-PC(MS-DOS), Apple(UCSD P-system), Apple(CPM) microcomputers
TEXAS	NA, Interactive program	Fortran	512K bytes of memory machine CDC 6600 & IBM 370
PASSER- II	Difficult, not interactive	Fortran IV	IBM pc or compatibles with 2 DSDD disk drives. (Unknown core requirement)
AAP	User friendly, Interactive program	NA	IBM and compatibles
TRANSYT -7F	Difficult, not interactive	Fortran IV	IBM pc or compatibles (320 K core requirement)
NETSIM	Difficult, not interactive	Fortran IV	IBM pc or compatibles, IBM 370, CDC 6600 and UNIVAC. (256 K core requirement)

	MAINTAINED BY:	DEVELOPED BY:	YEAR
SOAP	Florida Dept. of Trans.	The State of Florida and the University of Florida Research center for FHWA.	1977 updated in 82, 84 and 87
TEXAS	Texas Dept. of Highway and public trans.	The Center of Research at the University of Texas at Austin.	1977
PASSER- II	Texas Dept. of Hwys and public Trans.	C.J. Messer et al, Texas Transportation Institute	1974 Rev. in 1978
AAP	FHWA	University of Florida, TRC. Florida	1984
TRANSYT -7F	FHWA	TRANSYT is originally developed by TRRL in U.K. Version 7F was modified by University of Florida (TRC).	1967 1978. Revised in 1983
NETSIM	FHWA	E.B. Lieberman & W. Rosenfield, KLD Associates, Inc, and J.J. Bruggemann and R.D. Worrall, Peat, Marwick, Mitchell & Co.	1971 Rev. in 1977

	LIMITATIONS
SOAP	Does not consider right turns, in the case of traffic actuated no detector placement considered, split optimization algorithm which is based on equalizing the degree of saturation among conflicting critical movements, with simple input-output technique for oversaturated condition unrealistic queues will be build up which overestimate the delay
TEXAS	Required 512K bytes of memory, Does not provide for the interaction between pedestrians and vehicles moving simultaneously, The intersection approaches must be straight and zero grade.
PASSER-II	Maximum number of intersection that can be analyzed during one run is 20 and the min. number of intersections is 2. For a progressive system, the max. number of arterial phasing patterns that can be analyzed at a single intersection is 4. For an isolated intersection, the max. number of arterial phasing patterns is 1. The max. number of cross-street phasing patterns that can be analyzed at a single intersection is 1. Program output does not illustrate multiple solutions.
AAP	NA
TRANSYT-7F	Does not deal explicitly with unprotected left turns
NETSIM	The model limits the input volumes on entry links at 999 veh/hr, it allows a maximum of only 5 input lanes at intersections, it limits the storage in right-turn pockets to 9 vehicles, it does not allow for dual turns, and it cannot simulate four-way stop conditions with moderate to high volumes.

