DEVELOPMENT OF A FORWARD LINK OPPORTUNITIES MODEL FOR OPTIMIZATION OF TRAFFIC SIGNAL PROGRESSION ON ARTERIAL HIGHWAYS

By

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By

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Improved control of motor vehicle traffic on urban streets and highways has become increasingly important in recent years. Declines in freeway construction have placed an ever increasing burden on signalized arterial highways and, thus, the traffic signal control systems thereon. The design of optimal control strategies to provide for progressive movement of traffic on these major highways has been a subject of intensive research by the traffic engineering profession. The most successful methodology currently used is the maximization of progression for through traffic, or the maximal bandwidth theory.

This dissertation proposes a new concept for the design of traffic progression which expands upon the maximal bandwidth approach by considering the progression opportunities which present themselves within an arterial route, but do not necessarily extend throughout the full length of the route. The concept has been named the forward link opportunities method. When system optimization is based on the new measure as a

maximization objective function, improvements in both progression opportunities and system traffic operations can be realized.

This dissertation is concerned with the introduction of the forward link opportunities concept and the development of an optimization model with which to implement the new strategy.

An existing optimization model is modified to incorporate the proposed concept, and comparisons are made between the forward link opportunities optimization strategy and the maximal bandwidth optimization strategy. Investigations indicated that reasonable improvements can be realized in a variety of typical arterial system configurations.

Enhancements and expanded uses of the concept and the model indicate that the theory and model serve as viable design and evaluation enhancements to the state-of-the-art.

CHAPTER 1

INTRODUCTION

Need for the Research

Since the first electric traffic control signal for street traffic was introduced in 1912 (Sessions, 1971), the complexity of control hardware and the sophistication of control strategies has increased to maintain pace with the capabilities of more advanced automotive vehicles, higher traffic densities and the improved knowledge of driver behavior.

Technological advancements in traffic controller hardware have maintained a reasonable parity with advancements in mechanical and, in recent years, electronic technology. As signal hardware has grown more sophisticated, the need for effective design of signal timing to insure the best operation has increased. The cost-effectiveness of digital computers has led to a number of analytical models whose purpose is the design of the optimum signal timing.

The need for such design tools varies according to the geographic and traffic environment. Design for low density areas with widely spaced signalized intersections generally only needs to be concerned with signal performance at each individual intersection. For central business districts, grid systems are often coordinated to provide orderly flow through the network of signals. In the latter situation, there is little that can be done to accommodate all travel patterns, and networks are generally constrained by the physical spacing of signals and the relatively low travel speeds that are possible.

One of the most challenging aspects in the field of traffic engineering is concerned with the control of arterial highways. As the urban growth pattern has extended from the inner city to the suburbs, the impact on arterial highways connecting the residential and employment areas has become severe. Excluding high-type highways (freeways and expressways) arterial highways carry the majority of urban traffic in terms of vehicle-miles of travel, thus they are the most important nongrade-separated facilities in any major travel corridor. With increasing public resistance to expanding freeway systems, arterials hold an ever increasing significance in the highway system.

For decades, traffic engineers have sought to provide the best quality of traffic flow on arterial highways. Despite the fact that elimination of all control on such important routes is one way to move through traffic, this is impractical in most instances because cross-street and other conflicting demands must be satisfied as well. Thus, in most urban and suburban areas, arterial highways must be controlled by traffic signals to ensure access to the arterial for cross street traffic and safety to all traffic.

As early as the 1940's, traffic engineers recognized that one of the most effective means of providing a high quality of travel to through traffic was to coordinate the timing of traffic signals to provide a window of green time through a series of signals, within which the through traffic can travel without interruption by the signals. This traffic control technique is commonly known as progression. A band of green time is propagated through the system such that vehicles traveling within its limits progress through the system without being stopped.

Early signals were unsophisticated and traffic demand was often heavily oriented toward one direction during periods of congestion, so it was a fairly trivial task to determine the proper signal offsets (the time difference between the start of the green signal phase between adjacent signals) by manually plotting time-space diagrams. As noted initially, however, the expanding urban demand and sophistication of hardware has rendered simple design techniques obsolete.

The advent of the digital computer enabled engineers to develop more sophisticated strategies for designing coordinated traffic control systems. A variety of models has been offered for both off-line (i.e., prior to implementation) design and real-time control. Real-time control (i.e., on-line, usually traffic responsive) is generally adaptive to traffic conditions and is therefore not as critical from a design standpoint. Real-time control is also extremely expensive, making it impractical as a wide-spread control tool for arterials that are dispersed throughout an urban area.

Thus, the more challenging area of interest is the off-line design of systems which operate on a recurring, cyclical basis during particular periods of the day. Virtually all strategies for progression control are based on the objective of maximizing through progression. As discussed in greater detail in Chapter 2, the most popular approach to the design of progressive control has centered around the maximal bandwidth concept. This strategy simply determines the signal timing which will provide the maximum width of the through-green bands (generally bidirectional), subject to providing sufficient time to nonthrough movements to avoid oversaturation on their approaches.

The U.S. Department of Transportation, Federal Highway Administration (FHWA), has recognized the need for providing the traffic engineering community with a single design tool that will enable engineers to effectively analyze arterial traffic flow and design for optimal control. An Ad Hoc Committee on Arterial Traffic Control (MacGowan et al., 1977) investigated a number of potential computerized models for consideration in an integrated arterial control package. The candidate models which were considered represented, in the opinion of the Ad Hoc Committee, the most significant computer models for traffic signal system design and analysis. Models were examined from the perspectives of system optimization and system evaluation. The models investigated for their optimization capabilities are as follows:

1) TRANSYT - a network optimization model,
2) SIGOP II - a network simulation and optimization model,
3) PASSER II - an arterial progression optimization model,
4) EXPRESS - an arterial progression optimization model,
5) PASSER III - a diamond interchange optimization model and
6) SOAP - an intersection optimization model.

Three models were investigated solely on their analysis capabilities, for use in system evaluation. These were TRANSYT and SIGOP II from above, plus the TRANS model, which is a traffic simulation model.

Four models were selected for inclusion in the, so-called, Arterial Analysis Package because, in the opinion of the Ad Hoc Committee, these represented the best design and analysis capabilities. These models are SOAP, PASSER II, PASSER III and TRANSYT6C. The FHWA undertook to develop a software implementation package, which will enable these models to be coded according to a unified input standard, and to standardize the

outputs for ease of interpretation. The selection of PASSER II as the prevalent progression design model for the Arterial Analysis Package clearly established the importance placed on the validity of the maximal bandwith strategy, in comparison with models which minimize delay and/or stops.

However, maximum bandwidth does not address the totality of the progression optimization problem. With multiple phasing and differing distributions of green time at various intersections, there are potentially numerous opportunities of (at least) partial progression which are not explicitly recognized by the maximal bandwidth approach. These progression opportunities (called forward link opportunities) may be available to through traffic over a subsection of the artery or to cross street traffic entering (turning onto) the artery within the control system. Indeed, the progression opportunities available within the through band constitute a subset of the totality of forward link opportunities available within the system.

It is intuitively evident that all forward link opportunities should be considered in the design of coordinated systems; yet this aspect has never been explicitly addressed by researchers in developing design strategies.

The maximal bandwidth optimization strategy is well implemented in the PASSER II model. This model is extremely flexible in its consideration of design options, permitting virtually any feasible combination of design parameters for multi-phase signal systems. The design capabilities notwithstanding, PASSER II is a poor analysis model because it provides only limited estimates of traffic engineering measures of

effectiveness. Some important measures such as delay, stops and queuing are not provided. For this reason, the above mentioned Arterial Analysis Package includes TRANSYT6C to analyze designs produced by PASSER II.

Such a marriage of two disjoint computer programs is a rather awkward means of achieving an optimal design and obtaining estimates of the system's performance for evaluation purposes. A more realistic approach would seem to suggest a single model which optimizes design and provides the required figures of merit. Furthermore, if such a model improves upon the maximal bandwidth optimization strategy, a far more powerful design tool would be available to the traffic engineering profession.

The development of a model incorporating the stated improvements to the state-of-the-art progression design technology and having an analysis capability is the subject of this research.

Purpose, Objectives and Scope

This dissertation presents the methodology of the forward link opportunities concept of traffic signal control. The basic concept is developed in terms of a measure of effectiveness of progressive signal timing design, and a methodology for optimization of signal timing upon this measure is presented. Investigations are made to determine whether the proposed concept is a useful tool in the traffic engineering profession.

The specific objectives of the research are as follows:

1. Review the state-of-the-art with respect to design strategies for coordinated traffic signal systems on arterial highways.
2. Develop the measure of effectiveness referred to previously as "forward link opportunities."

3. Formulate and develop a methodology for modeling the optimization of progressive signal timing based on the new measure of effectiveness and produce an operational model.
4. Compare the effectiveness of the proposed strategy with the well-accepted maximal bandwidth technique.
5. Investigate alternative variations of the forward link opportunities model and identify other applications of the model.
6. Formulate guidelines for developing a complete signal design model.

The primary emphasis of this research deals with a fixed time, common cycle, coordinated arterial highway traffic signal control system. To this end the system of interest is a one-dimensional (linear) system of signalized intersections.

In developing the optimization model, a substantial computer programming effort has been undertaken to modify the TRANSYT6C program. This approach was used to facilitate demonstration of the new optimization strategy and is not necessarily suggested as the most effective modeling approach from the standpoint of data coding or computer processing time. Accordingly, presentation of computer coding is not within the scope of this work; and, as implied in objective number six above, the model developed is not intended to represent a completely final computer model. Nonetheless, the model developed is fully operational and can be used immediately within certain minor constraints.

The maximal bandwidth design strategy presented herein is based upon the PASSER II model which has been well accepted by the traffic engineering community in this country. In the case of the PASSER II model--as well as the TRANSYT6C model, which is the foundation of the

forward link opportunities optimization technique--it is assumed, for the purposes of this research, that the theory, model structure, analytical methodologies and program logic are soundly based on accepted engineering and programming principles and conventions, unless specifically stated otherwise. This is particularly cogent in the case of the results of comparative investigations. These investigations will be based on analyses produced by the TRANSYT6C model, which can simulate reasonably well conditions suggested by other traffic system models.

Organization

The dissertation is structured along the objectives enumerated earlier. The next chapter covers a review of coordinated traffic control theory and models that are pertinent to this research. Brief overviews of the PASSER II and TRANSYT6C models are presented, and are augmented by more detailed descriptions contained in Appendices A and B.

Chapter 3 contains the theoretical basis for the forward link opportunities concept and the optimization model development. Technical details on the new model are given in Appendix C.

Chapter 4 covers the experimental comparison of the new strategy with the commonly accepted maximal bandwidth strategy.

A comprehensive series of investigations into alternative variations of the forward link opportunities model is presented in Chapter 5. Investigations cover weighting of forward link opportunities by various physical and traffic characteristics, alternative explicit objective functions and optimization of several timing functions.

Conclusions and recommendations emanating from this research effort are given in the final chapter. These include assessments of the forward link opportunities (FLOS) concept as a measure of effectiveness and as

an effectiveness function for optimization. Recommendations include areas for further developing a complete FLOS optimization model and areas for further research.

CHAPTER 2

REVIEW OF ARTERIAL PROGRESSIVE SIGNAL CONTROL STRATEGIES

Introduction

A number of techniques have evolved over the past several decades for the coordinated progression of traffic on arterial highways (as well as other street systems). The underlying philosophy of all the techniques has been to move traffic along the facility with as few interruptions as possible.

This chapter contains a review of various theoretical approaches to signal progression and modeling approaches for the design of progressive systems.

Theory of Traffic Progression

A typical signalized arterial highway can be construed as a system of contiguous links connected to nodes, which are the intersections. Vehicles traveling from node to node along the links follow trajectories dictated by several factors. These factors include the desired speeds of the drivers, the relationship of demand to capacity of the roadway, environmental characteristics (e.g., nature of surrounding land use) and institutional constraints such as the speed limit. The factor having the greatest influence on progression is, however, the status of the traffic signals at each intersection at the time of the vehicles' arrivals at the intersections. When signals operate randomly with respect to one another, vehicles will be stopped in proportion to the amount of green available for their respective movements and, further, according to a

time-space relationship between adjacent intersections. This is illustrated in Figure 2.1, which is a time-space diagram of a typical, uncoordinated signal system. The trajectories of four vehicles are shown in the figure, from which it is evident that only one vehicle was fortunate enough to traverse the entire system without being stopped.

If the relative start times of the cycles at each signal are adjusted to match the desired speed of the traffic, perfect progression of traffic in both directions of travel results, with no other changes to the signal timing. This is shown in Figure 2.2. Such a progression scheme enables all vehicles, once traveling within the so-called green bands, to proceed unimpeded. This is the time-space relationship of traffic progression. Unfortunately, perfect progression cannot always be achieved, and the provision of the best progression under (the more common) less than perfect conditions is the subject of this research.

Before exploring the various strategies developed for the design of progressive timing, it may be useful to define the elements of progressive traffic signal timing. The quality of progression will ultimately be a function of the following elements (Bleyl, 1967):

1. Cycle length - the recurring amount of time available for the servicing of all required traffic movements. In progressive systems, this time must be constant for any given period of time. (Nonfixed-time signal controllers can certainly be employed in progressive systems, but they must conform to a fixed time, recurring pattern. Actuated and semi-actuated control are not pertinent to this research and are therefore excluded.)

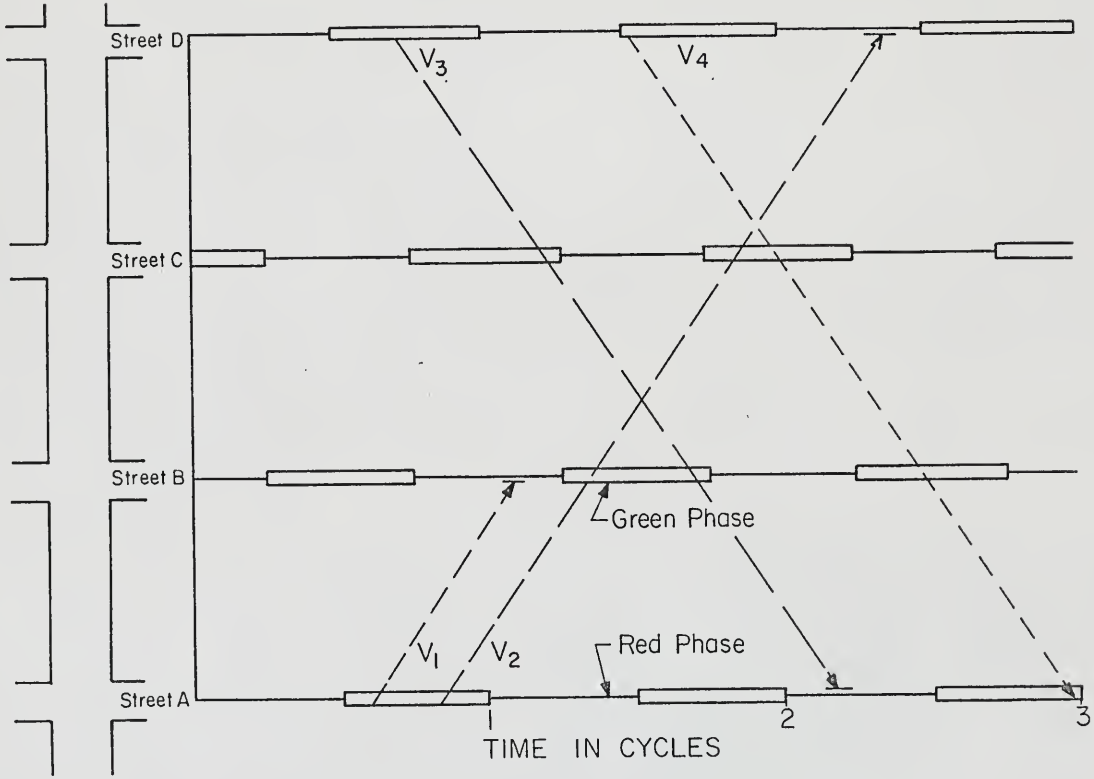


FIGURE 2.1 EXAMPLE OF THE TIME-SPACE RELATIONSHIP OF UNCOORDINATED TRAFFIC SIGNALS

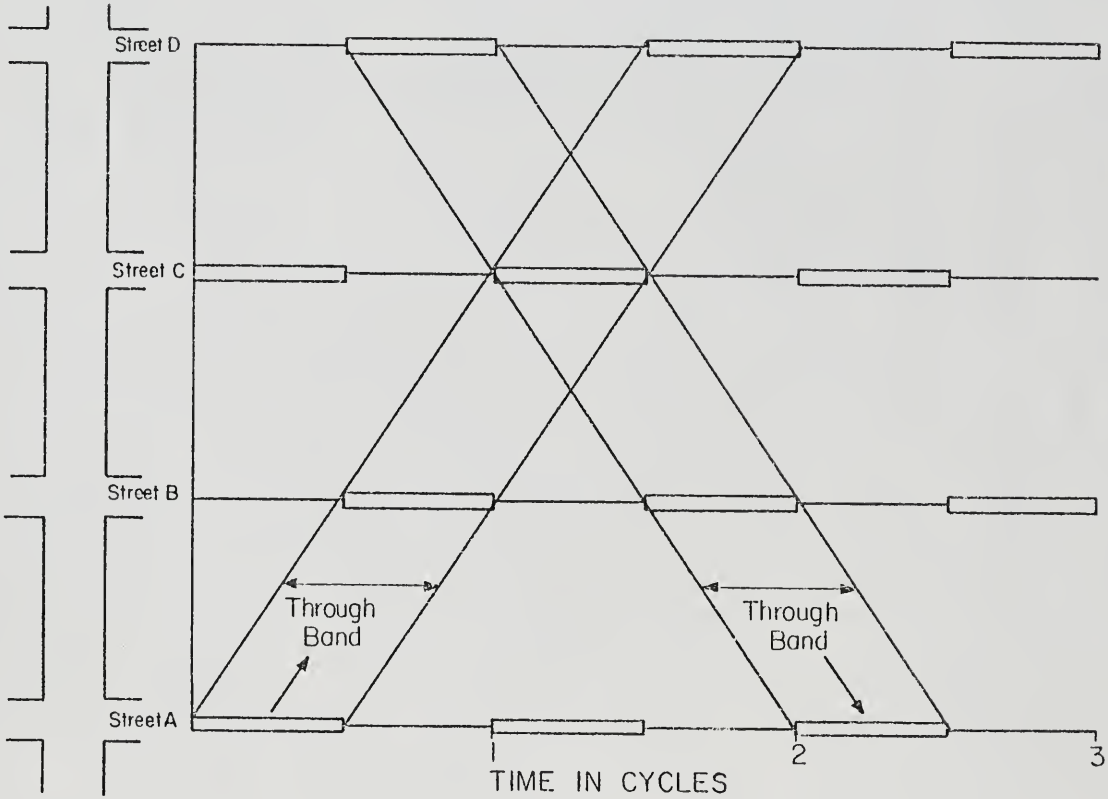


FIGURE 2.2 EXAMPLE OF THE TIME-SPACE RELATIONSHIP OF PERFECT PROGRESSION

2. Phasing pattern - the recurring sequence, or order, in which the several signal phases are displayed.
3. Splits - the distribution of the cycle length among the several phases, including green, amber and any all-red phase. A split is said to contain the total of these times for a particular movement and the sum of the splits equals the cycle length.
4. Offset - the relative start time of adjacent signal cycles. Offsets are commonly stated in terms of the number of seconds within a cycle (or percentage of the cycle) relative to a singular reference basis.

As stated above, all of these elements will be constant for a given operating period and for a given design. Bleyl (1967) also includes speeds in his list of pertinent elements, but in this research, it is assumed that progression speeds are not variable. This is due to the fact that drivers do not readily adjust their speeds to imposed progression speeds (Lai et al., 1977).

The subsections below review the theoretical development of arterial progression and modeling. The two are inexorably related, particularly in recent decades.

Past Research

The earliest techniques for the design of progressive timing of coordinated systems necessarily employed rather unsophisticated analytical or graphic representations of simple progression which merely projected green band(s) through the system. Such designs were often based on simultaneous or alternating phases of equal length balanced with respect to direction, if two-way progression, or totally devoted to a primary direction. The analytical techniques were based on travel time,

without regard to queuing, turning movements or other exogenous effects. Graphic techniques involved manually "balancing" bands by means of trial and error plots of time-space relationships among signals. More "advanced" approaches to this technique employed the use of strips of paper or other material which could be moved in the time dimension along an axis corresponding to the individual intersection locations.

In the early 1950's more sophisticated algorithmic techniques were introduced which allowed variations of speed, cycle length and irregularly spaced intersections to be more easily resolved. Such advancements were usually perpetuated by signal controller manufacturers to enhance the attractiveness of their equipment. For example, the Eagle Signal Company distributed a design technique which employed a nomograph relating cycle length to link length and speed and an algorithmic determination of resulting offsets (Fieser, 1951).

By the 1960's, traffic engineering researchers were actively involved in the development of improvements to the progressive design process which recognized the advances in control technology, the analytical capabilities of digital computers and the behavioral patterns of drivers. Since then, the theory of coordinated traffic control has evolved essentially in three directions: (1) maximal bandwidth, (2) minimal delay (often along with other measures of disutility) and (3) policies designed to separate stationary queues from moving platoons. The first two techniques usually involve off-line design, while the last virtually always involves real time, on-line control.

Because the several policy methodologies are functionally separable, they are discussed individually.

Maximization of Bandwidth

Of the various policies governing the control of signals on arterial highways, the concept of maximizing the through bands has been, and continues to be, the most popular (Lai et al., 1977 and MacGowan et al., 1977). The concept of signal timing to achieve the widest possible through-green bands was explicit in the earlier, primarily, graphic techniques using time-space diagrams. However, increasing use of multiphase signals and the increasingly irregular relative placement of signals (due to suburbanization) demanded more sophisticated, analytical approaches.

A significant advancement in the state-of-the-art, with respect to computational capability, came with the work by Yardeni (1964 and 1965). His maximal bandwidth model was based on the ratio of green time to cycle length, the cycle length itself and offsets designed to allow the maximum vehicle throughput in a system. The model minimizes the deviations of the center of green times at each intersection from the center of the through bands. Extensive inputs were required for this model. The level of computational sophistication was quite high, due to overly optimistic expectations in the technique, which had a somewhat faulty underlying theoretical basis. As a result, this model proved no more effective than conventional techniques (Wagner and Gerlough, 1969), but it served to inspire more theoretically complex design strategies.

The minimal deviation of split to bandwidth remained active for over a decade. Leuthardt's NO STOP-1 model (1975) employs the essential theory, but uses a Techebyscheff approximation to effect the minimization of the maximum deviations. This model has been analytically "proven" but experience and basic intuition suggest that balancing through greens

about the center of the through band does not properly consider all the germane aspects of arterial progression.

The Metropolitan Toronto Traffic Control System (1965) was a source of several innovations in both this area and the delay-based theory, discussed later. The SIGART model is a flexible model because it can consider a variety of control parameters, namely cycle lengths, splits and progression speed. The major drawback of SIGART is that the model is highly sensitive to changes in speeds and, thus, encourages designers to use such variations in the design speed to obtain wider progression bands. Unfortunately, drivers do not willingly adjust their speeds to conform to progression speeds, because such parameters are often transparent to them, and the urge to travel at their desired speed is more pertinent (Lai et al., 1977). A more realistic model based on an otherwise similar concept, but without the inherent problems existing in SIGART, was proposed by Morgan and Little (1964) and Little et al. (1966). For relatively homogeneous, well-defined systems, this model (called EXPRESS) produced realistic offsets which enhance progression. A good deal of preliminary engineering is required to establish all the other timing parameters, however. The model is based on mixed-integer linear programming.

Brooks (1965) first proposed the process which has ultimately become the underlying policy of current progression control from the perspective of analytical design. His maximal bandwidth model is based on the time-space relationship between the most critical intersection(s) (i.e., that with the least amount of available green time) and the remaining intersections which, if not properly offset, could interfere with progression through the critical intersection(s). Computationally,

the approach of minimizing interference with the critical intersection greatly reduces the number of combinations that have to be tried in an iterative computer solution. This allows very efficient testing of a wide range of cycle lengths (and ultimately other timing elements) to achieve an optimal solution.

A further simplification of computational complexity in time-space relationships was introduced by Bleyl (1967). The SIGPROG model converts speed and link distances to equivalent travel time diagram. This model tends to favor the direction with the greater traffic demand, but its optimal solutions, like SIGART, often require speed changes along the route.

All of the above maximal bandwidth models are somewhat restricted in the options they can consider in a single run, namely phase patterns, cycle lengths and splits, to varying degrees. A significant advancement was made when a maximal bandwidth optimization model was introduced, which internally optimizes cycle length (over a specified range), patterns and offsets, along with a realistic apportionment of green times among the various phases. Messer and his associates first introduced the Progression Analysis and Signal System Evaluation Routine (PASSER) model in 1963 (Messer et al., 1973) and later improved the model which is now called PASSER II (Messer et al., 1974 and Fambro, 1979).

PASSER II represents the state-of-the-art in maximal bandwidth optimization models (MacGowan et al., 1977) and is used extensively in the present research. Because of the latter, it is discussed later in this chapter.

Delay-Based Methodologies

A second active area of research in coordination of traffic signals utilizes various means of minimizing delay in the system, or minimizing some combination of delay and stops. These strategies are usually directed more specifically at two dimensional (grid) networks than at arterials (Lai et al., 1977), but most have been applied to arterials in practice. Minimization of delay and stops is clearly an underlying objective of maximal bandwidth models; however, the concepts discussed below use these variables as explicit objective functions.

In 1960 and 1964, Newell first reported the results of his theoretical studies of delay at coordinated intersections. His early research was purely analytical and was restricted to special cases of (1) equally spaced signals, (2) closely spaced signals and (3) widely spaced signals. Multiple phasing or wide ranges of other parameters were not included. Later, he and Bavarez (1967) developed a computer program which employed early findings in a model for minimizing various objective functions based on stops and delays for one-way streets. This early model assumed uniform arrivals with no platoon dispersion. This latter assumption was to be an area of intense research in this area.

Meanwhile another of the important early models was being developed for the Metropolitan Toronto Traffic Control System. The SIGRID network model (Marrus and Main, 1964) uses a disutility function comprised of a quadratic function to express delay and stops. The model determines offsets which minimize this function. Although SIGRID requires very extensive calibration to give realistic solutions, this model was considered a significant advancement in the state-of-the-art in 1964.

Realizing some of the drawbacks of SIGRID, the basic policy was advanced by the Traffic Research Corporation (1966) who developed the SIGOP model. Despite advancements over SIGRID, however, SIGOP is also highly sensitive to certain input parameters (e.g., its platoon coherence factor and minimum average headways); thus, the model remains difficult to calibrate. Selection of the appropriate design, in view of the sensitivity problems, is highly judgemental. Several comparisons of SIGOP with the TRANSYT model (see below) found the latter to be superior (Whirting, 1972; Kaplan and Powers, 1973; and MacGowan and Lum, 1975). Until TRANSYT was introduced, SIGOP was widely used in spite of the difficulties in preparing data and interpreting results.

Further improvements were made to SIGOP by Lieberman and Woo (1975), resulting in the SIGOP II model. This model retains the objective function policy of SIGOP, but bases the delay and stops estimates on more realistic (and analytically less complicated) relationships similar to those used in the TRANSYT model. In tests, SIGOP II has been demonstrated as being superior to SIGOP, and it is currently undergoing comparative tests against other network models.

A somewhat different approach to the minimal delay policy was first suggested by Hillier (1965 and 1966). The delay/difference of offset method is an extension of the stops and delay concepts introduced by Webster (1958). The model assumes that well-formed platoons move between adjacent signals at the free-flow speed. Given this assumption, it can be further assumed that the through traffic primarily occupies the link during the green interval. Thus, by associating the offset difference between adjacent signals with the expected queue length (which expresses delay), the latter can be minimized by adjusting the offsets.

The major difficulty of the delay/difference of offset method is that it deals only with connected pairs of signals. However, by combining links in series or parallel, the network can ultimately be condensed to a single link. The offsets which resulted in the minimum expression of delay in the single (condensed) link is the optimal solution. This approach was developed further by Hillier and Rothery (1967) and a computer model to simplify the computations was written by Wagner and Gerlough (1969).

Some networks are not completely condensable, however, and the delay/difference of offset model fails to provide a complete solution. To overcome this problem, Allsop (1968a and 1968b) formulated the so-called British Combination Method. The network is first condensed as far as possible using the delay/difference of offset method. Then Allsop's graph theory is applied to rebuild the network, link by link, where each link is optimized at each step. The delay/difference of offset policy remains active today (Lai et al., 1977), although it is used with less enthusiasm, because of validation findings which favor other techniques, particularly TRANSYT (Rach et al., 1974 and 1975).

Little et al. (1974) have also used a mixed-integer linear programming model (MITROP) to minimize delay in networks. The model utilizes IBM's Mathematical Programming System Extended (IBM, 1971) package to minimize an objective function which is a disutility function consisting of flow and queue length. Flow patterns are periodic, rectangular platoons with uniform arrivals. Stochastic effects are represented in terms of an overflow queue on each link, and these effects are incorporated into the objective function.

The major drawback of the delay (and stops) reduction models described above has been unrealistic estimates of the effectiveness functions. This is often due to unrealistic treatments of platoons, namely, the assumption of well-formed distributions. The classic work by Robertson and his associates has largely overcome the deficiencies of earlier modeling policies, as discussed below.

The most widely accepted analytical simulation of traffic operations at signalized intersections has been based on Webster's work in the timing of signals and the delays and stops occurring at them (Webster, 1958 and Webster and Cobbe, 1966). Robertson (1968 and 1969) developed the TRANSYT model around the theory of Webster's delay equations. Webster's method has, of course, been used in other works, but Robertson added a more realistic treatment of platoons. Recognizing the observations of Hillier and Rothery (1967), which demonstrated that platoons disperse according to a predictable recurring pattern, Robertson included a platoon dispersion factor (PDF) in his model so that the delays and stops would be responsive to realistic arrivals and queuing at the stop line of a link. The validity of the PDF has been verified by Seddon (1972). This significant advancement led to an effectiveness function (e.g., a linear combination of stops and delays) which, when optimized, produces predicted results that correlated well with field measurements when the design signal settings are implemented.

The optimization methodology employed by Robertson is a so-called "hill climb" search technique that produces a true optimum, given sufficient iterations. (It should be noted, however, that Robertson's algorithm is actually a "valley descent" method, as explained in Appendix B.) The original TRANSYT model was improved over the next ten years

(indeed, further refinements are presently being made). The most commonly used version today is TRANSYT6 (Robertson and Gower, 1977). The Institute of Transportation Studies at the University of California at Berkeley has modified this model to include estimates of fuel consumption and vehicle exhaust emissions, as well as demand responses to the optimal design vis-a-vis the base (usually existing) condition. This version is referred to as TRANSYT6C (Jovanis et al., 1977). Version seven has been developed (Hunt and Kennedy, 1979) but is not readily available at this time.

TRANSYT6C is an integral part of the present research and, therefore, is discussed in more detail later in this chapter and in Appendix B. It should also be reiterated that the delay (and stops, where appropriate) reducing models were all specifically directed at grid networks, rather than linear arterial highways.

Real-Time Control Models

Several real-time, dynamic control models for coordinated signal systems are pertinent to the present research. The models of interest have in common the fundamental strategy, or policy, of minimizing interference to through platoons moving through the system.

Among the earliest of these is the "smooth flow theory" introduced by Chang (1967). The model dynamically controls a network in a manner designed to minimize congestion by releasing stopped queues ahead of oncoming through platoons. Queues at downstream signals are measured and offsets are timed to release the downstream queues such that the queues have just dissipated when the upstream platoons arrive. The strategy may apply well to small networks (or better still, at isolated critical intersections), but it quickly degenerates in larger systems and through

progression is eliminated over several signals (Lai et al., 1977). A similar strategy, called the PLIDENT model (Holroyd and Hillier, 1971) was also found to increase delay and reduce progression.

Another similar policy operates primarily in oversaturated networks. The "queue-actuated signal control" technique (Lee et al., 1975) may operate either in coordinated or uncoordinated networks with actuated controllers. The approach employs detectors near the input of each link that detect the extension of the queue over the entire length of the link. When this "spill-over" is detected, the signal on the critical link is switched to green to clear the offensive queue. This strategy works well only in oversaturated, uncoordinated networks where the variation of offsets is not as critical, because there is no progression per se.

A third policy lies between the foregoing extremes. Rosdolsky's model (1973) does not require interconnect (coordination) within a network. Detectors measure the momentary degree of concentration to sense the relative positions of stationary queues and moving platoons. As in the case of the smooth flow theory, the offset is advanced to clear the queue to avoid interference with the moving platoon. Thus, the necessary control information is "carried" by the traffic stream, negating the need for coordination within the system. The major difference in Rosdolsky's strategy is that signals on the perimeter of the network are coordinated to stagger offsets to traffic entering the system in order to avoid "collisions" of conflicting moving platoons. However, this technique also fails in larger systems (Lai et al., 1977), for the same reasons as before.

From the perspective of arterial control, these dynamic models would appear to have a certain degree of appeal, particularly on one-way streets. That is, the dissipation of queues ahead of through platoons would enhance the propagation of the platoons and minimize stops and delay. The common drawback is that the variation of cycle lengths and splits, and, therefore, offsets, tends to have a degenerative throttling effect on through movements. This aspect is investigated as part of the present research.

Existing Models Pertinent to the Forward Link Opportunities Model Development

As noted in the previous section, the maximal bandwidth optimization policy is presently the most widely accepted basis for arterial progressive control. A state-of-the-art model embodying this policy is the Progression Analysis and Signal System Evaluation Routine, Version Two (PASSER II). The maximal bandwidth strategy is directed at through traffic, as is the forward link opportunities strategy (developed in the next chapter), thus PASSER II is an appropriate model to use for comparative purposes.

For reasons discussed more thoroughly in the next chapter, the TRANSYT6C model has been selected to form the framework of the proposed forward link opportunities model.

Both of these models are described in some detail in Appendices A and B, respectively, for the benefit of readers who are unfamiliar with the models. Table 2.1 contains a summary of the models in terms of their computer requirements, inputs, outputs and optimization techniques.

TABLE 2.1 SUMMARY DESCRIPTIONS OF THE PASSER II AND TRANSYT6C MODELS

ITEM	PASSER II	TRANSYT6C
1. Computer Requirements		
Language	FORTRAN IV	FORTRAN IV
Computer System	IBM 370	IBM 370/CDC 6400
Program Length (incl. comments)	1425 (approx.)	5870 (approx.)
Execution Time	1 second (max.)	Varies with the square of the number of nodes
2. Inputs		
Geometric Descriptors	None explicit, except link length	Implicit in link-node formulation, and link length
Traffic Volumes	Total per link (vehicles/hour)	Total per link and upstream inputs (vehicles/hour)
Capacities	Vehicles/hour of green	Vehicles/hour of green
Minimum Greens	Seconds	Seconds or fractions of cycle
Cycle Length	Specify range	Fixed
Phasing	Optional, multiphasing	Fixed, multiphasing
Splits	Optional (if specified, dubbed in as minimum greens)	Optional, direct entry or computed internally
Offsets	No	Optional, may be input for analysis
Speed or Travel Time	By link	By link

TABLE 2.1 (CONTINUED)

ITEM	PASSER II	TRANSYT6C
3. Outputs-MOE		
Saturation Ratio (v/c)	By movement	By link
Delay	No	Uniform plus random
Stops	No	Yes (may be weighted by length of delay)
Fuel Consumption	No	Yes
Emissions	No	HC, CO, and NO_x
Progression Speed	Yes	No
Average Speed	No	Yes
Vehicle-miles of Travel	No	Yes
Vehicle-hours of Travel	No	Yes
Bandwidth	Yes	No
Attainability	Yes	No
4. Optimization		
Cycle Length	Yes	No
Phasing	Yes, two to six	No
Splits	Yes, distribution of v/c ratios	Yes, distribution of v/c ratios
Offsets	Yes	Yes
Progression Speed	Yes($\pm$2mph of average)	No
Objective Function	Max. bandwidth efficiency	Min. ftn(delay, stops, fuel and emissions)

CHAPTER 3

DEVELOPMENT OF THE FORWARD LINK OPPORTUNITIES MODEL

Introduction

In the previous chapter, the maximal bandwidth strategy was identified as the most common methodology used in the design of optimal progression on arterial highways. A widely accepted model embodying this concept is the Progressive Analysis and Signal System Evaluation Routine, Version Two (PASSER II). The focus of this research is to determine whether improvements in the design of traffic signal progression can be made over the maximal bandwidth method.

The maximal bandwidth strategy considers only the relative alignment of signal offsets which produces the maximum widths of the bidirectional bands. No explicit consideration is given to intersections that are not critical to the bounding of the through bands. The uncertainty of how to treat signal timing at the noncritical intersections introduces a form of entropy into the system design. That is, some available portion of the cycle may not be transformed into useful progression. This is illustrated in the time-space diagram shown in Figure 3.1. Note the outlined areas, which represent partial progression opportunities outside the through bands.

If the offsets are adjusted somewhat, these additional (partial) progressive opportunities can be increased as illustrated in Figure 3.2. This is the purpose of the forward link opportunities concept, which is described in the following section.

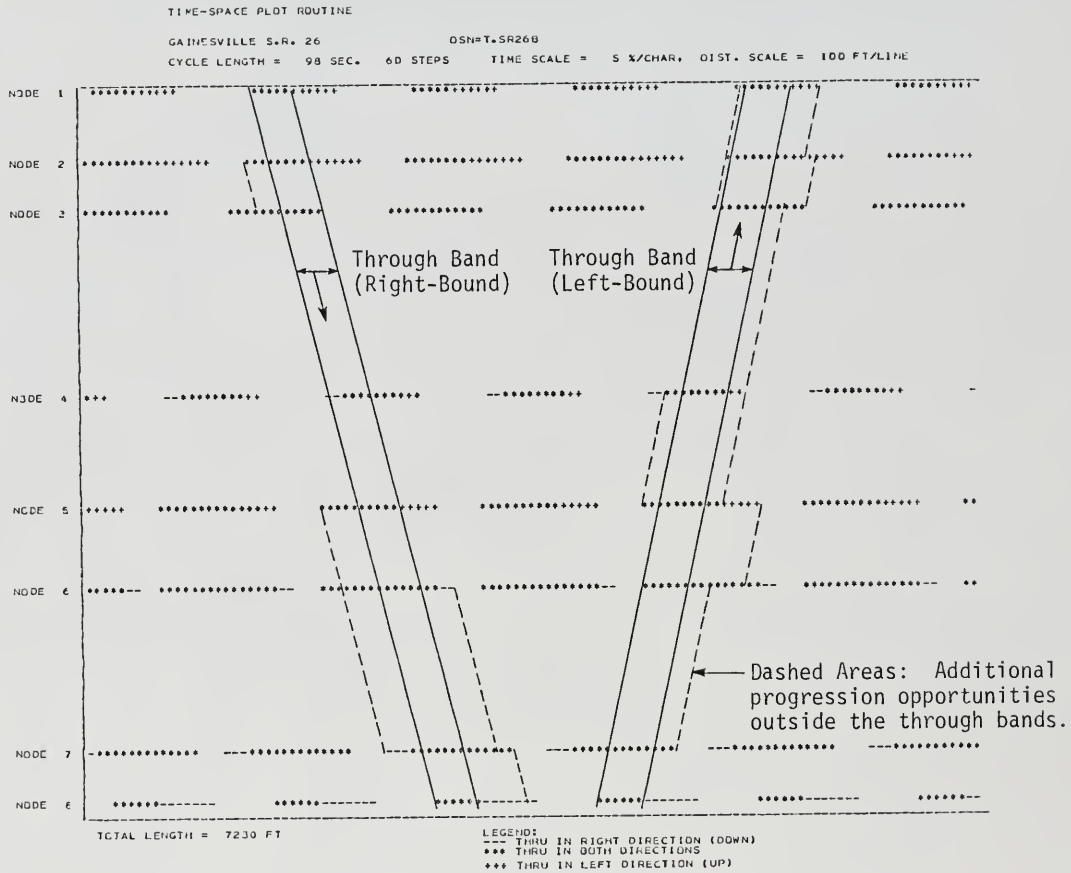


FIGURE 3.1 TIME-SPACE DIAGRAM OF A MAXIMAL BANDWIDTH SOLUTION ILLUSTRATING UNUSED PARTIAL PROGRESSION OPPORTUNITIES

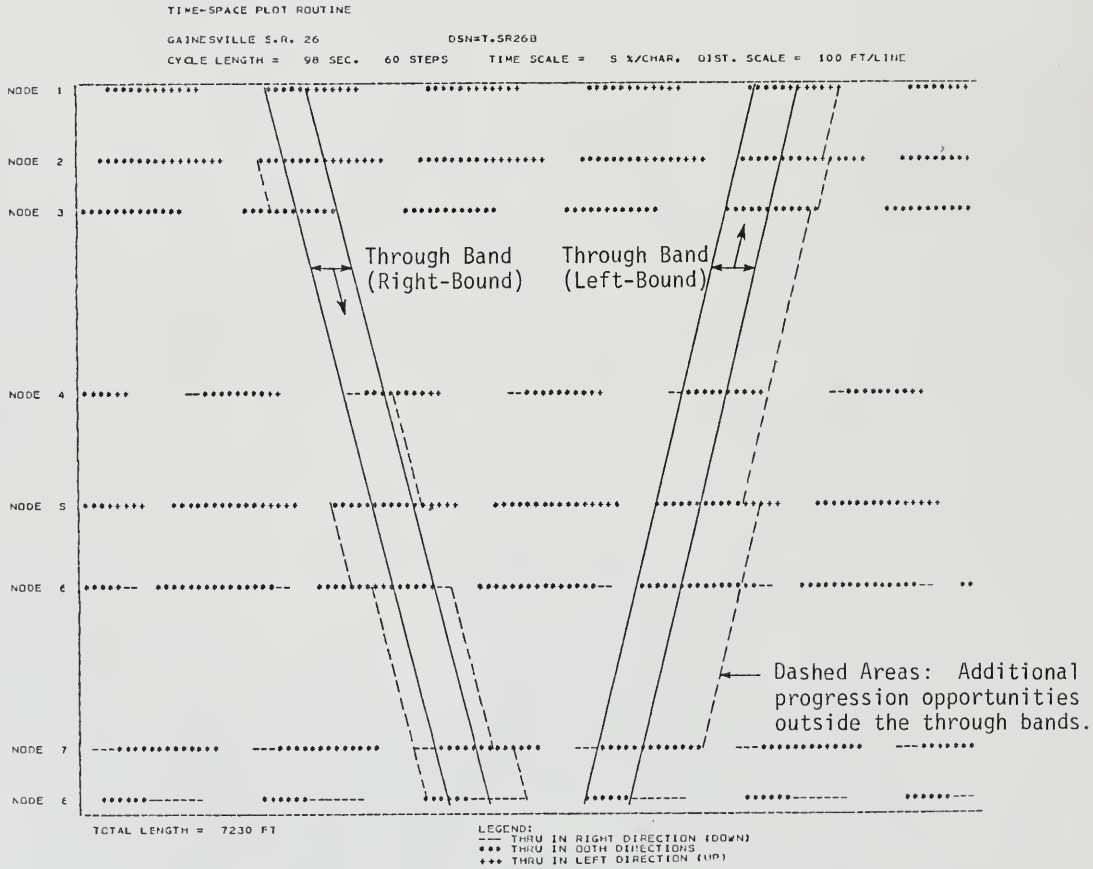


FIGURE 3.2 TIME-SPACE DIAGRAM OF PREVIOUS EXAMPLE ADJUSTED TO MAXIMIZE FORWARD LINK OPPORTUNITIES

Concept of the Forward Link Opportunities Model

Forward link opportunities (FLOS) derive from the time-space relationship of traffic signal timing along the arterial highway. As the name implies, there is no explicit consideration given to the presence of traffic demand to accept the progressive opportunities (although in Chapter 5 a strategy which recognizes the periodic demand is presented).

Forward link opportunities are defined as the number of successive links along an arterial roadway, from an intersection displaying a green signal indication (including amber and any all-red phase), that will have green signal indications at their downstream ends, in progression; that is, when encountered at times dictated by given link travel speeds. In other words, FLOS are the number of successive links downstream of any green signal over which progression could occur, during a finite increment of time, without interruption by a red signal indication.

The variables that determine the availability of FLOS are time, progression speed and the timing of the traffic signals. In addition, the parameter, link length, must be included. Time is a continuous variable, but events which conveniently describe traffic signal operations are discrete (e.g., the start and end times of the signal phases). Therefore time can be divided into discrete intervals of uniform duration for the purposes of conceptual development. These intervals can be sufficiently short to yield a realistic representation of time and effect the identification of events that describe the status of the traffic signals.

For a given system, progression speeds are assumed to be constant (by link) for the reasons stated in Chapter 2. Signal status is cyclical for any given set of timings being considered.

Forward link opportunities are derived from these variables as described below.

A fundamental element in the determination of FLOS is dependent on the event that signals are in the green interval at the appropriate times (where, "green" is defined to include the actual green, plus amber and any all-red time). This is described in terms of a binary event function as follows:

$$E_{jt} = \begin{cases} \text{True, if } \mathrm{mod}[(t + \frac{D_j}{FV_j} - \phi_j + T), T] \leq P_j T, \text{ or} \\ \text{False, otherwise;} \end{cases} \tag{3.1}$$

where E_{jt} = the event that signal j is green at time increment t, and t ranges from one (1) to T;

D_j = the distance in feet from the first intersection to intersection j;

V_j = the average progression speed (mph) between intersections one (1) and j which is determined as follows: $V_j = D_j/[\Sigma_{i=1}^{j} (d_i/v_i)]$, where d_i and v_i are link-specific lengths and speeds, respectively;

F = a factor to convert from mph to feet per time increment;

ϕ_j = the offset (i.e., the positive difference in start times of the through-green phases) of intersection j, relative to the first intersection, in time increments;

T = the cycle length in time increments; and

P_j = the fraction of the cycle that the through phase at intersection j is green.

A single forward link opportunity exists at intersection j whenever E_{jt} and $E_{(j+1)t}$ are true at any time increment, t. This relationship can be illustrated graphically. When the signal timings are adjusted for travel time according to the modulo function in Eq. (3.1), the time-space diagram (such as Figures 3.1 and 3.2) can be adjusted such that the progression speed has zero slope with respect to the time axis. When this is done, the distance between intersections is no longer relevant (at the progression speed) and the distance scale can be "collapsed" into a unitless scale where only the relative order of intersections is pertinent. When Figures 3.1 and 3.2 are transformed in this manner, the time-location diagrams shown in Figures 3.3 and 3.4, respectively, result. The through bands and partial progression opportunities outside the through bands are also identified in these diagrams. The partial progression opportunities conform to the definition of single forward link opportunities given above, if it is envisioned that the blank "cells" of the diagram represent that E_{jt} is true and the stars represent the fact that E_{jt} is false. All conditions where adjacent events (with respect to locations at any time t) are true are outlined in the figure. These outlined areas represent the presence of FLOS.

Figure 3.4 clearly shows more potential FLOS than Figure 3.3. For example, a vehicle entering the arterial (left-bound) from a side street at intersection eight at time t_1 can expect to travel the remainder of the system without encountering a red signal, if it travels at the progression speed.

The above has described the FLOS concept in qualitative terms. The quantification of FLOS is now presented.

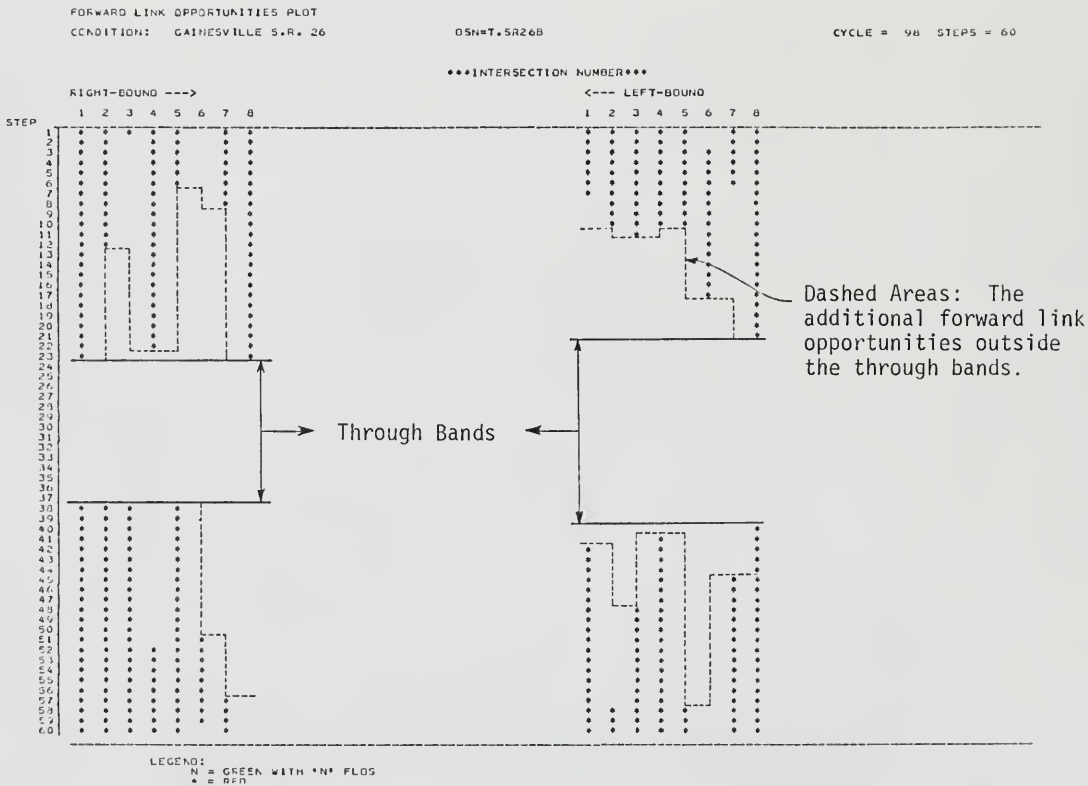


FIGURE 3.3 TIME-LOCATION DIAGRAM OF A MAXIMAL BANDWIDTH SOLUTION ILLUSTRATING PARTIAL PROGRESSION OPPORTUNITIES

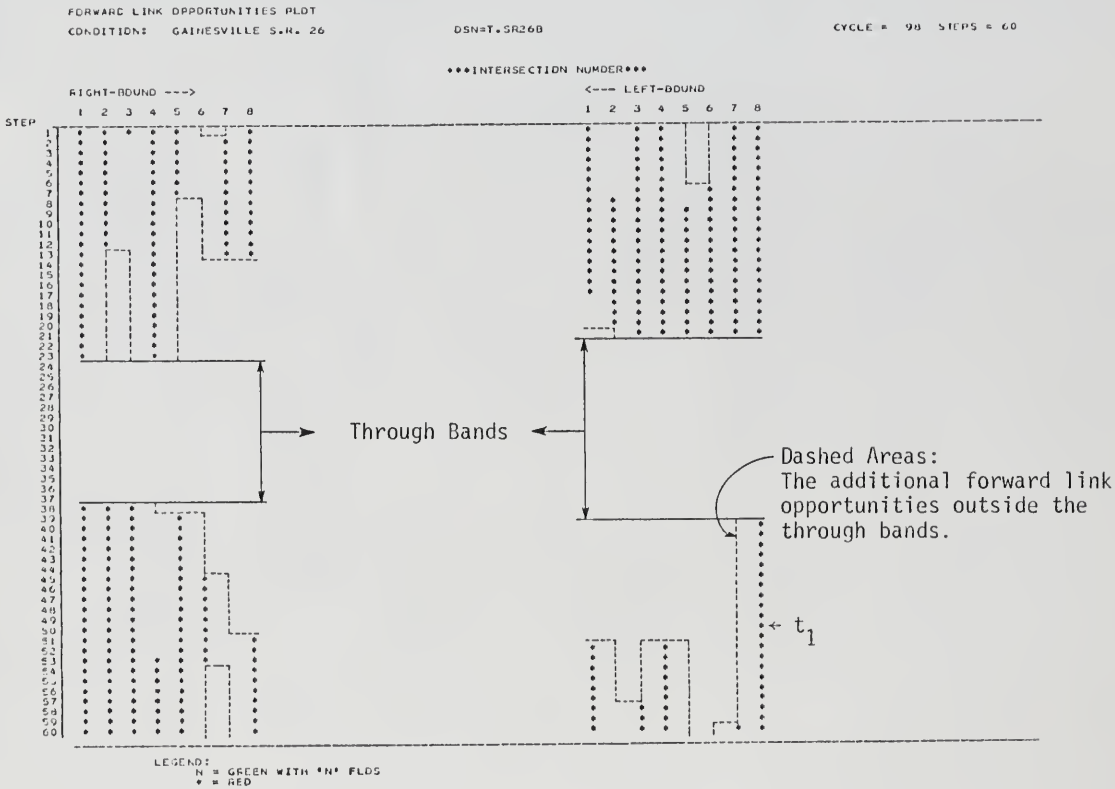


FIGURE 3.4 TIME-LOCATION DIAGRAM OF PREVIOUS EXAMPLE ADJUSTED TO MAXIMIZE FORWARD LINK OPPORTUNITIES

The logical function, E_{jt}, is readily converted to a numerical function as follows:

$$S_{jt} = \begin{cases} 1 \mid E_{jt} \text{ , or} \\ 0 \mid \overline{E}_{jt}; \end{cases} \tag{3.2}$$

where S_{jt} = a binary status function, which is equivalent to the event function E_{jt}, and describes the status of signal j at time interval t.

To complete the quantification of actual FLOS for each intersection and at each time interval, the products of the binary status variable are summed over all intersections for each increment of time as follows:

$$FLOS_{it} = -S_{it} + \sum_{j=i}^{N} \prod_{k=i}^{j} S_{kt} \; ; \tag{3.3}$$

where $FLOS_{it}$ = the forward link opportunities from intersection i at time interval t, and

the other variables are as defined before.

The product of terms in the above equation is necessary to count only those successive intersections for which all of the binary status variables are unity (for time increment t). Furthermore, it is necessary to decrement the sum by one (if S_{it} is equal to unity) to indicate that the value of FLOS represents the number of downstream forward link opportunities from intersection i. [An example of the function of Eq. (3.3) is given later, following the introduction of the diagrams which result from its use.]

When Eq. (3.3) is exercised separately for both directions of travel on the arterial, a "FLOS diagram" can be produced to illustrate the FLOS for each signal at each time increment. The FLOS diagrams for Figures 3.3 and 3.4 are shown in Figures 3.5 and 3.6, respectively. Note that the individual FLOS at each signal, and for each time interval, fill out the areas previously outlined in Figures 3.3 and 3.4 (and, for that matter, Figures 3.1 and 3.2).

Having illustrated the results of Eq. (3.3) in Figures 3.5 and 3.6, an example of the application of Eq. (3.3) may clarify the meaning of the equation. In Figures 3.5 and 3.6 one cell or, the respective values of $FLOS_{it}$ in each figure, are circled--namely, the values for intersection five (5) at time increment twenty (20). Table 3.1 gives the detailed solution of Eq. (3.3) applied to these $FLOS_{5,20}$ calculations.

The improved number of FLOS in the 5,20 cell is demonstrated in the example as they increased from two (2), in the maximal bandwidth solution, to three (3) in the solution which maximizes FLOS.

The FLOS concept thus recognizes and quantifies the availability of both continuous and discontinuous bands which can serve trips that originate within the system and can also serve trips which exit the arterial within the system. Another important aspect of this concept is that it can consider the quality of progression from the driver's perspective--namely, how many additional signals will permit continuous passage of vehicles which have already traveled some distance within the system.

FLOS is a useful measure of effectiveness, but more significantly, when used as an optimization variable, it can apportion available green

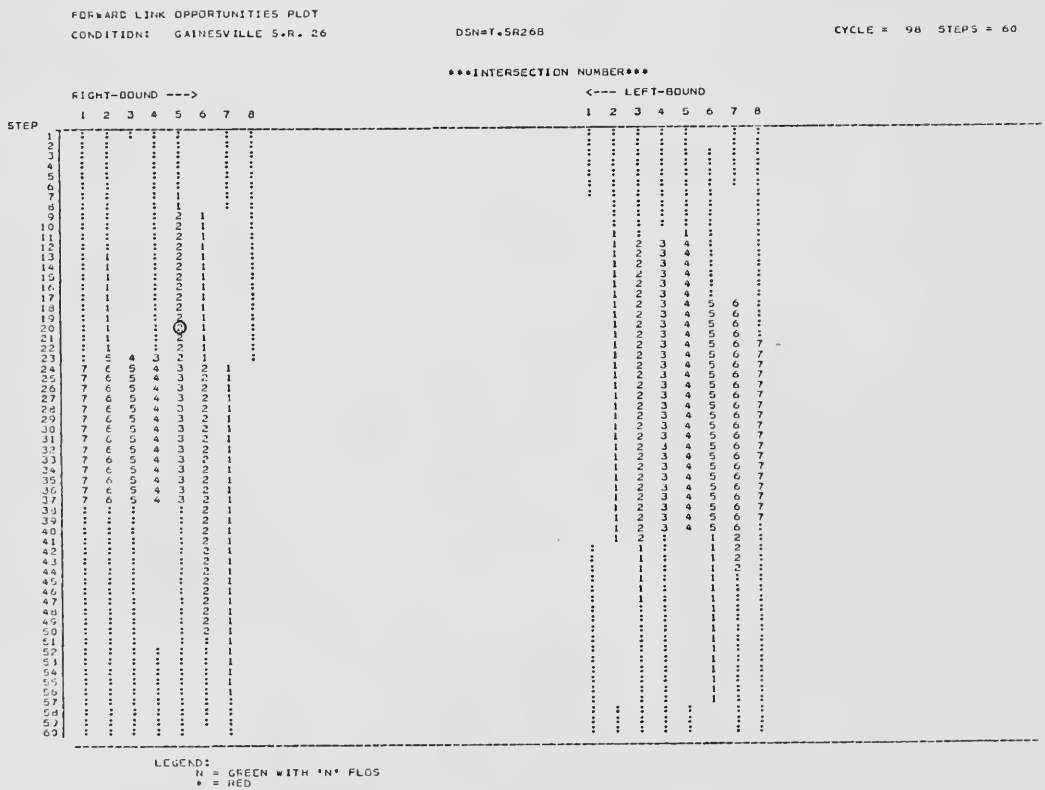


FIGURE 3.5 FLOS DIAGRAM ILLUSTRATING THE OPTIMAL OFFSETS FOR MAXIMAL BANDWIDTH ONLY

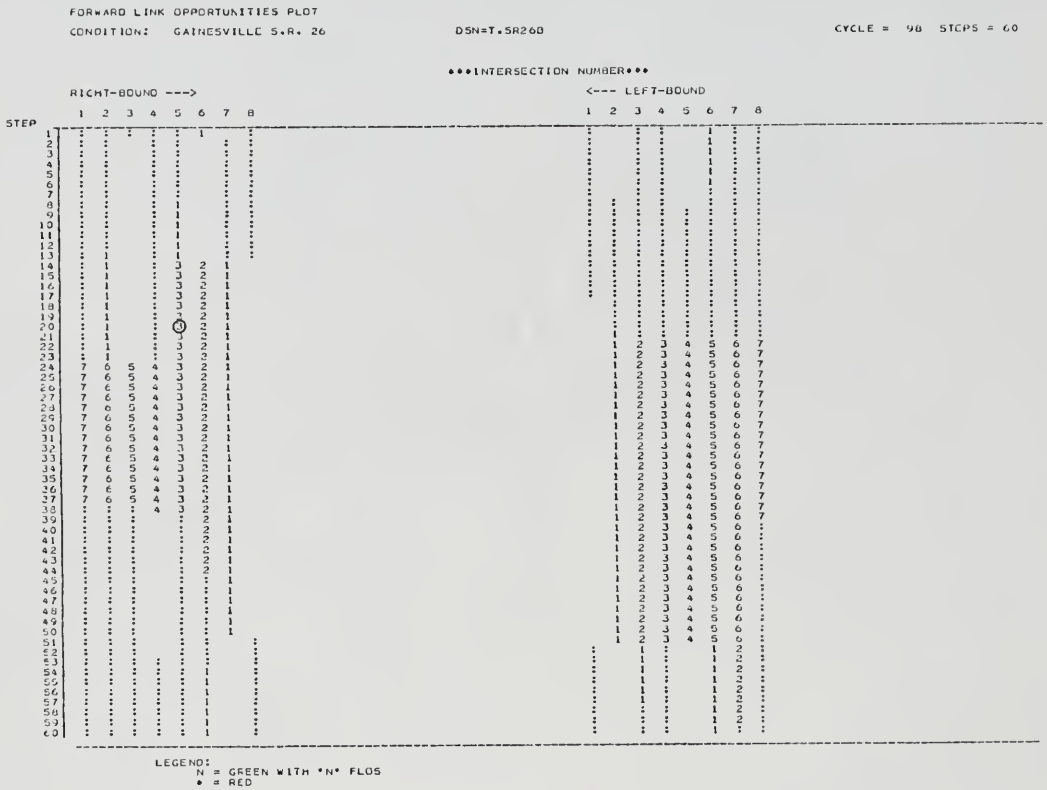


FIGURE 3.6 FLOS DIAGRAM ILLUSTRATING THE OPTIMAL OFFSETS FOR FORWARD LINK OPPORTUNITIES

TABLE 3.1 APPLICATION OF EQUATION (3.3) TO TWO EXAMPLES

VARIABLE	EXAMPLE FROM FIGURE 3.5			EXAMPLE FROM FIGURE 3.6		
$FLOS_{5,20}$ =	$-S_{5,20}+\sum_{j=5}^{8}\prod_{k=5}^{j} S_{k,20}$			$-S_{5,20}+\sum_{j=5}^{8}\prod_{k=5}^{j} S_{k,20}$		
Incrementing j and k:						
j = 5, k = 5,5	$-S_{5,20}+S_{5,20}$	= -1+1	= 0	$-S_{5,20}+S_{5,20}$	= -1+1	= 0
j = 6, k = 5,6	$+S_{5,20}S_{6,20}$	= +1·1	= +1	$+S_{5,20}S_{6,20}$	= +1·1	= +1
j = 7, k = 5,7	$+S_{5,20}S_{6,20}S_{7,20}$	= +1·1·1	= +1	$+S_{5,20}S_{6,20}S_{7,20}$	= +1·1·1	= +1
j = 8, k = 5,8	$+S_{5,20}S_{6,20}S_{7,20}S_{8,20}$	= +1·1·1·0	= +0	$+S_{5,20}S_{6,20}S_{7,20}S_{8,20}$	= +1·1·1·1	= +1
Total, $FLOS_{5,20}$			2			3

time and assign offsets in such a manner that these forward link opportunities are maximized, thus providing the best progression from the driver's perspective. This is demonstrated in a comparison of Figure 3.5, which is the FLOS diagram of the maximal bandwidth solution, and Figure 3.6, which is the FLOS diagram of the maximal FLOS solution.

The aggregate FLOS is found by summing Eq. (3.3) over all time intervals and all signals. For one direction (say right-bound), this is accomplished as follows:

$$FLOS_r = C/T \sum_{i=1}^{N} \sum_{t=1}^{T} FLOS_{it} \; ; \tag{3.4}$$

where $FLOS_r$ = the aggregate number of forward link opportunities for the right-bound direction;

C = the cycle length in seconds;

T = the cycle time in time increments; and

$FLOS_{it}$ is defined by Eq. (3.3).

The ratio C/T converts the aggregate FLOS from time increments to seconds.

The aggregate number of FLOS for the left-bound direction is computed similarly, but it must be recognized that the scan for individual FLOS in Eq. (3.3) is done from intersection N to the first intersection, or in the left direction. The total FLOS is simply the sum of the FLOS in each direction.

The generalized model for total aggregate FLOS is given below,

$$FLOS = C/T \sum_{k=1}^{2} \sum_{i=1}^{N} \sum_{t=1}^{T} FLOS_{jt}, \quad j = \begin{cases} i \,|\, k=1 \text{ (right-bound), or} \\ N+1-i \,|\, k=2 \text{ (left-bound);} \end{cases} \tag{3.5}$$

where all variables have been previously defined.

FLOS are represented on a per-cycle basis, aggregated over all time increments (corrected to seconds if required).

In the example which has been used in Figures 3.1 through 3.6, the total FLOS increased from 1,978 in the maximal bandwidth solution, to 2,131 when offsets were changed to maximize FLOS. This is about an 8% improvement.

Two additional measures related to forward link opportunities are useful. In the absence of any signalized traffic control, the full cycle would be available as forward link opportunities. This hypothetical measure (referred to as cycle forward link opportunities, or CFLS) can be computed directly for unweighted CFLS as follows, for both directions:

$$CFLS = 2 \sum_{t=1}^{C} \sum_{k=1}^{N-1} k = 2\, CN(N-1) \; ; \qquad (3.6)$$

where C = the cycle length in seconds and

N = the number of intersections.

The ratio FLOS/CFLS, called a progression quality ratio (PQR_C), is analogous to the bandwidth efficiency (see Chapter 2 and Appendix A), which is the PASSER II objective function, but in this case for FLOS. By the nature of its definition, PQR_C will always be less than unity. In the example considered earlier, the bandwidths did not change in the two solutions; however, the PQR_C increased from 0.35 in the maximal bandwidth solution, to 0.38 in the maximal FLOS solution.

The through-only FLOS are those forward link opportunities within the through bands. For any given solution the through forward link opportunities (TFLS) is simply a fraction of the CFLS, or,

$$TFLS = CFLS \times BW/C; \tag{3.7}$$

where BW = the sum of the bandwidths in both directions of travel, in seconds (see Appendix A for a detailed description of the bandwidths); and

the rest is as before.

A progression quality ratio based on FLOS/TFLS (or PQR_t) is a measure of the partial progression opportunities outside, or in addition to, the through bands.

Since more partial progression opportunities resulted from maximizing FLOS (e.g., opportunities outside the through bands), the PQR_t increased similarly (from 1.35 to 1.45). Examining only the FLOS outside the through bands, a net increase of 153 FLOS resulted, or about 30%.

In summary, when consideration is given to partial progression opportunities, offsets can be shifted to improve short-term progression over the solution derived by the maximal bandwidth optimization policy.

This example has demonstrated the FLOS concept, which serves as the basis of a new traffic progression optimization model. Outwardly, the FLOS concept is neither analytically complex, nor overly sophisticated from a theoretical perspective. It is, however, an innovative approach to signal progression design which has a good deal of intuitive appeal. Since, at the surface level, the concept embodies the principles of the maximal bandwidth methodology, it is consistent with the current direction the traffic engineering profession is taking with regard to arterial control. That this concept can potentially improve the quality of

traffic progression beyond that provided by existing maximal bandwidth models, suggests that model development and comparative investigation in this area are warranted.

The remainder of this chapter covers the development of a candidate FLOS optimization model.

Model Development

The basis of the FLOS formulation was given in Eq. (3.3). Forward link opportunities are a function of location, time, velocity and signal status. Location is simply a discrete function equivalent to signal position. Time refers to displacement within the cycle. Velocity can generally be considered to be a scalar quantity, because satisfactory progression will generally be responsive to the desired speed of the drivers (as noted in Chapter 2). Signal status is a function of the signal settings and, of course, time in the cycle.

Fundamental Elements of Progression

Signal progression is a composite of four signal timing parameters. These were defined in Chapter 2 and are (1) cycle length, (2) phasing pattern, (3) green splits and (4) offsets. All four of these parameters affect the quality of progression to varying degrees.

Offsets explicitly define the speeds of the progression bands. The progression band speed is determined by the desired speed of travel, which defines travel times between adjacent signals. But irregular phasing and splits require an offset that will position the green phases to best accommodate the progression bands. Splits determine the proportion of the cycle available for progression. The PASSER II maximal bandwidth model distributes green time in proportion to the demand/capacity ratio as discussed in Appendix A. Splits favoring the arterial

traffic would provide more time to move traffic on the main street, to the detriment of the cross street.

Since the progression band, or partial bands, may only be a fraction of the cycle, the cycle length dictates the widths of the bands. While over a long period, say an hour, the total time available for arterial green will be proportionately the same, regardless of the cycle length, shorter cycles tend to restrict through bandwidths, resulting in increased stops and delays. Longer cycles tend to accommodate more through traffic, but queuing can become excessive during the longer red signal periods.

Patterns dictate the flexibility of the timing plan which enables phase arrangements to accommodate the through bands. Patterns which maximize green time for through movements will permit wider through bands, but it is not always ideal to have the opposing through traffic moving simultaneously. Often, better two-way progression can be obtained by allowing one through movement and the parallel left-turn to go first, followed by an overlap of both through movements, then the through and left-turn in the second direction.

Formulation of the Model

Optimization upon forward link opportunities is based on the following objective function:

$$\max \text{FLOS} = C/T \sum_{k=1}^{2} \sum_{i=1}^{N} \sum_{t=1}^{T} \text{FLOS}_{jt}, \; j = \begin{cases} i \,|\, k=1 \text{ (right-bound), or} \\ N+1-i \,|\, k=2 \text{ (left-bound).} \end{cases} \tag{3.8}$$

This objective function is subject to certain constraints on the decision variables, which are discussed below.

Minimum Green and Demand Satisfaction

The minimum green on any approach is governed by safety considerations. Common practice dictates that the green display should be no less than five seconds, followed by a four second amber and, often, a one second all red interval. Thus, ten seconds is generally an appropriate minimum green interval, provided pedestrians are not a consideration (e.g., for exclusive left-turn movements). When pedestrians do move with traffic on a particular phase, the crossing time is generally three seconds times the number of lanes to cross, plus four seconds clearance. The minimum green constraint is, for the purposes of this research, defined as

$$MG_i = \begin{cases} 3\ LN + 4, \text{ if pedestrians are a consideration, or} \\ 10, \text{ otherwise;} \end{cases} \tag{3.9}$$

where MG_i = minimum allowable green time for phase i and

LN = number of lanes the pedestrian must cross.

In an optimal solution, traffic demand on all approaches should be satisfied without recurring congestion. Webster's method (Webster and Cobbe, 1966) is generally used to calculate required green time to satisfy their demand according to the following (Fambro, 1979).

$$G_i = [(y_i/Y) \times (C-L)] + l_i \ ; \tag{3.10}$$

where G_i = length of green, including amber and all red, for phase i;

y_i = ratio of actual demand (veh/hr) to saturation flow (veh/hr of green) for phase i;

Y = sum of the y_i for all phases;

C = cycle length;

l_i = lost time due to starting up the gueue at the beginning of phase i; and

L = total lost time.

If green periods are allowed to vary, the design value of minimum green shall be subject to the following constraint:

$$\text{Min Green}_i = \max\,(G_i,\ MG_i)\ ; \tag{3.11}$$

where G_i = a value of green for which y_i in Eq. (3.10) is no greater than a given upper limit, and

MG_i = as defined above.

The subject of absolute capacity (i.e., maximum vehicles per hour of green time per lane) is not addressed in this research. A reasonable, and accepted, value is assumed to be valid, namely 1,800 vehicles per lane, per hour of green time (Courage and Landmann, 1978).

Finally, the sum of all design minimum green times for p phases must be less than or equal to the cycle length, or,

$$\sum_{i=1}^{p} \text{Min Green}_i \leq C. \tag{3.12}$$

The sum of the actual greens (where amber and all-red intervals are included in the "green" times) must equal the cycle length.

Design Speed

Signal timing designs which provide progression at speeds substantially different than the desired speed of the traffic do not adequately serve the motoring public. Slight variations in speed are certainly permissible since desired speed is a stochastic function. However, for the purposes of this research, it is assumed progression speeds will be constant for a given link, but may vary among links as required.

Model Implementation

The aggregate forward link opportunities expressed in Eq. (3.8) is a multi-dimensional function of the disjoint elements defined earlier, which are by their nature either nonlinear (e.g., location with respect to time), or linearly dependent (e.g., proportionately equivalent periods of time). Thus, computation of the objective function is necessarily algorithmic in nature and its solution requires an iterative, search and find approach.

An exhaustive search approach is computationally prohibitive. For example, in a system of n intersections, with a fixed set of signal patterns and fixed green splits, the number of trials would equal C^n, where C is the cycle length, just to examine all possible offsets. A six signal system would require over 46 billion iterations for a 60 second cycle. Clearly, such large numbers of computations would tax even the largest of modern digital computers.

On the other hand, Eq. (3.8) is a bounded concave function since, for a given set of signal timings, the objective function will vary between some minimum value representing the worst possible progression and a maximum representing the optimal solution.

A variety of technologies exist for solving nonlinear concave functions (Wagner, 1969); however, the present objective function is discontinuous with respect to the multiplicity of possible signal settings. Stated otherwise, a change in one setting to influence the FLOS in, say, one direction of travel, may have a correspondingly opposite effect on the opposite direction. The nature of this effect (e.g., beneficial or adverse) is analytically unpredictable without using extremely complex mathematical formulations.

Faced with this same dilemma, the developer of the TRANSYT model (Robertson, 1969), formulated a search technique he referred to as hill climbing. As stated in Chapter 2, "hill climbing" is a misnomer, for in the TRANSYT model the objective is minimization of a combination of stops and delay, thus "valley descent" is more appropriate. In the proposed model, however, the objective is to maximize forward link opportunities so the algorithm is truly a hill climb in this application.

The principle is illustrated idealistically in Figure 3.7. The ordinate axis is aggregate forward link opportunities, or the objective function, Eq. (3.8). The abscissa is a representation of the universal set of timing elements which produce the FLOS. Although the plot suggests a continuous function, it must be stressed that this is not the case. The optimization technique proceeds as follows:

1. The initial settings are evaluated for FLOS, represented in Figure 3.7 by the set of conditions, S_1.
2. The offset of each link in the system is varied in turn by a small amount and the objective function is recalculated for each new set. When disimprovement is noted, the direction of the search reverses until a local optimum is found, depicted by set S_1^*.
3. Offsets are varied by medium or large increments specified in the input data (generally 15% or 40% of the cycle length, respectively) to force the investigation in other regions of the solution space. This is depicted by the medium jump to S_2 and the large jump to S_3 which resulted in improved local optima at S_2^* and S_3^{**}, respectively.

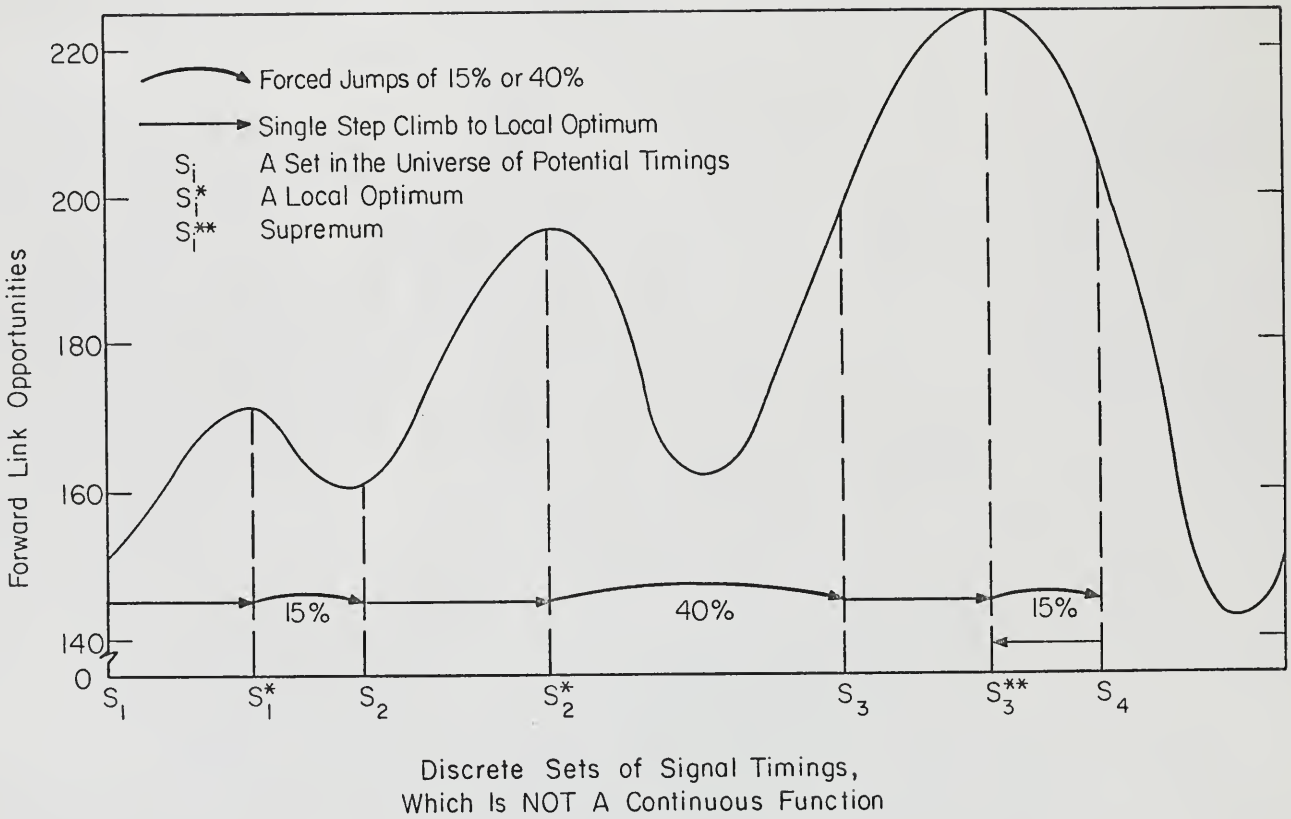


FIGURE 3.7 GRAPHICAL ILLUSTRATION OF HILL CLIMBING TECHNIQUE

4. The global optimum is the value of the objective function surviving all attempts to examine other regions. In the simplified graphical example, a jump was made to S_4, but the objective function was lower and the solution converged on S_3^{**}.

The above process completely describes the optimization technique employed in the forward link opportunities model. To implement this model, the TRANSYT6C model was modified to substitute the forward link opportunities objective function for the TRANSYT6C objective function (e.g., the Performance Index, see Chapter 2 and Appendix B) in the hill climbing routine.

Four subroutines were added to the existing program to accomplish the calculation of the FLOS objective function. Another subroutine was added to calculate a new measure of effectiveness--namely, percentage of arrivals on the red signal (derived from Courage and Parapar, 1975). A sixth subroutine was added to plot a time-space diagram, which was not in the existing program. A generalized flow chart of the program is shown in Figure 3.8.

A detailed description of all program modifications to achieve the FLOS model is given in Appendix C. As noted therein, certain other modifications were implemented to improve the output formats of the existing program.

The TRANSYT6C/FLOS model is fully operational. The new model fully retains all of the existing capabilities of the TRANSYT6C model and includes either analysis of, or optimization upon, the forward link opportunities. There are no restrictions on the model's use as a network model (TRANSYT6C) without consideration of forward link opportunities.

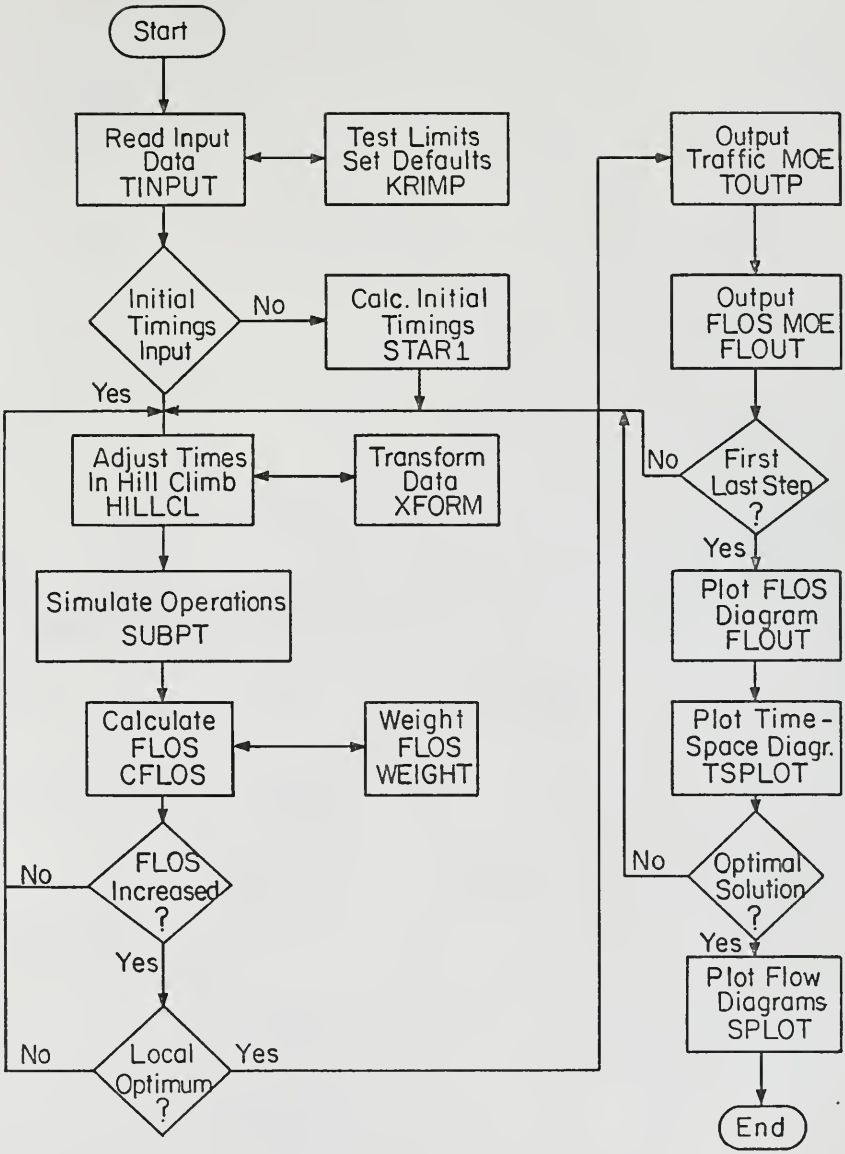


FIGURE 3.8 GENERALIZED FLOW DIAGRAM OF THE TRANSYT6C/FLOS MODEL

When FLOS are included in the analysis, the following restrictions apply to the present model:

1. Only a one-dimensional (e.g., linear) network configuration may be modeled.
2. Link-node numbering must conform to a specified format, but such a practice is generally preferred in any case.
3. No grouping of nodes or sharing of links by various distinct classes of traffic is allowed (both are available in the normal network model).
4. Variation of green splits is permitted, but minimum design greens must be generated externally to conform to the constraint expressed in Eq. (3.11).
5. No priority lane or demand response functions of the original model may be exercised.

The following limitations, inherent to the original TRANSYT6C model, remain similarly in the new model:

1. Cycle length may not be internally varied. Multiple runs, with corresponding changes to input data, are required to examine different cycle lengths.
2. Phasing of signal displays may not vary within a given run; however, any reasonable phasing can be modeled.

A variety of FLOS weighting factors or functions and alternative objective functions are available. These are identified in Appendix C. Since Chapter 5 is devoted to investigations of such alternatives, further discussion in the text is deferred to that chapter. Further potential improvements are noted in Chapter 6.

CHAPTER 4

COMPARISON OF THE FORWARD LINK OPPORTUNITIES AND OPTIMAL BANDWIDTH OPTIMIZATION STRATEGIES

Introduction

This chapter contains a detailed comparison of the forward link opportunities (FLOS) optimization strategy with the maximal bandwidth strategy. Its purpose is to demonstrate that, for similar conditions, the FLOS optimization strategy produces offsets which provide progressive opportunities equal to or superior to a maximal bandwidth optimization.

Equivalent physical and traffic conditions for several typical arterial configurations are tested. The tools for optimizing under the two methods utilize the newly developed TRANSYT6C/FLOS model, described in Chapter 3 and in Appendix C, and the PASSER II model described in Chapter 2 and Appendix A.

All comparative measures of effectiveness (MOE) are produced by the TRANSYT6C/FLOS model, which calculates MOE for both the maximal bandwidth optimal solution and the FLOS optimal solution.

Experimental Design

Both the maximal bandwidth and FLOS optimization strategies are time-space solutions to a progressive design. In Chapter 3, four elements were identified as components of a progression design. These are signal offsets, cycle length, splits and phasing pattern. In a direct comparison of the two methodologies, the only parameter which should be allowed to vary is offsets. To allow the remaining parameters to vary would result in a biased comparison. This is not to say that a FLOS

optimization of these other parameters would not result in their differing from a maximal bandwidth optimization. Indeed, variation of green splits is treated in Chapter 5.

The principal question addressed in this chapter is whether the signal offsets can be realigned to provide improved forward link opportunities compared to a maximal bandwidth solution, all other considerations being equal. Accordingly, all tests in this chapter are limited to fixed conditions with respect to cycle length, splits and patterns, as well as the fixed physical and traffic characteristics.

Test Systems

The number of signals in a given system is likely to have a perceptible effect on the relative solutions from these two strategies. Five typical arterials are tested. All five are actual arterial highways for which data were readily available to the author. The characteristics of the five systems are summarized in Table 4.1.

All test facilities are geometrically and functionally similar, but they differ in the average spacing of intersections, configuration of intersections and traffic demands. They represent a typically diverse set of test conditions.

Evaluation Methodology

For a given system configuration, the following sequence is exercised:

1. The base geometric and traffic conditions are exercised for the maximal bandwidth solution using the PASSER II model.
2. The cycle length, splits and phasing patterns, along with comparable base data, are input to the TRANSYT6C/FLOS model. Since this model analyzes the initial input conditions, the

TABLE 4.1 CHARACTERISTICS OF TEST ARTERIAL SYSTEMS

DATA SET NAME	CITY	ARTERIAL (LIMITS)	NO. AND TYPES OF INTERSECTIONS[a]		LENGTH (AVERAGE SPACING)	DESCRIPTION
BUF	Tampa, FL	Buffalo Ave. (Highland to Nebraska)	6	3W-4 4W-2	3,450 (690)	Partially divided 4 lane urban arterial with left-turn bays at all major intersections.
SR26	Gainesville, FL	SR26, Newberry Rd. (Tower Rd. to NW 8 Ave.)	8	T-6 4W-2	7,230 (1,033)	Divided 4 lane suburban arterial with left-turn bays at all major intersections on artery.
SR7.2	Ft. Lauderdale, FL	SR7 (Orange Dr. to Hallendale Bch. Blvd.)	12	T-1 4W-11	29,900 (2,718)	Divided 4 lane urban arterial with left-turn bays at all major intersections.
BED	Detroit, MI	Beech Daly (7 Mile Rd. to Kennedy St.)	16	T-4 3W-2 4W-9 J-1	32,250 (2,150)	Divided 4 lane urban arterial with left-turn bays at all intersections on the artery and major cross streets.
SR7.1	Ft. Lauderdale, FL	SR7 (Kimberly Blvd. to Broward Blvd.)	20	T-7 3W-2 4W-10 J-1	34,450 (1,813)	Divided 4 lane urban arterial with left-turn bays at all major intersections.

a. Type intersections: T = tee intersection, 3W = 3-way (cross street one-way), 4W = 4-way, J = skewed.

offsets from the maximal bandwidth solution are input as well; thus, the PASSER II solution is analyzed completely.

3. TRANSYT6C/FLOS then optimizes for unweighted forward link opportunities by varying the offsets, and produces the resulting MOE.

Results of the tests are presented in tabular form. The MOE of interest are identified below.

Unweighted forward link opportunities (FLOS) are reported in their actual values, as calculated by Eq. (3.5). Improved progression should increase the FLOS.

The progression quality ratios (PQR) corresponding to the ratios of actual FLOS to the several control values are calculated according to Eqs. (3.6 and 3.7). The PQR defined by FLOS/CFLS, where CFLS are the cycle forward links, is similar to the bandwidth efficiency (see Chapter 3). But here, it is the ratio of actual FLOS to the total forward link opportunities potentially available in a cycle, in the absence of any signal control. The PQR defined by FLOS/TFLS, where the latter are the through-only forward links, is a measure of the partial progression opportunities existing outside the through bands. As their names imply, the ratios should increase with improved progression.

Delays in vehicle-hours per hour (veh-hr/hr) are reported for the through-only movements on the artery and for the total system, including cross street traffic. With improved progression, delay should decrease on the artery, and thus, in the entire system.

Stops are presented in terms of percentages of vehicles stopped, first for only the through movements on the artery and secondly, for the entire system. As in the case of delay, the number (or percentage) of stops should decrease as progression is improved.

The percentage of arrivals on the red signal phase is related to the number of stops, although the relationship is not linearly proportionate. Still, improved progression should result in a reduced proportion of the through traffic arriving during the red phase. (The percent red arrivals is reported in lieu of the more positive percent green arrivals to reduce confusion in the comparisons. Thus, all three traffic measures, delay, percent stops and percent red arrivals should decrease with improved progression.)

Because it is theoretically possible that optimization upon FLOS may cause a change in through bandwidth, these are reported as well, along with the bandwidth efficiency and attainability, as defined for the PASSER II model. Other measures are discussed as needed to qualify specific results, and several peculiarities inherent to either the FLOS concept, or the limitations of the TRANSYT6C (and thus, TRANSYT6C/FLOS) model, are noted as appropriate.

In the following sections, references are occasionally made to direction of travel. For simplicity, all systems should be viewed as being laid out from left to right, regardless of actual orientation, where "right-bound" is taken as the "A" direction as defined in the discussion of the PASSER II model in Appendix A (also see Figure C.1 in Appendix C).

Analysis of Alternative Arterial Configurations

Six-Signal System

A typical six-signal system is Buffalo Avenue in Tampa, Florida (see data set BUF in Table 4.1). Results of the maximal bandwidth and FLOS optimizations for this system are presented in Table 4.2.

TABLE 4.2 COMPARATIVE RESULTS OF MAXIMAL BANDWIDTH AND FLOS OPTIMIZATIONS FOR BUFFALO AVENUE (SIX-SIGNAL SYSTEM)

MOE	MAXIMAL BANDWIDTH	NORMAL FLOS	PERCENT DIFFERENCE
Cycle Length (sec)	60	60	-
Bandwidths (sec)	42	43	2.4
Efficiency (%)	35	36	-[a]
Attainability	0.98	1.00	2.0
FLOS	675	684	1.3
PQR = FLOS/CFLS	0.37	0.38	-
PQR = FLOS/TFLS	1.07	1.06	-0.9
Delay (veh-hr/hr):			
Through on Artery	21.0	21.1	0.5
Total System	46.0	46.0	0
Percent Stops:			
Through on Artery	52.6	51.5	-2.1
Total System	62.2	61.3	-1.4
Percent Red Arrivals	41.0	40.4	-1.5

a. Percent differences for these values are not given in this and subsequent tables because round-off errors would produce different numerical values. The percent changes are actually as indicated for bandwidths and FLOS, respectively.

This example resulted in very limited improvement in the number of FLOS when the maximal bandwidth solution was further optimized for the new measure. Indeed, there was effectively no improvement in the progression quality ratio of FLOS to cycle forward links (CFLS).

The FLOS optimization resulted in one interesting occurrence--the bandwidth was increased by one second, specifically in the right-bound band (from 20 to 21 seconds). This increase, of a supposedly already maximum bandwidth, does not suggest that PASSER II fails to achieve a maximal bandwidth solution, but is due to the fact that the PASSER II model deals internally in real values of time, while TRANSYT6C/FLOS deals in integer values of time. This occasionally allows the TRANSYT6C/FLOS model to produce bands that vary slightly from PASSER II because of roundoff. In this and all subsequent tests, if in the first simulation of a PASSER II solution, the bandwidth calculated by TRANSYT6C/FLOS is less than that calculated by PASSER II, offsets are changed to correct for roundoff error so that the timing ultimately used produces at least the same bandwidths as PASSER II.

The increased bandwidth explains the slight decline in the ratio of total FLOS to through forward link opportunities (FLOS/TFLS). The through FLOS were proportionately higher than the increase in total FLOS for the system in the right-bound band.

Regarding the more traditional traffic engineering measures, a very slight increase in delay to through traffic on the artery is observed, despite slight decreases in both the percentages of stops and arrivals on red. Total delay in the system remained unchanged, however, suggesting that increased delay to some through traffic was offset by decreased delay to some turning traffic. Delay to cross-street traffic is unaffected

by any changes in offsets because their proportion of green time remains the same. But why has delay increased for some through traffic despite marginally improved forward link opportunities and a slightly wider through band in one direction?

The phenomenon suggested by the above question is significant to this research. Considering that FLOS optimization considers only the relative alignment of green phases (as does PASSER II in determining offsets), it is entirely possible that a shift in an offset can result in greater delay because a more highly concentrated portion of a platoon may arrive on the red signal, particularly at the leading edge of the through band. Indeed, this occurred in the present example on one link which experienced an 8% increase in delay due to a 2% increase in the proportion of red arrivals. This increase in red arrivals was not offset by other declines in delay to through traffic; although, as stated earlier, it was offset by decreases to turning traffic which resulted in no change in the total delay in the system.

In summary, the comparison of maximal bandwidth and forward link opportunity optimizations on a small system of six signals produced virtually no differences in the two solutions despite the occurrence of an adverse phenomenon in the FLOS optimization. The quality of progression was negligibly improved by the FLOS optimization.

Eight-Signal System

A slightly larger system of eight signals on State Road (S.R.) 26 in Gainesville, Florida, was tested similarly. The results of this study are summarized in Table 4.3.

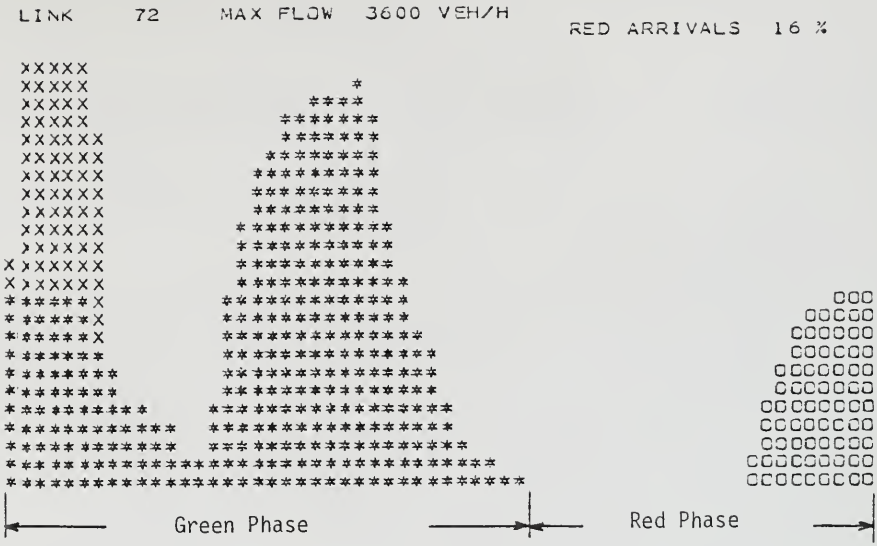
In this example, a more discernible improvement in the quality of progression was realized after the maximal bandwidth solution was further

TABLE 4.3 COMPARATIVE RESULTS OF MAXIMAL BANDWIDTH AND FLOS OPTIMIZATIONS FOR S.R. 26 (EIGHT-SIGNAL SYSTEM)

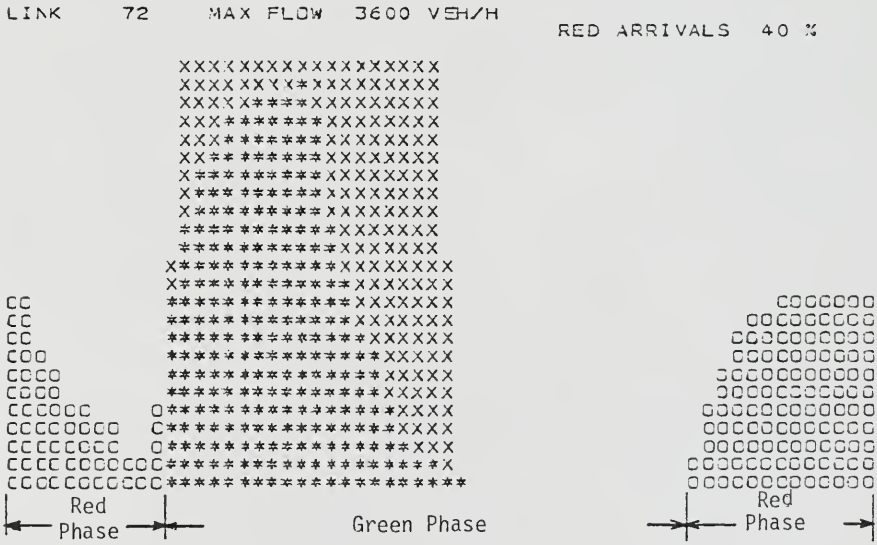
MOE	MAXIMAL BANDWIDTH	NORMAL FLOS	PERCENT DIFFERENCE
Cycle Length (sec)	98	98	-
Bandwidths (sec)	52	52	0
Efficiency (%)	27	27	-
Attainability	1.00	1.00	0
FLOS	1,978	2,131	7.7
PQR = FLOS/CFLS	0.36	0.39	-
PQR = FLOS/TFLS	1.35	1.46	8.1
Delay (veh-hr/hr):			
Through on Artery	33.5	33.8	0.9
Total Systems	67.8	66.8	-1.5
Percent Stops:			
Through on Artery	35.8	34.5	-3.6
Total Systems	46.0	45.0	-2.2
Percent Red Arrivals	26.7	23.7	-11.2

optimized by maximizing FLOS. The raw number of FLOS increased about 8%, thus FLOS/CFLS increased from 0.36 to 0.39. The improvement of partial progression opportunities outside the through bands increased similarly in their aggregate. If only nonthrough FLOS are considered (i.e., counting only those FLOS outside the through bands, or FLOS - TFLS), these additional opportunities increased from 515 to 668, or 30%.

The proportions of through vehicles stopped or arriving during the red signal declined, as did all stops in the system. But, once again, the delay to through traffic increased slightly (1%) despite a nearly 2% decrease in delay system-wide. The phenomenon described earlier was repeated in this case, but even more dramatically. On a single link delay increased from 0.85 veh-hr/hr to 5.78 veh-hr/hr, or 680%. This was due to an increase in red arrivals from 16% to 40%. Because this case is far more dramatic than the previous one on Buffalo Avenue, a graphical illustration of the effect of such a shift in red arrivals is warranted. Figure 4.1 shows the arrival and departure patterns at the end of the subject link (link 72) for the maximal bandwidth solution (top) and the maximal FLOS solution (bottom), from the patterns produced by TRANSYT6C. Shifting the start of green on this approach relative to the upstream signal resulted in substantially more queuing as the departure pattern indicates, despite very little change in the arrival pattern. According to TRANSYT6C's analysis, the average maximum queue increased from five to thirteen vehicles per cycle. This is despite a significant increase (from 146 to 196, or 34%) in the FLOS at this link. Unfortunately, the additional FLOS occur during a period when virtually no traffic is arriving (i.e., the later portion of the green period which has negligible arrivals).



Maximal Bandwidth Solution



Maximal FLOS Solution

FIGURE 4.1 ARRIVAL AND DEPARTURE PATTERNS ON LINK 72 OF THE S.R. 26 SYSTEM UNDER MAXIMAL BANDWIDTH AND FLOS OPTIMIZATIONS

Thus, generally reduced delays on the remaining through links did not offset this extremely high increased delay on link 72. Additional time savings on other non-through links (e.g., those assigned to left-turning traffic) did compensate for the single major problem.

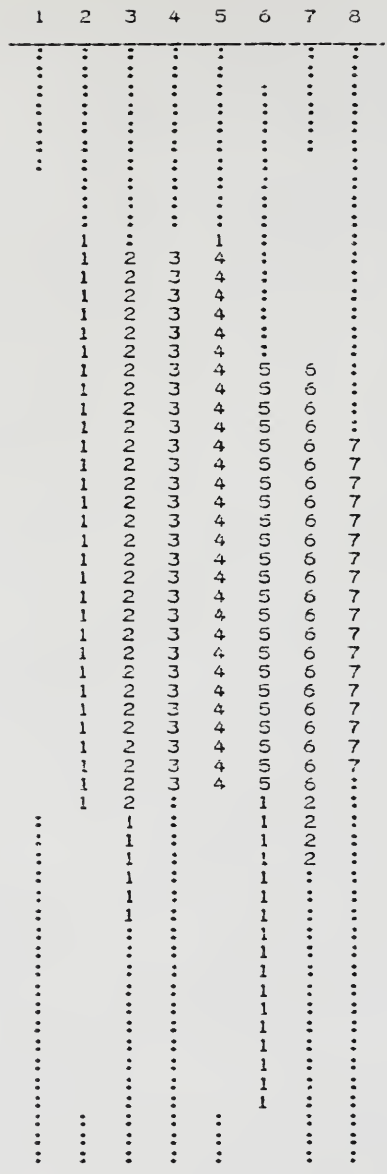
Most of the increased FLOS actually occurred in the left-bound direction and the FLOS diagrams for this direction are given in Figure 4.2 for both the maximal bandwidth and FLOS solutions, for comparison. As noted above, link 72 (intersection seven) experienced a large part of the increased FLOS.

Summarizing this example, a more appreciable improvement in the quality of progression was observed on this system when FLOS were optimized beyond the maximal bandwidth solution. A severe problem resulted at one intersection, however. This problem notwithstanding, all system-wide MOE improved under FLOS optimization.

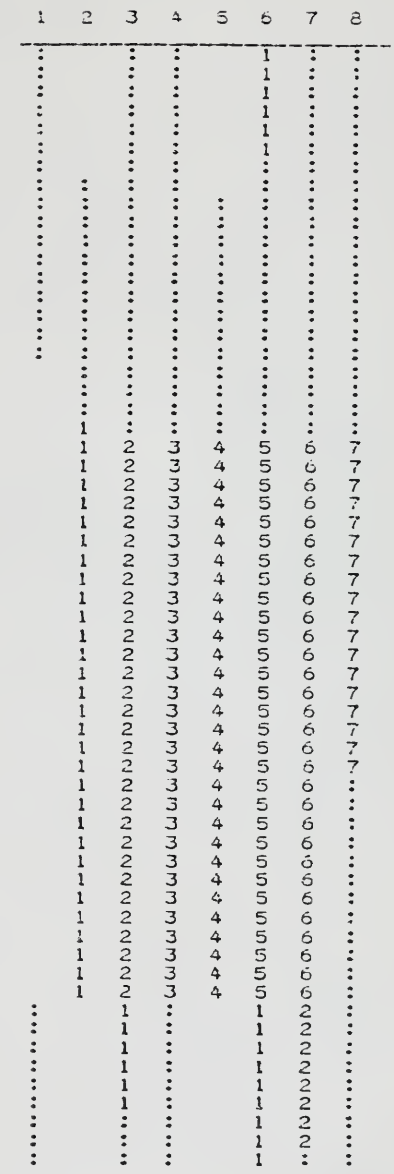
Twelve-Signal System

The test facility discussed below is a section of State Road (S.R.) 7, also U.S. 441, in Ft. Lauderdale, Florida. This test raises an issue that constitutes a minor limitation of the TRANSYT6C model, namely the computational resolution of the model. Since the new model is based upon the frame of the original TRANSYT6C model, this limitation carries forward. The issue is discussed with the description of the test results, which are summarized in Table 4.4.

First reviewing the results of this test outright, there was a negligible increase in FLOS and the corresponding progression quality ratio under FLOS optimization, but a slight increase in all the traffic-related MOE, including total delay in the system. These results suggest that the PASSER II solution, as analyzed by the TRANSYT6C/FLOS model, is very close to an ideal optimum.



Maximal Bandwidth



Maximal FLOS

FIGURE 4.2 FLOS DIAGRAMS FOR THE LEFT-BOUND DIRECTION ON S. R. 26 FOR THE MAXIMAL BANDWIDTH AND FLOS OPTIMIZATIONS

TABLE 4.4 COMPARATIVE RESULTS OF MAXIMAL BANDWIDTH AND FLOS OPTIMIZATIONS FOR S.R. 7 (TWELVE-SIGNAL SYSTEM)

MOE	MAXIMAL BANDWIDTH	NORMAL FLOS	PERCENT DIFFERENCE
Cycle Length (sec)	102	102	-
Bandwidths (sec)	34[a]	36	5.9
Efficiency (%)	17[a]	18	-
Attainability	0.74[a]	0.75	1.4
FLOS	1,720	2,762	1.5
PQR = FLOS/CFLS	0.20	0.21	-
PQR = FLOS/TFLS	1.15	1.17	1.7
Delay (veh-hr/hr):			
Through on Artery	90.9	92.2	1.4
Total System	210.6	212.0	0.7
Percent Stops:			
Through on Artery	63.8	65.9	3.3
Total System	72.3	73.4	1.5
Percent Red Arrivals	48.5	48.8	0.6

a. These values are based directly on PASSER II output, the remainder of this column are based on the TRANSYT6C/FLOS analysis of this condition with the bandwidth, efficiency, and attainability as indicated for the FLOS optimization.

As noted in Table 4.4, the bandwidths calculated by PASSER II totaled 34 seconds (16 seconds right-bound and 18 seconds left-bound). Since TRANSYT6C operates in steps rather than seconds (see Appendix B), with a maximum of 60 steps per cycle, the resolution of a 102 second cycle is reduced. Indeed, neither 16 nor 18 seconds can be achieved exactly, given a conversion factor of 1.7 seconds per step. The signal timing input to the TRANSYT6C/FLOS model thus produces bandwidths one second greater than the PASSER II solution, in each direction.

It would not be meaningful to simulate a condition wherein the initial bandwidths resulting from a TRANSYT6C/FLOS analysis were less than those produced by PASSER II (namely, 15 and 17 seconds, respectively). This could be easily accomplished by shifting one or two offsets, but such a move is arbitrary, and further, the FLOS optimization would converge on the same solution reported earlier.

The salient conclusion resulting from this test is that the maximal forward link opportunities solution was effectively no better than the maximal bandwidth solution in terms of the progression opportunities; and indeed, the shifts in offsets had a minimally detrimental effect on stops and delay.

Sixteen-Signal System

A somewhat larger arterial system, in terms of the number of intersections, was tested for data from Beech Daly Road in Detroit, Michigan, although the signal spacing is 21% less than the previous example.

The comparative results are summarized in Table 4.5. These results are not particularly dissimilar from the previous test in terms of the absolute magnitudes of the proportional changes. But, here all indicators tended in the direction of total improvement, albeit the improvements

TABLE 4.5 COMPARATIVE RESULTS OF MAXIMAL BANDWIDTH AND FLOS OPTIMIZATIONS FOR BEECH DALY ROAD (SIXTEEN-SIGNAL SYSTEM)

MOE	MAXIMAL BANDWIDTH	NORMAL FLOS	PERCENT DIFFERENCE
Cycle Length (sec)	87	87	-
Bandwidths (sec)	35[a]	36	2.9
Efficiency (%)	21[a]	21	-
Attainability	0.60	0.60	0
FLOS	5,574	5,574	1.6
PQR = FLOS/CFLS	0.27	0.27	-
PQR = FLOS/TFLS	0.52	0.53	1.9
Delay (veh-hr/hr):			
Through on Artery	94.8	93.6	-1.3
Total System	209.0	208.3	-0.3
Percent Stops:			
Through on Artery	51.1	49.9	-2.3
Total System	61.6	60.8	-1.3
Percent Red Arrivals	35.8	34.9	-2.5

a. These values are based directly on PASSER II output, the remainder of this column are based on the TRANSYT6C/FLOS analysis of this condition with the bandwidth, efficiency, and attainability as indicated for the FLOS optimization.

were minor. Once again the roundoff error due to the lower resolution of the TRANSYT6C/FLOS model has occurred. Indeed, the original bandwidths in the PASSER II solution were 17 and 18 seconds for the right- and left-bound directions, respectively. These were converted to 17 and 19 seconds, respectively, in the PASSER II solution, as simulated by TRANSYT6C/ FLOS. The final bandwidths were 16 and 20 seconds after FLOS optimization. In this case, the FLOS optimization caused a slight (1 second) decrease in bandwidth, which, as was stated earlier, is not an unexpected occurrence.

Twenty-Signal System

The largest system that can be analyzed by PASSER II is a twenty signal system. Because of this, the TRANSYT6C/FLOS model was written with a similar maximum (although it is expandable, up to 50 signals, at considerable increase in run time, as explained in Appendix C).

The site used for this test is also a section of State Road (S.R.) 7, or U.S. 441, in Ft. Lauderdale, but this section is mutually exclusive of the twelve-signal system. The results of the test are given in Table 4.6.

In this case all measures showed discernible improvement when FLOS optimization was applied to the PASSER II solution. The most significant improvements were realized in the right-bound direction where FLOS increased by 8% (5,254 to 5,658); delay and the fraction of red arrivals decreased for through traffic on the artery by 9% and 11%, respectively; and the number of through stops decreased by 6%.

The FLOS diagrams for the two solutions are shown in Figures 4.3 and 4.4. The staggered alignment of the right-bound greens, particularly

TABLE 4.6 COMPARATIVE RESULTS OF MAXIMAL BANDWIDTH AND FLOS OPTIMIZATIONS FOR S.R. 7 (TWENTY-SIGNAL SYSTEM)

MOE	MAXIMAL BANDWIDTH	NORMAL FLOS	PERCENT DIFFERENCE
Cycle Length (sec)	106	106	-
Bandwidths (sec)	51	51	0
Efficiency (%)	24	24	-
Attainability	0.88	0.88	0
FLOS	11,150	11,719	5.1
PQR = FLOS/CFLS	0.28	0.29	-
PQR = FLOS/TFLS	0.56	0.59	5.4
Delay (veh-hr/hr):			
Through on Artery	158.1	146.8	-7.1
Total System	384.7	374.9	-2.5
Percent Stops:			
Through on Artery	47.8	46.1	-3.6
Total System	58.6	57.2	-2.4
Percent Red Arrivals	34.9	32.4	-7.2

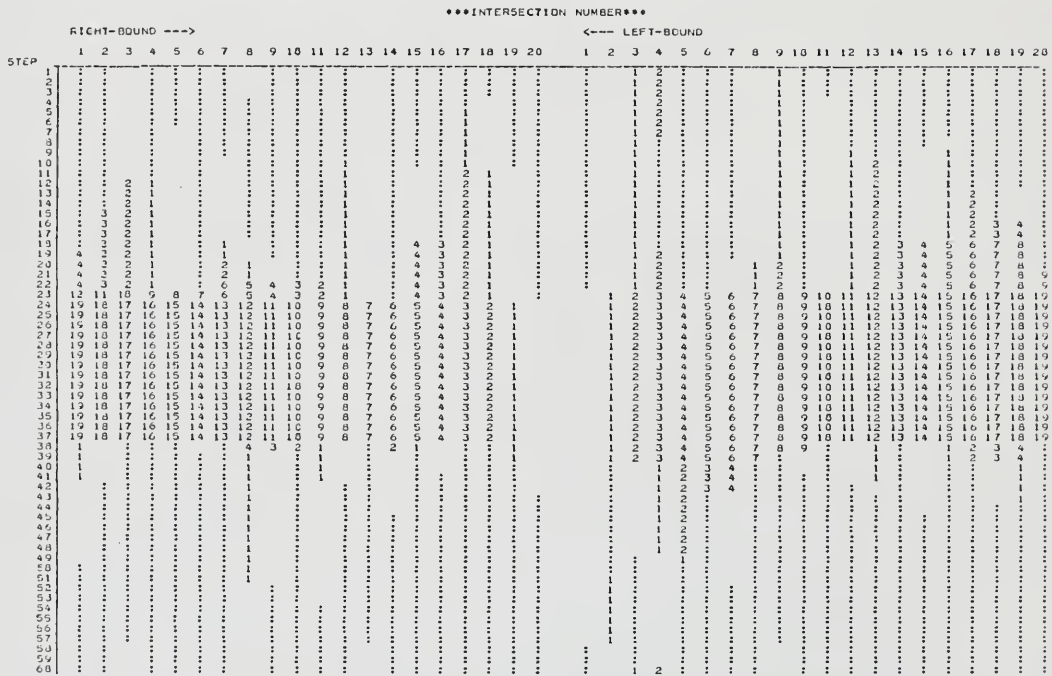


FIGURE 4.3 FLOS DIAGRAM FOR THE TWENTY-SIGNAL SYSTEM--MAXIMAL BANDWIDTH SOLUTION

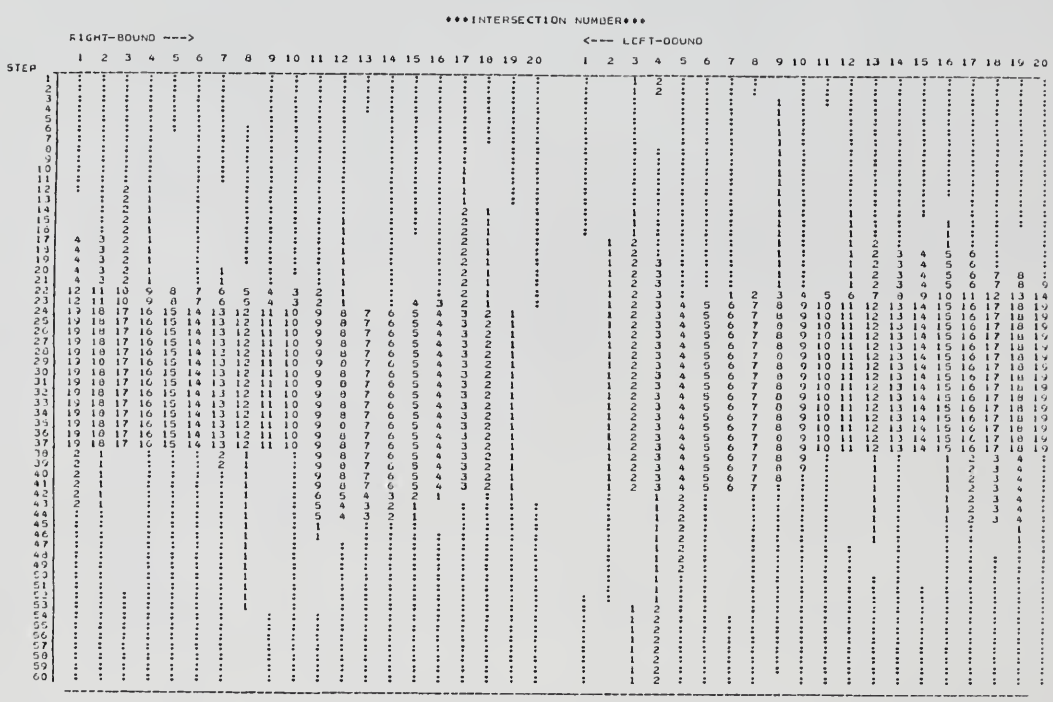


FIGURE 4.4 FLOS DIAGRAM FOR THE TWENTY-SIGNAL SYSTEM--MAXIMAL FLOS SOLUTION

from intersections twelve through twenty of the maximal bandwidth solution (Figure 4.3), has been smoothed considerably in Figure 4.4 to account for most of the improvement. The net increase in nonthrough FLOS in this direction was 72%. The change in nonthrough FLOS leftbound was 19%, for a net total increase of 40%.

Trend Analysis

Comparing the relative results of the foregoing tests revealed no discernible trends in the relationships between FLOS, delay, stops or the percentage of red arrivals. The five case studies were sufficiently diverse in nature that the results would appear to depend largely upon the particular geometric and traffic compositions of the various test sites.

An apparent trend emerged which relates the percentage change in forward link opportunities (between the maximal bandwidth and FLOS optimizations) with the dispersion of signals in the system. Table 4.1 contains the average intersection spacings of the five sites, and observation of these indicates a good deal of variance among them. Average spacing itself had no discernible correlation with the comparative optimal solutions; however, if the variation of signal spacing within the systems is considered, a trend is observed. Since the average spacings differ in magnitude, the coefficient of variation (ratio of the standard deviation to the mean) is used as a normalized measure of signal dispersion. Plotting the coefficients of variation against the percent change in FLOS results in the trend shown in Figure 4.5.

The plot suggests that in systems having more uniformly spaced signals, the improvement that may be achieved under FLOS optimization, compared to maximal bandwidth optimization, will tend to increase. This

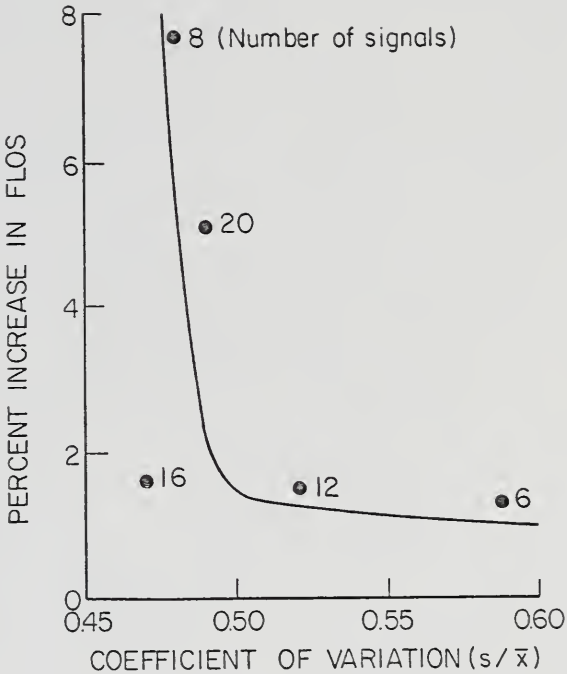


FIGURE 4.5 TENDENCY BETWEEN IMPROVEMENTS IN FLOS AND COEFFICIENT OF VARIATION OF SIGNAL SPACING

is logically explained in the nature of time-space relationships. Namely, highly irregular spacings would tend to constrain the flexibilities of the offsets, thus, reducing the potential for improving signal offsets for forward link opportunities over the maximal bandwidth solution.

A specific test supports this contention. The example for twelve traffic signals, State Road 7 in Ft. Lauderdale, Florida, experienced the poorest degree of improvement among the five sites, all measures considered. This arterial system had the largest average signal spacing as well as the largest variation of signal spacing (1410 feet, compared to a range of 410 feet to 1000 feet for the remaining sites). One link in particular is extremely long (6170 feet), which is 2.5 times the length of the remaining links. For the purpose of demonstration, this excessively long link was reduced by one-half and the system was tested as before, with the results shown in Table 4.7. Comparing these results with Table 4.4, which is the analysis based on actual geometric conditions, the adjusting of one excessively long link length to reduce the variation of link lengths has reversed all the earlier negative trends in traffic operations and the improvement in FLOS was doubled, relatively speaking.

No mathematical relationship is hypothesized about the above findings. Extensive testing would be required with additional data to establish a firm relationship. On the other hand, it appears both reasonable and rational to conclude that forward link opportunities are likely to be more productive in more uniformly spaced signal systems.

Summary

The foregoing tests demonstrated that, for various sets of conditions, optimizations of signal offsets upon forward link opportunities

TABLE 4.7 COMPARATIVE RESULTS OF MAXIMAL BANDWIDTH AND FLOS OPTIMIZATIONS FOR S.R. 7 (TWELVE-SIGNAL SYSTEM WITH ONE DISTANCE REDUCED)

MOE	MAXIMAL BANDWIDTH	NORMAL FLOS	PERCENT DIFFERENCE
Cycle Length (sec)	102	102	-
Bandwidths (sec)	34[a]	35	2.9
Efficiency (%)	17[a]	18	-
Attainability	0.74[a]	0.75	1.4
FLOS	2,686	2,780	3.5
PQR = FLOS/CFLS	0.20	0.21	-
PQR = FLOS/TFLS	1.20	1.18	-1.8
Delay (veh-hr/hr):			
Through on Artery	84.6	84.2	-0.5
Total Systems	208.5	205.9	-1.2
Percent Stops:			
Through on Artery	62.2	61.4	-1.3
Total System	70.7	69.9	-1.1
Percent Red Arrivals	47.1	46.8	-0.6

a. These values are based directly on PASSER II output, the remainder of this column are based on the TRANSYT6C/FLOS analysis of this condition with the bandwidth, efficiency, and attainability as indicated for the FLOS optimization.

were virtually equal to or superior to the maximal bandwidth optimizations in terms of the time-space relationships among signals. When compared with the maximal bandwidth optimizations, FLOS optimizations increased the number of forward link opportunities from over 1% to nearly 8%. Monodirectional improvements were naturally higher.

In the majority of cases, the overall quality of traffic flow, measured in terms of stops and delays, was similar or improved. In isolated cases (and at one location in particular, the twelve-signal system), the traffic measures declined slightly; but a rationale was presented to explain this phenomenon. It was demonstrated that shifts in offsets may have a deleterious effect on certain approaches which may result in unsatisfactorily large numbers of stops and, thus, increased delay. This may occur even if the percentage of arrivals during the red phase is unaffected or reduced. This phenomenon is covered further in the next chapter.

Several computational limitations of the TRANSYT6C/FLOS model in its present form have been identified. These may affect the resolution of the signal timing, particularly under conditions of long cycle lengths.

On balance, however, substantial improvements were generally gained in the regions outside the through bands, where the only areas for real improvements exist. Considering the five cases collectively, as a measure of overall potential of the new model, both the quality of progression as well as the quality of traffic operations improved under the FLOS optimization concept. The FLOS optimization concept would, therefore, appear to have merit as a design strategy for progressive signalization.

CHAPTER 5

EXTENDED APPLICATIONS OF THE FORWARD LINK OPPORTUNITIES MODEL

Introduction

The previous chapters have demonstrated that the concept of maximizing forward link opportunities to effect progressive signal designs is conceptually and functionally feasible. Chapter 4, which included tests of five typical system configurations, demonstrated that the alteration of signal offsets alone can provide improved progression opportunities. In addition, these evaluations have demonstrated that the FLOS optimization strategy can improve system operations in most circumstances tested. Finally, the TRANSYT6C/FLOS model clearly has potential as a useful design and analysis tool in the traffic engineering profession.

In this chapter, the capabilities of the FLOS concept are expanded through the use of capabilities existing in the TRANSYT6C/FLOS model.

The major concepts covered are the weighting of forward link opportunities (FLOS) by various physical and traffic aspects, variations in the explicit FLOS objective function and extended applications of the model. Certain of these extended applications of the TRANSYT6C/FLOS model identify solutions to the problem observed in Chapter 4 of shifting offsets that serve to increase delay and stops.

To insure continuity and consistency with earlier investigations, the precepts of the PASSER II and TRANSYT6C models and their theoretical bases continue to be promulgated in these investigations.

Weighting by Physical and Traffic Aspects

Forward link opportunities or their relationship to other system opportunities are important measures of the overall quality of progression on an arterial highway. Other considerations, however, might suggest the favoring of various other elements of the system. The weighting policies are discussed below (also see Appendix C).

Weighting by Link Length

The distance of unimpeded travel on a given link is important to the motorist who values total time spent traversing a section of highway. Specifically, a time-conscious driver may tend to be more satisfied having successfully passed through an intersection which enabled him to travel a more significant portion of his trip, than on a short section where the potential of being stopped shortly downstream is more evident. Consequently, the weighting of individual intersection FLOS by the lengths of the downstream links would seem to be of importance. The formulation of this weighting for one direction only (and assuming time is in seconds) is,

$$\text{FLOS(link-length)}_r = \sum_{i=1}^{N} \sum_{t=1}^{C} \text{FLOS}_{it} \times l_{i+1} \; ; \qquad (5.1)$$

where l_{i+1} = length of link i+1, and

the rest as before.

This weighting strategy was applied on three of the data sets that were examined in Chapter 4 (the six, eight and twelve-signal systems). These three conditions were used because the results of normal FLOS optimizations in Chapter 4 were not totally consistent. The two larger systems of sixteen and twenty signals yielded more consistent results in

the earlier application and thus, would not be expected to benefit as much from weighting. Summarized results from weighting the three smaller systems, comparing the percentage change in aggregate MOE from the maximal bandwidth solution to the FLOS solution, with and without weighting, are listed in Table 5.1. The optimal solution for FLOS weighted by link length was virtually the same as the solution for unweighted FLOS in the two smaller systems. In the twelve-signal system, the adverse results reported earlier diminished slightly. But the small increase in FLOS under unweighted FLOS optimization was decreased even more under distance-weighted FLOS.

It would thus appear that this weighting strategy has little practical value in the systems examined.

Weighting by Platoon Dispersion Factor

The complement of the above weighting strategy is one that weights FLOS by the inverse of link length. This weighting accounts for the motorist's desire to successfully traverse several closely spaced signals, as opposed to successfully passing through only one intersection, even though the passage enabled a perceived time savings. This policy would tend to have a more rational basis in theory as well. As spacing between intersections increases, dispersion of traffic increases (Hillier and Rothery, 1967). There is also a greater tendency for traffic to operate in a manner more common to isolated intersections than coordinated intersections where there are lengthy separations between intersections (Papapanou, 1976).

A significant advancement in deterministic simulation of traffic operations was made by Robertson (1969) in his use of the Platoon Dispersion Factor (PDF), as discussed in Chapter 2 and Appendix C. The relationship is repeated below,

TABLE 5.1 COMPARISON OF MAXIMAL BANDWIDTH, UNWEIGHTED FLOS AND LINK LENGTH-WEIGHTED FLOS OPTIMIZATIONS

	PERCENT CHANGE FROM MAX. BANDWIDTH[a]					
	6-SIGNALS		8-SIGNALS		12-SIGNALS	
MOE	UWF	WF	UWF	WF	UWF	WF
FLOS	1.3	1.3	7.7	7.7	1.5	1.0
Total Delay	0.5	-0.2	-1.5	-1.5	0.7	0.3
Total Stops	-1.4	-0.5	-2.2	-2.2	1.5	0.4

a. The abbreviated column headings in this and subsequent tables of this type are: UWF = unweighted FLOS optimization, WF = optimization under FLOS, weighted as indicated.

TABLE 5.2 COMPARISON OF MAXIMAL BANDWIDTH, UNWEIGHTED FLOS AND PDF-WEIGHTED FLOS OPTIMIZATIONS

	PERCENT CHANGE FROM MAX. BANDWIDTH					
	6-SIGNALS		8-SIGNALS		12-SIGNALS	
MOE	UWF	WF	UWF	WF	UWF	WF
FLOS	1.3	1.3	7.7	7.7	1.5	1.5
Total Delay	0.5	0.5	-1.5	-1.5	0.7	-0.5
Total Stops	-1.4	-1.4	-2.2	-2.2	1.5	-0.7

$$PDF = (1 + kt)^{-1} ; \qquad (5.2)$$

where t = link travel time and

k = a coefficient, generally 0.5.

Equation (5.2) is essentially an inverse function of link length, if the assumption of constant progression speed on the link is held. Because this factor is recognized as an important component of the TRANSYT6C simulation of traffic flow, and expresses the desired FLOS weighting strategy, it is logical to use the PDF as the explicit weighting factor.

The formulation is similar to Eq. (5.1), except that the PDF for link i+1 is substituted for l_{i+1} in Eq. (5.1).

Tests using this weighting factor were also performed on the three data sets used above (see Table 5.2). In the cases of the six and eight-signal systems, the optimal solutions were virtually identical to the solutions under unweighted FLOS.

It may be recalled that all tests of the twelve-signal system (a section of S. R. 7 in Ft. Lauderdale, Florida) have exhibited less than expected results under FLOS optimizations, except when the single excessively long link was shortened for a demonstration. When PDF-weighting is applied to the FLOS optimization of this system in its actual configuration, the negative trend is reversed, as shown in the summary results given in Table 5.2.

While the actual improvements in FLOS are identical, the net difference in total delay between normal FLOS optimization and PDF-weighted FLOS optimization is slightly over 1%. Although all the tests on this site have demonstrated very minor changes in the pertinent MOE, this exercise illustrates the fact that FLOS optimization results can be improved somewhat by applying the PDF weighting factor.

Weighting by Total Demand

Demand weighting is common in traffic engineering analysis. Since the FLOS concept in its simplest form is purely a time-space function, no consideration is given to the relative demand when optimizing offsets. It should be noted, however, that signal splits are proportioned on the basis of demand, specifically the demand to capacity ratio; thus demand is indirectly considered.

Weighting the FLOS according to demand would seem to have some intuitive appeal. The function is formulated similarly to Eq. (5.1), except the flows on the individual links are substituted for the downstream link lengths in the equation.

When this weighting was tested on the three cases presently being considered, the results indicate that the strategy does not improve the solution. No MOE were superior to those produced by normal FLOS optimization, and in several cases, both FLOS and traffic operations were adversely affected. Thus, direct weighting by link demand does not appear, in these tests, to be a significant optimization strategy. This strategy would probably be of greater significance under conditions where traffic demands are highly imbalanced with respect to direction of travel.

Weighting by Stopline Arrival Pattern

In Chapter 2, and above, the concept of platoon dispersion has been discussed. Robertson's (1969) modeling of platoon dispersion is specifically described in Appendices B and C. The effect of platoon dispersion is to predict an arrival pattern at the downstream end of a link, considering the release patterns from the upstream inputs. The release patterns are determined by the phasing (i.e., the order of release from

several approaches to the link) and by the travel time to the downstream stopline, smoothed by the PDF discussed above, also see Eq. (C.3) in Appendix C. As a result of this modeling approach, realistic momentary flow rates at the stopline may be predicted.

Another important aspect of Robertson's flow model is that, as stated previously, demand from cross streets which turn onto the artery and become part of the through traffic stream are also included in the arrival patterns. In a progressive system, link-to-link through traffic tends to form platoons which propagate downstream within the through band. Other inputs (e.g., from side streets) tend to fall between these through platoons in platoons of their own. Weighting of FLOS by the actual arrival pattern thus considers the microscopic aspects of traffic, simulating, in effect, a "real-time" condition, as influenced by activities occurring upstream of each signal.

Finally, consideration of the moving platoons in an optimization policy is analogous to the real-time, on-line control strategies described in Chapter 2. If offsets can be set to insure that the largest concentrations of traffic arrive on the green, preferably after the queue has dissipated, good operations should result. As stated in Chapter 2, this strategy often fails in real-time control systems where the cycle lengths and offsets are changed dynamically. It could be theorized, however, that the strategy would work better under fixed-time control, provided the desired progression of platoons was achievable, and given the constraints imposed by providing two-way bands.

To accomplish this, it is necessary to propagate traffic on each link, from upstream to the signal of interest, in small slices of time and to project these, more individualized, forward link opportunities downstream from their time of arrival.

The arrival, or in-flow, pattern (IFP) model is formulated for one direction as,

$$FLOS(IFP)_r = \sum_{i=1}^{N} \sum_{t=1}^{C} FLOS_{it} \times q_{it} \; ; \qquad (5.3)$$

where q_{it} = the microscopic flow rate at signal i at time interval t, a function of the upstream demand, travel time and the platoon dispersion factor (see Appendix C).

To illustrate the use of this objective function, data from State Road 26 in Gainesville, Florida, were used. The objective function of Eq. (5.3) was applied to the initial timings from the PASSER II optimal bandwidth solution. Summary results are shown in Table 5.3. Because bandwidths are quite likely to change under this optimization strategy, the changes in bandwidths are also reported, as are the percentage of through red arrivals on the artery, which are significant to this study.

The values presented are the relative effectiveness of unweighted FLOS optimization and in-flow pattern-weighted FLOS, both compared against the maximal bandwidth solution. As observed in the table, the quality of progression (measured by the number of FLOS), and the proportion of stops and through red arrivals decreased using the weighting function. This demonstrates that the proposed strategy will not fully produce the desired effects discussed above, even though total delay was reduced further by this optimization.

The constraints upon the offsets were simply too severe to permit improvements in the system design using this weighting factor alone.

TABLE 5.3 COMPARISON OF MAXIMAL BANDWIDTH, UNWEIGHTED FLOS AND IN-FLOW PATTERN-WEIGHTED FLOS OPTIMIZATIONS

MOE	PERCENT CHANGE FROM MAX. BANDWIDTH UNWEIGHTED	WEIGHTED
Bandwidths	0	0
FLOS	7.7	-2.5
Total Delay	-1.4	-2.5
Total Stops	-2.2	3.5
Through Red Arrivals on Artery	-11.2	-1.9

TABLE 5.4 COMPARISON OF MAXIMAL BANDWIDTH, UNBIASED FLOS AND LEFT-BOUND BIASED FLOS OPTIMIZATIONS

	PERCENT CHANGE FROM MAX. BANDWIDTH					
	UNBIASED			LEFT-BOUND BIASED		
MOE	RIGHT	LEFT	TOTAL	RIGHT	LEFT	TOTAL
Bandwidths	0	0	0	-21.7	0	-9.6
FLOS	1.1	12.7	7.7	-5.1	13.6	5.7
Total Delay	-	-	-1.4	-	-	-1.2
Total Stops	-	-	-2.2	-	-	-2.7
Through Red Arrivals	-17.4	-4.9	-11.2	-16.6	11.6	-2.6

The same tendency was found in similar tests on other systems. In Chapter 4, it was noted that one link in particular (see Figure 4.1) had experienced an increase in red arrivals from 16% to 40% under unweighted FLOS optimization. In the present test, the weighted FLOS optimization produced 23% red arrivals on this same link. However, this improvement was offset by disimprovements elsewhere.

These trends observed would tend to support the conclusions reported in Chapter 2 with regard to the several dynamic, real-time control systems. On the other hand, the in-flow pattern-weighted FLOS optimization strategy does have merit when considered in concert with other objective functions. This is discussed later in this chapter.

Weighting by Direction of Travel

Finally, from the designers' point of view, it may be desirable to favor one direction of travel over another, such as during peak periods, irrespective of other considerations. This policy would, for example, recognize the more critical needs of the commuter predominantly traveling in the peak direction vis-a-vis the more casual traveler driving in the direction of nonpeak period prevailing flow. The formulation is simply a modification to Eq. (5.1), or any of its other variations, as follows:

$$FLOS = W_1 \times FLOS_1 + W_2 \times FLOS_2 \; ; \qquad (5.4)$$

where W = a weighting factor for the two directions of travel and the subscripted FLOS are as before, without the directional summation.

To illustrate this weighting strategy, the State Road 26 example was optimized on FLOS with the coefficients of the right-bound and left-bound FLOS set to unity and ten, respectively. This approach would be used to favor the left-bound direction which is the primary direction

of travel in the afternoon peak period. The FLOS diagrams for the system with unbiased FLOS optimization and directionally biased optimization are shown in Figures 5.1 and 5.2, respectively. Summary results are given in Table 5.4. An unexpected outcome resulted from this test. While FLOS were increased significantly left-bound (as seen in Figures 5.1 and 5.2) and the system-wide totals of stops and delay changed only imperceptibly, the changes in percentages of red arrivals were reversed from what would be expected. Examination of the arrival patterns for the left-bound links reveals that all platoons arrived at the intersections coincidentally with the start of green, when stationary platoons were just being released. Thus, the platoons were stopped and delayed. The nearly horizontal edge of the beginning of the through band left-bound (seen in Figure 5.2) accounts for this, and this phenomenon suggests that the queue clearance strategies of the real-time models discussed in Chapter 2 would have an application in this approach, at least for the one direction.

In further support of the queue-clearance theory, it is observed that the right-bound progression pattern is funnel shaped with a large diverging band which does advance the start times of the green phases, thus clearing the queues ahead of the platoons.

This effect is not necessarily universally applicable, since the resulting FLOS for this case are constrained by the splits provided. However, it is clear that, in this example, the left-bound greens could be shifted by advancing offsets increasingly from right to left, which would rotate the left-bound funnel to a more horizontal orientation. The desired effect would thus be achieved.

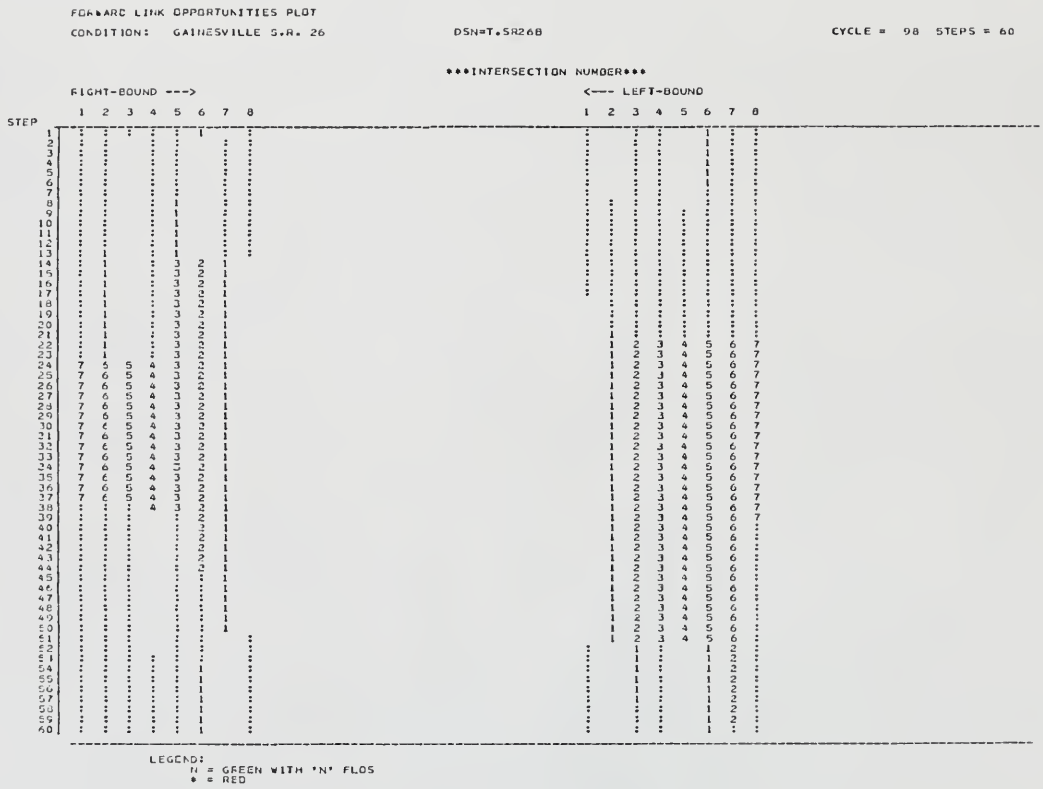


FIGURE 5.1 FLOS DIAGRAM FOR UNBIASED FLOS OPTIMIZATION ON STATE ROAD 26

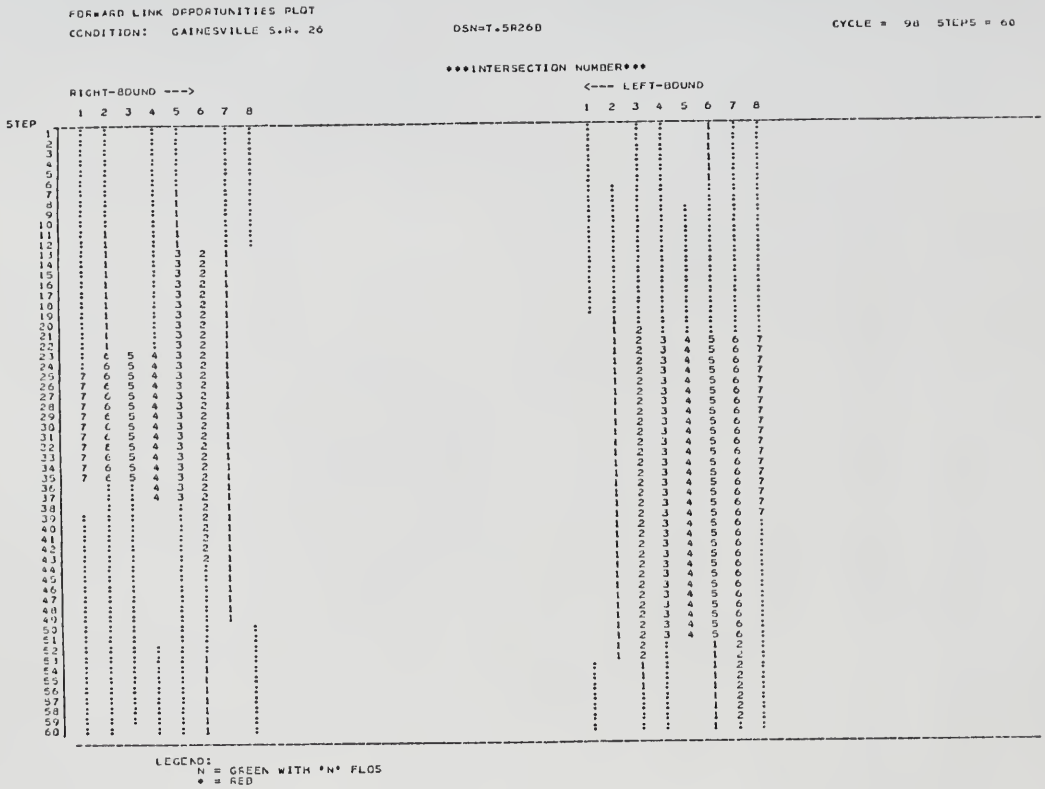


FIGURE 5.2 FLOS DIAGRAM FOR FLOS OPTIMIZATION FAVORING THE LEFT-BOUND DIRECTION ON STATE ROAD 26

This finding opens an area which has not been explicitly considered in the FLOS analysis, namely, the advancement of offsets for queue clearance. Recommendations for further research in this area are made in Chapter 6.

Alternative Objective Functions

All the weighting strategies discussed above represent alternative objective functions, but they all deal solely with the aggregate forward link opportunities. This section contains alternative objective functions available in the TRANSYT6C/FLOS model which focus on other aspects of the analysis process.

One such model is the maximization of the Progression Quality Ratio (PQR) of FLOS to cycle forward links (CFLS) which is analogous to the bandwidth efficiency MOE of the PASSER II model. Clearly, maximizing PQR = FLOS/CFLS is exactly the same as maximizing aggregate FLOS, except the MOE may have more appeal. In any case, this alternative is trivial and is not considered further.

The more meaningful functions are discussed in the sections below.

FLOS and Through Forward Links Optimization

The through forward links (TFLS) are defined in Appendix C as those FLOS falling exclusively within the through bands. Thus, they are a subset of the total FLOS. Due to the nature of the FLOS concept, it is possible that a FLOS optimization may cause the bandwidth to increase in one direction at the expense of the bandwidth in the other direction. Tests of this policy indicated no differences in the optimal solution, however. This is due to the fact that through forward links lost to one direction offset the gains in the other, and the solution will converge on the same one as normal, unweighted FLOS. A better approach to this

problem (i.e., reducing bandwidth in one direction) is the minimum bandwidth constraint (described in Appendix C).

FLOS and Performance Index Optimization

Throughout this research several traffic engineering variables have been used as measures of effectiveness of the FLOS optimization concept. Of particular significance among these are delay and stops. As reported in Chapter 2, various treatments of delay and stops have been used as explicit objective functions in a number of signal optimization models. Although the minimization of delay (and stops, depending on the model) is usually directed at networks, where progression, per se, is less important, the concepts can and have been applied to arterial designs.

Since delay and stops are of importance to a well-designed arterial progression system, it would follow that a strategy integrating the flows concept with these traffic measures is a logical extension of the work reported up to now.

The TRANSYT6C model expressly uses a linear combination of delay and stops. Indeed, other measures may be included as well (e.g., fuel consumption and vehicle emissions) but these are largely dependent on the primary variables: delay and stops. Consequently, only the primary variables are considered.

The simplified TRANSYT6C objective function, which is exactly the function used in the basic TRANSYT model (Robertson, 1969), is stated as follows:

$$\min PI = \sum_{i}^{n} (d_i + ks_i)_i \qquad (5.5)$$

where PI = Performance Index,

d_i = delay on link i of n links,

s_i = number of stops on link i, and

k = an arbitrary weighting factor.

The objective function can be varied (by different values of the factor, k) to indicate the relative importance of the two independent variables. However, for normal designs, Robertson states that values of four to eight tend to reduce stops without increasing delay (Robertson and Gower, 1977). In the studies to follow, a value of eight is used.

Formulation of a combinational objective function which considers both FLOS and the PI (as a measure of delay) must react monotonically with respect to improvement in the system design. Increasing FLOS and decreasing delay and stops are the desirable trends; thus, a ratio of FLOS to the PI constitutes an acceptable function. Since the PI is bounded by the constraints of the signal timing (e.g., cycle length and splits, demand satisfaction and minimum greens), the function will not degenerate. The objective function is formulated as follows:

$$\max \text{FLOS/PI}. \tag{5.6}$$

Again, the State Road 26 example is used to demonstrate this optimization strategy, and the summary results are reported in Table 5.5. A small reduction in the FLOS resulted from this test (compared to the normal FLOS optimization), but a 5% increase over the maximal bandwidth solution occurred. More significantly, the delay savings was nearly three times greater than the normal FLOS optimization and the reduction in stops quadrupled.

The FLOS/PI ratio clearly has merit as an optimization strategy.

TABLE 5.5 COMPARISON OF MAXIMAL BANDWIDTH, UNWEIGHTED FLOS AND FLOS/PI OPTIMIZATIONS

MOE	PERCENT CHANGE FROM MAX. BANDWIDTH UNWEIGHTED FLOS	FLOS/PI
Bandwidths	0	0
FLOS	7.7	5.0
Total Delay	-1.4	-4.1
Total Stops	-2.2	-8.8

TABLE 5.6 COMPARISON OF PASSER II AND TRANSYT6C/FLOS OPTIMIZATIONS OF BANDWIDTHS

MOE	PERCENT CHANGE FROM PASSER II INITIAL SPLITS BY: PASSER II	STAR1
Bandwidths	0	-1.9
FLOS	7.7	3.2
Total Delay	-1.4	-2.9
Total Stops	-2.2	-5.8

Maximal Bandwidth

To complete the alternative objective functions available in the TRANSYT6C/FLOS model, maximizing bandwidth is included. It must be re-emphasized that this model does not select optimal cycle lengths or phase patterns; consequently, it is not suggested that the new model could replace the PASSER II model. In order to use TRANSYT6C/FLOS to determine the best values of these timing parameters, multiple runs would be required, which could be quite expensive in terms of computer and evaluation time.

Allocation of green times among the conflicting phases is available within the new model through the use of the STAR1 subroutine, which computes splits similarly to PASSER II.

The model was tested on State Road 26 with splits calculated both externally by PASSER II and internally by the STAR1 subroutine. The results are given in Table 5.6. Clearly, there are minor differences in the split calculations, for the bandwidth calculated by STAR1 for the right-bound direction was two seconds less (23 - 21) than that calculated by PASSER II. Because of differences in initial splits the relative improvement in FLOS was less with splits calculated internally, although delay and stops were slightly improved.

This finding suggests a more detailed investigation of the relative methods of calculating splits may be warranted. It should also be noted, however, that splits were not allowed to vary during these optimizations. If splits are allowed to vary, both solutions converge on a common solution (see the discussion of split variation later in this chapter).

Extended Analyses

The preceding two sections have presented a variety of alternative objective functions available within the TRANSYT6C/FLOS model. A multiplicity of potential objective functions can be formulated by appropriate combinations of weighting functions, use of the several explicit objective functions (e.g., normal FLOS, combined FLOS and the PI, bandwidth, etc.) and assigning directional priority.

Generally, none of the alternatives described above surpassed the use of unweighted FLOS in terms of the improvements in forward link opportunities. On the other hand, improvements in traffic measures were experienced in several cases.

This section deals with several tests which involve combinations of objective function components, variation of splits and comparisons with minimization of delay and stops. The latter is introduced below.

Consideration of Minimum Delay and Stops

Having introduced delay and stops into a FLOS-related optimization, a legitimate question arises--namely, how do the time-space optimization policies compare with minimization of stops and delay? Clearly, the minimization of TRANSYT's PI will produce the minimum values of delay and stops. The concern rests with the trade-off with bandwidth and FLOS.

The same example data used previously (S.R. 26) were optimized using the TRANSYT objective function expressed in Eq. (5.6) for comparison with the unweighted FLOS optimization and the FLOS/PI optimization. Comparative results are shown in Figure 5.3, where the maximal bandwidth solution is the basis for comparison of the other optimization policies. For simplicity, delay and stops are expressed as the PI where PI = total

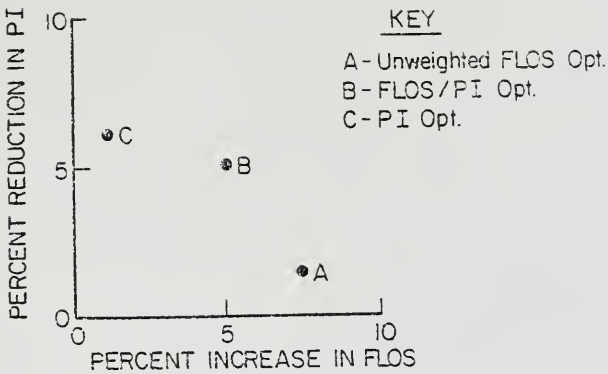


FIGURE 5.3 COMPARISON OF UNWEIGHTED FLOS, FLOS/PI AND PI

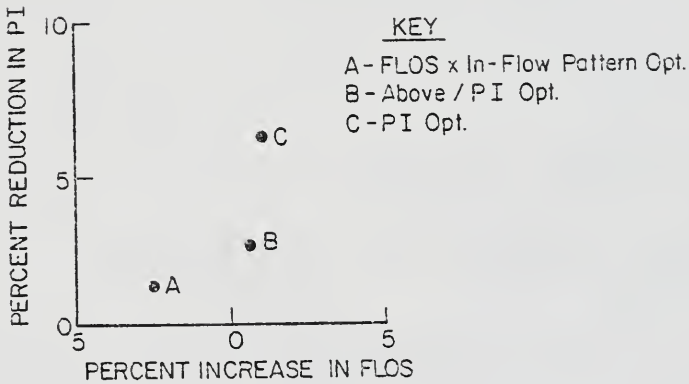


FIGURE 5.4 COMPARISON OF IN-FLOW PATTERN-WEIGHTED FLOS

delay (vehicle-hours/hour) plus eight times the number of stops (vehicles/second). Note also that, in this figure and the others to follow, changes in stops and delay are referred to as net reduction in the PI, such that a decreasing trend is plotted as a positive value, indicating improvement.

The minimal PI solution produced, as expected, the greatest reduction in the Performance Index, while the FLOS optimization produced a proportionately greater improvement in the number of forward link opportunities. It should also be noted that the PI optimization produced slightly higher (1%) FLOS than did the maximal bandwidth solution. The ratio of FLOS to PI as the objective function produced a reasonable compromise between the two.

The next investigation compares the minimal stops and delay solution with the same FLOS objective functions, however, with FLOS weighted by the stopline arrival patterns. Figure 5.4 shows the results of these analyses. In this test, the minimal stops and delay solution is clearly superior to either of the FLOS-related solutions. Indeed, the maximal bandwidth solution has more FLOS than the weighted FLOS solution (as noted earlier).

In summary, the inclusion of stops and delay in the FLOS objective function appears to be a reasonable optimization strategy for unweighted FLOS, but not for FLOS weighted by the stopline arrival patterns (when splits are not allowed to vary). Unweighted FLOS, both with and without this weighting function, compare favorably with the minimum PI solution, depending on the designer's preference for the emphasis to be placed either on progression or on stops and delay.

Variation of Signal Splits

The treatments of splits by the PASSER II and TRANSYT6C/FLOS models have been noted earlier. PASSER II apportions the cycle length among the conflicting movements, subject to satisfying the minimum specified green times. Since FLOS optimization is explicitly concerned with the time-space relationship of through movements, it is intuitively obvious that an unweighted FLOS optimization will force all available time to the through movements, sacrificing time otherwise assigned to cross streets and arterial left-turns (unless, of course, the latter move simultaneously with the through movements). This has the effect of driving the minor phases to their respective minimum green times. Oversaturation on these movements could easily result if the minimums are set according to normal traffic engineering principles, namely that the minimums consider only the safety of motorists and pedestrians (see Appendix C).

On the other hand, it is entirely plausible that some green time could be shifted from the minor movements to the through movements with advantageous results. Specifically, the detrimental effect on the minor movements may be offset by the beneficial effects to the through traffic.

The time available for the minor movements would still have to be sufficient to avoid oversaturation. In the present TRANSYT6C/FLOS model, the only way to insure that this constraint is not violated is to set the minimum greens high enough to preclude demand to capacity (v/c) ratios exceeding unity, or some lesser upper limit.

In order to simulate such conditions, a program was developed which would externally calculate pseudo-minimum greens which would insure that v/c ratios would be less than some arbitrary value (0.9). The resulting values are input as minimum greens in the normal manner.

A normal optimization run may then be exercised, in this case allowing splits to vary by encoding negative ones (-1) on the hill climb step sizes card in the input deck.

To demonstrate this technique, the data set from State Road 26 in Gainesville, Florida, was run with the appropriate pseudo-minimum greens, and allowing splits to change. Comparative results including maximal FLOS solutions with and without split variations are shown in Figure 5.5. The unweighted, normal FLOS optimization produced results which would be expected. The increase in FLOS was the largest that could possibly be achieved (2,540), given the minimum green times. But, while no phases became oversaturated, stops and delay on minor movements increased substantially. The major proportion of the increase in the PI under FLOS optimization was in delay, which increased by 17.7%. Stops only increased by about 1% because of the greatly increased forward link opportunities.

On the other hand, when the PI is combined with FLOS, appreciable improvements were made in all MOE. Indeed, the PI for the FLOS/PI solution is only about 3% higher than the value of the PI under the TRANSYT6C minimization function. The latter value (78.4) is the absolute minimum value of the PI that can be achieved under the constraints on this optimization.

To complete this series of tests, split variation was applied to FLOS weighted by the in-flow patterns, the results of which are shown in Figure 5.6. A similar trend occurred in this set of tests, but with somewhat less improvement than in the foregoing comparisons. Nonetheless, the emergence of the in-flow pattern-weighted FLOS/PI function as a definite improvement tends to revitalize this weighting strategy as a

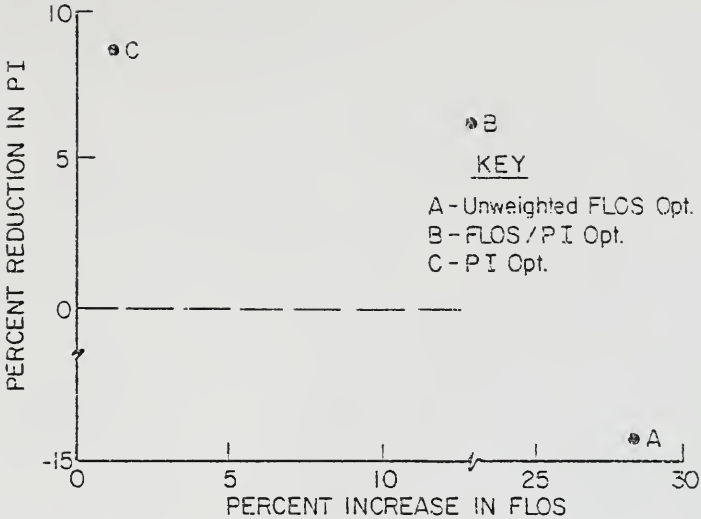


FIGURE 5.5 COMPARISON OF UNWEIGHTED FLOS AND PI OPTIMIZATIONS WITH MAXIMAL BANDWIDTH OPTIMIZATION, SPLITS VARYING

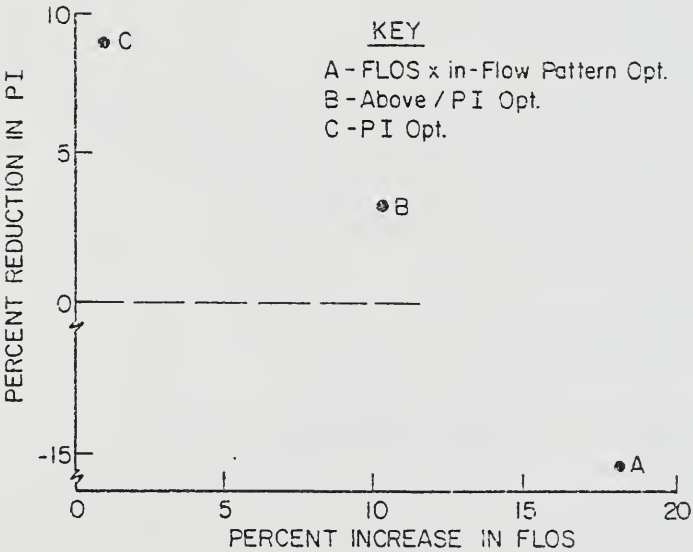


FIGURE 5.6 COMPARISON OF IN-FLOW PATTERN-WEIGHTED FLOS AND PI OPTIMIZATIONS WITH MAXIMAL BANDWIDTH OPTIMIZATION, SPLITS VARYING

legitimate subject of further research, given its functional appeal. Recommendations to this effect are given in the next chapter.

Summary

This chapter has demonstrated several of the capabilities of the forward link opportunities strategy in traffic signal optimization. A review of the findings should clarify the potential of the proposed design technique and the optimization model.

Since all the results reported in this chapter have been expressed in terms of percentage change, a summary tabulation of the actual numerical values is given in Table 5.7, for the State Road 26 system. In this review, split variation is not included unless otherwise stated.

Optimization strategies which did not produce meaningful results in these investigations are listed below.

1. Optimization of unweighted, normal FLOS, while allowing splits to vary, produces the maximal value of FLOS, but with unacceptably high delay and stops. An algorithm could be developed to better define the constraints on minimum (practical) green times, but a handier policy is already available (e.g., the FLOS/PI policy).
2. Optimization on FLOS weighted by link length and total demand do not appear to improve the designs in the cases tested.

Strategies which demonstrated limited potential for improvements in the system design are as follows:

1. Weighting of FLOS by the in-flow arrival patterns did not produce a greater number of FLOS than unweighted FLOS optimization. Although delay was reduced slightly, stops were increased.

TABLE 5.7 SUMMARY OF RESULTS OF EXTENDED INVESTIGATIONS OF THE FORWARD LINK OPPORTUNITIES OPTIMIZATION POLICY (STATE ROAD 26)

OBJECTIVE FUNCTION[a]	TIMING ELEMENTS[b]	TOTAL BANDWIDTH	EFFI-CIENCY	FLOS	PQR	TOTAL DELAY	TOTAL STOPS	PI[c]
Bandwidth (PASSER II)	Cycle, Patterns, Splits, Offsets	52	26.5	1,978	36.0	67.77	2.26	85.82
Unweighted, Normal FLOS	Offsets	52	26.5	2,131	38.8	66.81	2.21	84.47
Link Length-Weighted FLOS	Offsets	52	26.5	2,132	38.8	66.81	2.21	84.47
PDF-Weighted FLOS	Offsets	52	26.5	2,132	38.8	66.81	2.21	84.47
Total Demand-Weighted FLOS	Offsets	49	25.0	2,115	38.5	66.82	2.21	84.49
In-Flow-Pattern-Weighted FLOS	Offsets	41	20.8	1,929	35.1	66.10	2.34	84.40
Left-Bound Biased FLOS	Offsets	47	24.2	2,091	38.1	66.94	2.20	84.53
Unweighted FLOS/P. I.	Offsets	52	26.5	2,076	37.8	64.97	2.06	81.41
Bandwidth (TRANSYT6C/ FLOS, Splits Internally Calculated)	Offsets	51	25.8	2,042	37.2	65.78	2.13	82.83
Minimum P. I.[c]	Offsets	49	25.0	1,990	36.4	64.22	2.04	80.55

TABLE 5.7 (CONTINUED)

OBJECTIVE FUNCTION[a]	TIMING ELEMENTS	TOTAL BANDWIDTH	EFFI-CIENCY	FLOS	PQR	TOTAL DELAY	TOTAL STOPS	PI [c]
In-Flow Pattern-Weighted FLOS/P. I.	Offsets	46	23.3	1,991	36.3	65.48	2.28	83.69
Unweighted, Normal FLOS	Splits, Offsets	77	39.0	2,540	46.3	79.79	2.28	98.04
Unweighted FLOS/P. I.	Splits, Offsets	59	30.0	2,234	40.7	64.61	1.98	80.48
Minimum P. I.	Splits, Offsets	47	24.2	1,998	36.4	62.70	1.96	78.37
In-Flow Pattern Weighted FLOS/P. I.	Splits, Offsets	51	25.8	2,200	40.1	66.27	2.11	83.19

a. Objective functions are maximization unless otherwise stated.
b. These elements are the decision variables in the optimization.
c. P. I. = Total delay (veh-hr/hr) + 8 x Total Stops (veh/sec).

2. Assigning a priority to direction of travel by overweighting the FLOS in the priority direction resulted in little change in system-wide traffic operations, although FLOS were significantly increased in the priority direction.
3. FLOS weighted by the Platoon Dispersion Factors on each link demonstrated no change from the unweighted FLOS optimization on the State Road 26 system or the Buffalo Avenue system, but did improve upon the unweighted FLOS solution for the S. R. 7 (twelve-signal) system (see Table 5.2). Thus, giving priority to shorter spacings between intersections appears to have some merit, particularly on longer systems with greater variance in signal spacing.
4. Maximization of bandwidths using the TRANSYT6C/FLOS model exclusively (but with cycle length and patterns provided by the PASSER II model) produced fewer FLOS than a FLOS optimization using splits determined by PASSER II, but did produce lower values of delay and stops, due to differences in the split calculations.
5. Optimization on the ratio of FLOS, weighted by in-flow patterns, to TRANSYT's Performance Index (PI) demonstrated only a negligible reduction in delay and stops, compared to unweighted FLOS optimization. Also, FLOS were reduced to nearly the level of the maximal bandwidth solution. On the other hand, if splits are allowed to vary, using the same objective function, the FLOS are increased beyond the unweighted FLOS optimization, with a slight improvement in the traffic measures.

The objective functions displaying the most potential for system improvement are reviewed below.

1. Optimization of unweighted, normal FLOS provides greater assurance of improving forward link opportunities than the maximal bandwidth optimization strategy. Traffic operations are generally at least equal to the maximal bandwidth solution. In cases where this is not true, the variations below can improve the design.
2. Maximization of the ratio of unweighted FLOS to the PI reduces delay and stops, but at the cost of decreased FLOS. However, when splits are allowed to vary, the best solution results, in terms of both the available FLOS and the traffic measures.

In summary, the enhanced applications of the FLOS concept capabilities of the TRANSYT6C/FLOS model have demonstrated the viability of the forward link opportunities concept in the design of optimal signal timings for arterial highways.

The major shortcoming of the forward link opportunities optimization strategy is its propensity to propagate platoons into the standing queues in the early portion of the through phase, thus, delaying the platoons. The FLOS/PI objective function overcomes this problem, but further research into a more direct solution would appear to be warranted, as noted in the following chapter.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This dissertation has presented a new concept for the design and analysis of traffic signal progression on arterial highways. An existing traffic signal optimization model has been modified to incorporate the forward link opportunities (FLOS) concept as a measure of effectiveness and as an effectiveness function in the optimization of signal timing for progression. In comparison with the state-of-the-art methodology for arterial signal design, the FLOS strategy has been demonstrated to be a viable alternative. Likewise, the model has been shown to be a powerful analysis tool. The conclusions and recommendations listed below are offered as a result of this study.

Conclusions

Arterial progression design methodologies are typically concerned with the through bands which can accommodate nonstop progression through a system of signals. The concept of forward link opportunities considers not only these through bands, but likewise other short-term progressive opportunities within the system. It is concluded that the aggregate forward link opportunities is a viable measure of effectiveness of the quality of progression. This conclusion is supported by the following considerations:

1. The measure is based on functionally and practically sound theory.
2. A derivative of the measure is analogous to a measure of effectiveness which has been accepted in the profession as

an important figure of merit, namely, the progression quality ratio (FLOS/cycle forward links) is analogous to bandwidth efficiency.

3. The measure recognizes the totality of progression opportunities, in addition to the often limited widths of through progression bands.

With regard to the optimization model developed to maximize forward link opportunities, it is concluded that the approach taken is theoretically sound and that the model is a viable analysis tool. The following considerations support this conclusion:

1. The model is built around a proven optimization algorithm, the TRANSYT hill climbing model. The analysis capabilities of the parent model have also been demonstrated to yield realistic estimates of traffic operations in signalized systems.
2. In tests of real-world conditions, the model performed in a logical and predictable fashion with respect to the optimal solution.
3. The model can be used to investigate a variety of alternative design strategies, in addition to forward link opportunities.
4. Although the model is more expensive to use than the prevalent maximal bandwidth model (PASSER II), in terms of input data preparation and execution time, it is far more effective in production of measures of effectiveness. A variety of useful outputs are produced, including FLOS-related measures of effectiveness, time-space diagrams and time-location (FLOS) diagrams. These are in addition to the already available performance and timing tables and stopline flow pattern diagrams,

which exist in the TRANSYT6C model. Compared with the parent TRANSYT6C model, preparation of input data is the same except for the added card. The execution time of a FLOS optimization is approximately one-half that of a normal TRANSYT6C (stops and delay) optimization except when the TRANSYT Performance Index is included in the objective function. In this case the execution time is increased by about 20% over a normal TRANSYT6C optimization.

5. The model deals more effectively with signal design variables than the maximal bandwidth methodology for those variables which may currently be optimized (e.g., offsets and splits).
6. Diagnostic reports of both data inputs and conditions simulated by the model are superior to the prevalent maximal bandwidth model.
7. Signal designs produced by the model are directly implementable in the field.

In comparisons with maximal bandwidth optimal solutions, the proposed strategy was demonstrated to produce signal designs which were at least equal to and generally superior to the former strategy. Specific findings included the following:

1. Forward link opportunities were consistently increased using the FLOS optimization function.
2. Shifts in signal offsets generally resulted in greater percentages of vehicles arriving during the green phase as opposed to the red phase. Stops and delay to through traffic were accordingly improved in these cases. Even in cases where the shifts were detrimental to the through traffic, the system-wide traffic operations were generally improved.

3. Evaluations of alternative design strategies are readily made in a single run through the analysis of initial (preset) and final (optimal) timings. Examination of the performance tables permits immediate identification of problem locations which may be improved by other engineering actions.

The TRANSYT6C/FLOS model is quite flexible in terms of various refinements which can be placed on the objective function. The more salient observations emanating from the investigations in this area are listed below.

1. Weighting by the Platoon Dispersion Factor (an inverse function of travel time, which in turn is a function of link length and speed) can improve the solution over unweighted FLOS optimization in some cases. This optimization strategy favors short links, thus, maximizing progression through sections of closely (and more homogeneously) spaced intersections.
2. Weighting by stopline arrival pattern can reduce delay, but does not provide an optimal level of FLOS. This strategy does, however, offer potential for further development.
3. Optimization on the ratio of FLOS (either weighted or unweighted) to the TRANSYT6C Performance Index (PI) results in the least delay and stops among the various FLOS optimization strategies. The number of FLOS is reduced compared to a straightforward FLOS optimization, unless splits are allowed to vary.
4. Split variation, in addition to offset variation, provides the best overall design if the FLOS/PI optimization policy is

used. The PI should be included to prevent substantially increased delays on minor movements not considered in a normal FLOS optimization.

Finally, the comparative analyses of the PASSER II and TRANSYT6C/FLOS models and their respective functional capabilities support the following conclusions about the applicability of the two models:

1. With regard to determination of cycle length and phasing patterns, the PASSER II model strategy appears to be completely adequate. No basis for improving upon the methodology was found. The TRANSYT6C/FLOS model does not internally examine alternative variations of these parameters.
2. Phase splits as determined by PASSER II are adequate for a balanced distribution of green time; however, variation of splits permits more progressive opportunities for the arterial traffic. The positive gains on the artery offset the detriment to the cross streets if reasonable green times are imposed for the cross street movements. This can be assured by the use of the FLOS/PI optimization policy, as stated above.
3. Signal offsets are consistently set for improved progression under the FLOS optimization policy.

Recommendations

The recommendations emerging from the research described in this dissertation fall primarily in two areas. The first area covers recommendations concerning further improvements to the present model. The second set of recommendations are suggested areas which warrant further research.

Model Improvements

In its present status, the TRANSYT6C/FLOS model is fully operational, but with certain limiting characteristics and constraints. At the computational level, several improvements are suggested, as listed below.

1. The FLOS-related computations can be more efficiently incorporated into the parent model to further reduce execution time and memory requirements. Addition of a "FLOS link card," which would identify the links to be considered in a FLOS optimization, would eliminate the present constraint on the node-link numbering scheme. Such an improvement would also allow the FLOS optimization strategy to be extended to one-way pairs or even to arterials within a network of signals.
2. The sensitivity of the model could be improved by allowing signal timing to be varied in integer seconds rather than the time-base referred to as steps. It should be noted, however, that this would increase execution times for cycle lengths over 60 seconds.
3. A more recent version of the parent model, TRANSYT7, has become available since this research was initiated. It is reported to be more efficient in terms of coding requirements and execution. Consideration should be given to using this version as the parent computer program. The fuel consumption and vehicle emission predictions of TRANSYT6C would have to be added to this version as well as the FLOS analysis.
4. Neither the TRANSYT6C/FLOS model, nor the PASSER II model, can presently deal explicitly with permissive (or unprotected)

left-turns. They can be modeled in TRANSYT6C/FLOS by manually setting capacities proportionate to gaps in the on-coming through-traffic stream, but a more complete model should deal with these directly. The mechanism existing in a single intersection model called the Signal Operations Analysis Package (SOAP - Courage and Landmann, 1978) could be incorporated to estimate capacities for permissive left-turns. Thus, all turning strategies could be considered by the model.

At the functional level, the FLOS model should be expanded to a complete optimization model which examines all signal timing parameters. The following specific recommendations are offered in this regard:

1. The optimization algorithm should be modified to internally compute appropriate minimum green times which avoid oversaturation of minor movements under FLOS optimization.
2. Algorithms for determining the best cycle length and signal phases should be added. Those used in the PASSER II model are quite adequate. With some modification, the PASSER II model could be revised to serve as a preprocessor for the (improved) TRANSYT6C/FLOS model. Such an integrated model would automatically operate essentially the same as has been demonstrated in this research by means of manual interfacing.

Regarding these recommendations, it should be recalled from Chapter 1, there is presently a project in progress to develop an Arterial Analysis Package (AAP) which contains PASSER II and TRANSYT6C as well as two other models. Incorporation of the TRANSYT6C/FLOS model would not be difficult and the interfacing between this model and PASSER II should be present in the completed AAP.

An overall, integrated model to determine the optimum values of all signal timing elements would thus take a form as shown in Figure 6.1.

Recommended Future Research

Clearly the most essential research still needed in this area is empirical investigations to validate the analytical methodologies presented in this work. Specific topics of such research are suggested below.

1. The assumption inherent to the TRANSYT model that traffic moves in a recurring manner needs further study, particularly in well-designed progressive systems.
2. Signal timing suggested by FLOS optimization may create a condition where progression through noncritical intersections will significantly increase the periodic rate of demand at critical downstream intersections. Such a heavily peaked arrival pattern may cause problems at the critical intersection. Field studies should be conducted to assess the impact of this phenomenon.
3. Both maximal bandwidth and FLOS optimizations tend to establish the offsets such that the start of through green in at least one direction falls on the leading edge of the through band. This results in platoons arriving downstream before the stationary queues have dissipated. A timing policy which advances the greens to clear standing queues should be examined. Such an approach is particularly applicable to optimization strategies involving FLOS weighted by stopline arrival patterns.

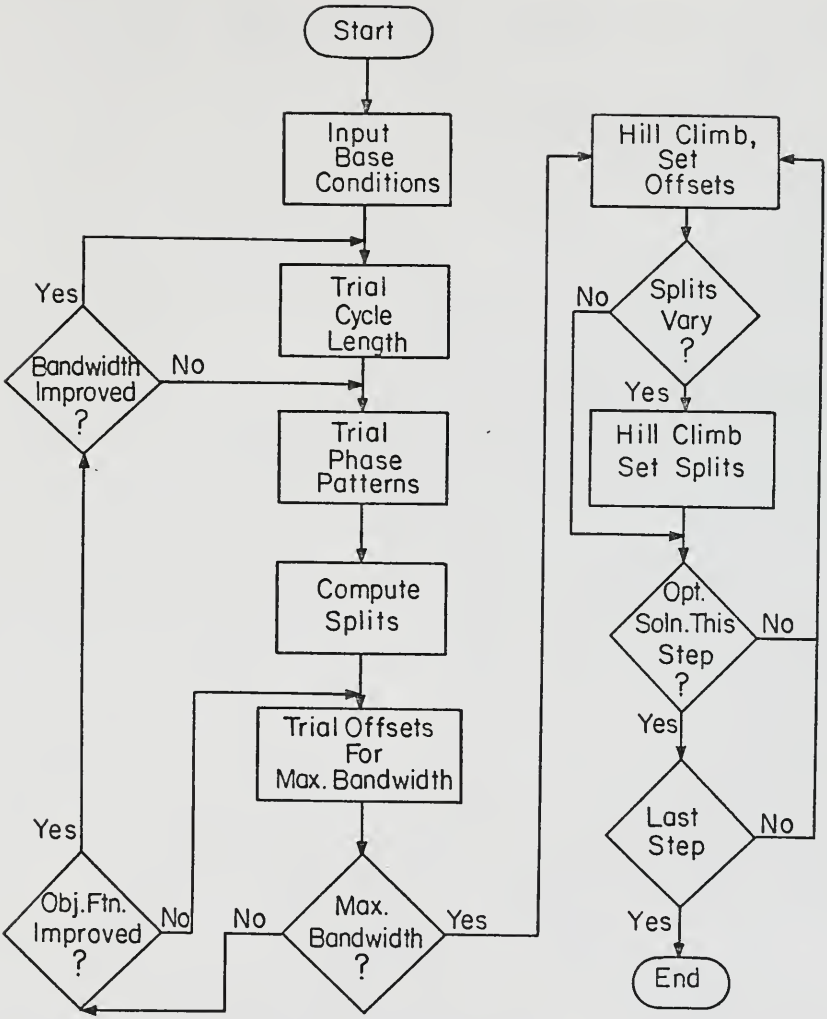


FIGURE 6.1 CONCEPTUALIZATION OF A COMPLETE OPTIMIZATION MODEL FOR COORDINATED ARTERIAL TRAFFIC SIGNAL TIMING

APPENDIX A

DESCRIPTION OF THE PASSER II MODEL

Overview

The maximal bandwidth arterial design strategy included in this work is, according to an official authority (MacGowan et al., 1977), best represented as state-of-the-art in the PASSER II model, developed by the Texas Transportation Institute at Texas A & M University (Messer, et al., 1973 and 1974).

For the benefit of readers who are not familiar with the model, it is described briefly in this appendix. When deemed pertinent to the research reported in this work, critical assessments are offered, but only for the purpose of fostering improvement in future development. Covered are the model's: (1) purpose and specified applications, (2) background, (3) functional description (including computational methodologies), (4) input requirements and (5) output reports.

Purpose and Applications

PASSER II is an acronym for Progressive Analysis and Signal System Evaluation Routinge, Version Two. It was developed to provide the timing design for a coordinated system of signals on a arterial highway.

The model is somewhat limited in that only two-way progression is provided and the singular objective function, to maximaize total bandwidth, does not permit significant variation of design objectives. The model is primarily applicable to high-type intersections (i.e., those having separated left-turn lanes and exclusive left-turn phases). By

proper coding of inputs, however, intersections of lesser standards can be included with some loss of information. This is discussed in more detail in a later section.

The major advantage of PASSER II over most arterial progression models is the ability to consider multiphased signals and selection of the optimal phase patterns.

Background

Brooks (1965) developed a computerized progression program which determined the signal timing and offsets for through progression bands which maximized total bandwidth. This early model did not, however, give adequate attention to multiple phasing and signal sequencing, although the maximal bandwidth concept enjoys popular support among practitioners. Indeed earlier manual progression techniques are essentially based on the maximum bandwidth theory.

The Texas Transportation Institute of Texas A & M University was contracted by the Texas Highway Department to develop an advanced progression model which overcame the earlier deficiencies. PASSER II is the resultant model, and the program has been documented by Messer et al. (1973 and 1974) and Fambro (1979). PASSER II has gained increasingly widespread use by practitioners throughout the United States.

The program is written in FORTRAN IV for an IBM 370 computer. Its transferability is high, core storage requirements are low and execution time is quite short thus the program is an attractively inexpensive design tool for traffic engineers. While the user's manual and programmer's manual are generally adequate, the source code is not well documented.

Functional Description

Overview

PASSER II is a macroscopic, deterministic optimization model using a fixed time-step sequencing technique for each condition examined. The optimization process is a controlled search which considers, for each allowable cycle length, permissible phase pattern specified and proportionately distributed green times, those offsets which maximize the sum of the bandwidths.

The decisions normally required in the progressive design process are summarized as follows:

1. What left-turn strategies are to be considered in a multiphase system?
2. What range of cycle lengths is appropriate for the best progression?
3. Is progression to be favored in one direction over the other?
4. What progression speed provides the minimum bandwidth?
5. What cycle length and green splits provide the best progression?
6. What phasing sequence and offsets provide the best progression?

Several of these decisions require engineering judgement or, at least, multiple runs to determine the global optimum, using PASSER II.

Selection of appropriate left-turn strategies is largely a function of the geometric and traffic characteristics. For example, where particular movements simply do not exist, the program inputs must reflect the absence of such movements. A deficiency of the PASSER II program allows illegal or improper movements to be assigned, and the program will execute without warning the user of the error.

The user documentation for PASSER II suggests that cycle lengths only be specified for a ten second range in any run. The reasoning of this advice is based on the optimization algorithm (discussed below), which may allow a recommended solution to the maximum bandwidth objective which is technically infeasible. That is, the design with the global maximum bandwidth may contain phase times which are oversaturated. Thus, the limitation on the range of cycle lengths forces the user to make multiple runs that can be compared for adequacy in all respects. This notwithstanding, the cost-effectiveness of computer runs of this program encourages the multiple runs that may be required to arrive at a satisfactory design recommendation.

PASSER II has a facility for allocating a minimum percent of total bandwidth to one direction, provided, of course, that the amount of green time at the most critical intersection(s) has not already been fully utilized for the through bands. Any shift of the progression from one direction to the other will depend upon the attainability (see below) of the gaining band.

The progression speed is based on the measured free speeds, with an option to vary by two mph over or under this speed. The speed may vary from intersection to intersection, and by direction, but the bandwidths do not vary as a function of distance.

In PASSER II, the cycle length and splits are inputs to the optimization algorithm, but are computed separately; thus, these are discussed separately from the optimization algorithm.

Cycle Length and Splits

The optimal cycle length is determined by means of an exhaustive search of all user-allowed values (e.g., from the specified minimum to

the specified maximum at the specified step size). In the optimization progress, discussed below, the cycle length producing the minimal value of the objective function is stored. After all possible trials have been tested, the complete analysis is re-run at that cycle length to produce the final results.

Splits are calculated initially by Webster's method (Webster and Cobbe, 1966) by the following:

$$G_i = [(y_i/Y) \times (C-L)] - l_i \; ; \qquad (A.1)$$

where G_i = length of green time plus amber and any all-red for critical movement i, in seconds;

y_i = the ratio between demand and the saturation flow;

Y = sum of all y_i for the n critical phases;

C = cycle length;

l_i = lost time (assumed to be 4 seconds); and

L = sum of lost time of n phases.

The calculated cycle length (sum of the G_i) is compared with the trial cycle length and any available time is distributed proportionately among the critical phases. The resulting splits are tested against the minimum greens specified and any necessary adjustments are made. If the sum of the user-specified minimum conflicting greens exceeds the cycle length, an erroneous result will occur.

Patterns and Offsets

As stated previously, the optimization process is a controlled search of the user-permitted design parameters to find that unique combination which maximizes the following function:

$$B = G_{a\ min} + G_{b\ min} - I_{b\ min}\ ; \qquad (A.2)$$

where B = total bandwidth;

$G_{a\ min}$ = minimum progressive green time in the 'A' direction;

$G_{b\ min}$ = minimum progressive green time in the 'B' direction; and

$I_{b\ min}$ = minimum possible band interference in the 'B' direction.

This technique is an extension of Brook's (1965) interference algorithm. The algorithm is based on the physical constraint that the widest possible (maximum) band in each direction will be governed by the minimum available green in each direction, among the several intersections. All offsets are initially set to perfect progression in the 'B' direction and projections of green bands from each signal to the critical signal result in the interference (or encroachment into the maximum band). Clearly there will be no interference in the 'B' direction since all non-critical greens will exceed the critical green, thus all interference is with respect to the 'A' direction. The amount of these interferences is quantified according to position (i.e., interfering with the "left" side or "right" side of the band) and the offsets are shifted accordingly to reduce the interference in the 'A' direction, without introducing interference in the 'B' direction. Once the minimum interference has been achieved, the resulting bandwidth is compared with any previous trial and, if lower, is stored as the currently best cycle length, progression speed (if appropriate) and pattern. The efficiency, E, is stored as B/2C, where B is determined by Eq. (A.2), and C is the cycle length.

This process is repeated for each of the following trial conditions, in descending order of the frequency of iteration.

1. Each allowable phase pattern is examined each time one of the following analyses is executed.
2. Step 1 above is accomplished for one complete iteration if no variation in progression speed has been allowed, or five times if a ± 2 mph variation has been specified.
3. The above steps are repeated for each allowable cycle length from the minimum to the maximum specified, at the specified step size (when the specified limits must be congruent). Green splits are calculated at this time as well.
4. Once the optimal solution has been determined, any specified shift from the 'A' direction to the 'B' direction band is analyzed and the above steps are repeated, but only for the optimal cycle length.
5. When the shift has been achieved, the entire process is repeated for the fixed optimal cycle length, fixed optimal progression speed (which sets the offsets) and for the fixed, adjusted bandwidths.

While this iterative approach can result in a very large number of iterations, run times are acceptably low.

Measures of Effectiveness (MOE)

The MOE produced by PASSER II are somewhat limited.

Bandwidth efficiency. This value, E, is defined previously in Eq. (A.2) as the objective function, and is more simply stated as

$$E = 100(B_A + B_B)/2C; \qquad (A.3)$$

where B = bandwidth in the 'A' and 'B' directions and

C = cycle length.

Attainability. This is a measure of how well the optimum band makes use of available green time. In the discussion of Brooks' interference algorithm above, it was stated that (at least) one intersection would govern the maximum possible bandwidth. This controlling green time is referred to as the minimum green and a value is applicable to both directions on the artery. Attainability, A, is defined as,

$$A = (B_A + B_B)/(MG_A + MG_B) \; ; \qquad (A.4)$$

where B = bandwidths as before and

MG = minimum greens in the 'A' and 'B' directions as defined above.

Thus, if $A = 1.0$, the bandwidths cannot possibly be increased. While this is intuitively a useful measure, it must be emphasized that increases in the minimum green(s) may not result in increasing the bandwidth(s); thus, the MOE would decrease even though more through traffic could be serviced at the critical intersection(s).

Volume/capacity ratio (v/c). The v/c ratio is calculated as follows:

$$X_i = (q_i C)/[(G_i - l_i)S_i)] \; ; \qquad (A.5)$$

where X_i = v/c ratio for movement i,

q_i = volume on movement,

C = cycle length,

G_i = green time available,

l_i = lost time and

S_i = saturation flow.

Input Requirements

The inputs to PASSER II are straightforward and easily obtained. The only field data required are the volumes for each approach, but it is also highly recommended that the free-flow speeds be obtained through field studies. Detailed specifications for the inputs are given in the user's manual (Messer, et al., 1974), and are summarized in Table A.1.

Input data are stored in common block arrays and are transformed as required by the program. This feature, along with the cyclical computational methodology described earlier, makes it difficult to recover the some of the input data once it has been output in the input data report.

Program Outputs

Input data report

This report echoes all inputs in a formatted report, enabling the user to compare it with the intended inputs. There is only one diagnostic check of input data, to warn the user if a phase pattern is missing.

The "Best Solution" report

This report gives the calculated cycle length, bandwidths, efficiency, attainability and speeds for the system and the offsets, phase patterns, timing and v/c ratios for each phase or movement. These results are reported only for the optimal solution as PASSER II does not report intermediate results. This is considered a deficiency since it is often useful to evaluate alternative designs which otherwise would be available from intermediate reports. The intermediate data are not stored; thus, recovery for such use would be extremely difficult.

TABLE A.1 INPUT REQUIREMENTS FOR THE PASSER II MODEL

CARD TYPE	INPUTS	DESCRIPTION
Arterial Header	Title Information	Name of city and arterial, district number, date and run number.
	Number of Intersections	The total number of intersections in the system.
	Cycle Limits	Minimum and maximum cycle lengths and step size for trial iterations.
	Options	Progression speed may be varied by ±2 mph and a minimum percentage of time to the B-direction band can be specified.
	Plots	Options for printer or line plots.
Intersection Headers	Name	Name of cross street.
	Number	Number of the intersection.
	Distances	Link lengths (may vary by direction).
	Q-clear	Seconds to advance the green to clear queues.
	Phasing	Specify all permissible phase patterns.
Data	Volumes	Traffic volumes (veh/hr) of all movements.
	Capacities	Capacities (veh/hr of green) of all movements.
	Minimums	Minimum green times (sec) of all movements.

Time-space diagrams

A time-space diagram is plotted for the optimal solution, if requested by the user. This is a valuable tool for the practitioner; however, the printer plot does not have the capability of altering the plotting scales except to automatically decrease the time scale as the system length increases. A line plot (Calcomp, Gould, etc.) is also available, but such plotting routines vary sufficiently among computer facilities that transferability is often a problem.

APPENDIX B

DESCRIPTION OF THE TRANSYT6C MODEL

Overview

The TRANSYT6C program serves several extremely important purposes in the present research. Most significantly, it forms the basis of the optimization model incorporating the forward link opportunities concept. Secondly, it performs the analysis which produces estimates of delays and stops which are vital to the evaluation of the two time-space based optimization techniques--maximal bandwidth and forward link opportunities. Finally, it supplies minimal stops and delay optimization for comparison with the previous techniques, as required.

TRANSYT6C is described briefly in this appendix for the benefit of readers who are not familiar with the program. Further information is contained in Appendix C, which is devoted explicitly to the combined TRANSYT6C/FLOS model, but necessarily extends the present discussion as required to describe the FLOS optimization technique.

The organization of this appendix is similar to that of Appendix A.

Purpose and Applications

TRANSYT6C is among the latest of a series of signal network optimization models, generally referred to simply as TRANSYT, which stands for TRAffic Network StudY Tool. The purpose of the model is to determine the optimal signal timing for a coordinated, two-dimensional network of traffic signals. Network optimization is substantially different from arterial optimization. The latter can effectively use time-space

techniques, while the former must generally rely on optimization of some more homogeneously consistent criteria, such as minimizing delay, stops, other traffic measures or combinations of these. In any case, progression, per se, is not explicitly considered. The minimal stops and delay concept has a legitimate place in this research, the foregoing notwithstanding, and is considered in Chapter 5 of this work.

Background

The TRANSYT model was first proposed by Robertson (1968), as a new concept in network optimization. The original user's instructions for the model, originally written for a Myriad computer, were published by Robertson in 1969. The machine-specific program could not be widely used, so the program was rewritten for an IBM computer and issued as TRANSYT2.

The program underwent various improvements in computational algorithms, input coding and checking, increased flexibilities in control strategies and computational efficiency from 1970 until 1975, when version six was issued (Robertson and Gower, 1977). By this time, the model was widely used in a number of nations and had been favorably compared with other existing network models such as SIGOP, SIGRID, and the British Combination Program (Wagner and Gerlough, 1969 and Rach, et al., 1974-5).

Because of the increasing concern with energy consumption by motor vehicles and automobile exhaust emissions, the Institute of Transportation Studies, University of California at Berkeley, undertook to modify the TRANSYT6 model to include estimates of fuel consumption and exhaust emissions as well as demand responses to recommended improvements. The resulting model is called TRANSYT6C, which is the version used in the

present research. For complete user instructions, both the original sixth version's documentation (Robertson and Gower, 1977) and the modified version's documentation (Jovanis et al., 1977) should be used.

TRANSYT6 is written in FORTRAN IV for an IBM 360 computer system, but the 6C version was written for a CDC 6400 computer system. This resulted in a number of conversion problems to translate the new program for use on an IBM system. The conversion of the version used in this research was performed by the programming staff of the University of Florida Transportation Research Center, and the translated version is easily transferrable to any IBM 370-compatible system. Certain other program modifications were made to this version for exclusive use in the present research. These are described in Appendix C.

TRANSYT6C is moderately efficient for small linear signal systems, requiring slightly over 1.5 seconds of CPU time per intersection. However, the execution time varies with the square of the number of nodes, and can become fairly costly to run on large networks. Core requirements are 384k bytes of memory.

The program is well documented, both internally and externally, but, despite improvements in recent versions, coding of the network and input data can be relatively arduous and subtle errors are often difficult to detect.

Functional Description

TRANSYT6C is a large-scale macroscopic, deterministic optimization model which uses a combination variable/fixed length time scan technique to arrive at the optimal solution. The optimization algorithm is called a "hill climb" approach, but as will be seen, it is really a "valley descent" approach. The objective function, referred to as the Performance

Index, or PI, is a non-distributive function over a set of signal offsets from zero to the cycle length. Furthermore, the PI may be multimodal, requiring relatively large displacements of the decision variables to achieve the global maximum, or supremum. The optimization algorithm is discussed further below and in Chapter 3.

TRANSYT6C estimates a number of useful measures of effectiveness which make it not only an excellent design tool, but an equally valuable analysis and evaluation tool.

Left-turn strategies are not explicitly analyzed by TRANSYT6C, thus the user must preselect the desired strategies. Neither does TRANSYT6C internally optimize cycle length or phase patterns. All of these design elements must be determined, if they, too, are to be optimized, by multiple runs of the model with varying inputs.

Important capabilities of the model are discussed below. When a concept is peculiar to the general TRANSYT model, it is referred to thusly. Only concepts peculiar to the 6C version are referred to as TRANSYT6C.

Distribution of Arrivals

A significant input to the FLOS optimization process (discussed in Appendix C) is the distribution of traffic arriving at the end of a link, or the stopline. This recognizes the effect of upstream traffic on the arrival pattern, which, in turn, influences the delay, stops and other MOE which are significant to the present research.

The approach used is a platoon dispersion recurrence relationship. In all versions of TRANSYT the arrivals are estimated by defining incoming and outgoing flows on a link. An 'IN' pattern is the pattern of

traffic arriving at the stop line if traffic is not impeded by the signal at the present node. This pattern is quantified by,

$$IN_i = F_{ij} (P_{ij} - OUT_j) ; \tag{B.1}$$

where IN_i = inflow to link i,

F_{ij} = a smoothing process (see Appendix C),

P_{ij} = the proportion of the OUT_j pattern feeding link i and

OUT_j = the departing pattern on link j, which feeds link i.

The number of vehicles held at the stopline during the tth time interval is,

$$Q_t = \max [(Q_{t-1} + q_t - d_t), 0]; \tag{B.2}$$

where Q = queue at a stopline during time interval t or t-1,

q_t = the arrivals during t (from an upstream IN pattern) and

d_t = departures during t.

Further d_t may be a GO pattern, or the departure pattern if the approach is saturated, namely the departure rate defined by the specified saturation flow, s. The GO pattern only causes the resulting queue to dissipate, after which the OUT pattern becomes the departure rate.

The OUT pattern for period t is simply,

$$OUT_t = Q_{t-1} + q_t - Q_t. \tag{B.3}$$

Since TRANSYT is a single period (i.e., one cycle length) analysis model, the link patterns must be loaded by beginning with an empty queue for one period, then patterns are estimated for one cycle to obtain the steady state and for a further cycle to determine periodic queuing fluctuations.

Optimization: Offsets and Splits

Signal offsets and the distribution of cycle time among the preselected phases are the primary decision variables of the TRANSYT optimization algorithm. A cycle, no matter how long, is divided into equal steps of up to 60 per cycle. Although most timing inputs may be in seconds, all internal calculations are in steps.

The objective function, called the Performance Index, or PI, of TRANSYT6C is defined as

$$\min PI = \sum_{i}^{n} [(k_1 d_i + k_2 s_i + k_3 f_i)_N + (k_4 d_i + k_5 s_i + k_6 f_i)_P + (k_7 CO_i + k_8 NO_i + k_9 HC_i)] \; ; \qquad (B.4)$$

where

n = total number of links optimized,

d_i = vehicle-hours of delay on link i,

s_i = number of stops on link i,

f_i = gallons of fuel consumed on link i,

CO_i = carbon monoxide emitted on link i in kilograms,

NO_i = nitrous oxide emitted on link i in kilograms,

HC_i = hydrocarbons emitted on link i in kilograms,

k_j = weighting factors of each variable and

N, P = refer to non-priority vehicles and priority vehicles, respectively.

A wide variety of design objectives can be examined with this objective function by properly assigning the weights of the components of the PI. (Note that assignment of unity for k_1 and a non-zero value for k_2 and zero for k_j, j = 3,9, yields the delay/stops objective function of TRANSYT6.)

The PI is clearly a nonlinear function as all variables are functions of speeds, speed changes and flow patterns, which, in turn, are functions of the signal timing and offsets. This is a very complex problem to model as a normal nonlinear programming model, but the speed of the digital computer permits a trial and error approach. The approach is, as stated earlier, a "hill climb" technique, which proceeds as follows.

1. Initial timings may be input by the user or may be calculated internally on the basis of proportionate volumes. Initial offsets may be input or set at zero at the user's option.
2. Offsets are varied by node according to a user-specified number of steps. Then the model iteratively shifts these new offsets in one-step increments, calculates the pertinent MOE and PI and converges on the local minimum.
3. Step two is repeated using large steps of about 40% of the cycle to span the entire decision space, moderate steps of about 15% of the cycle to escape small local minima and single steps to "fine tune." Periodically splits are adjusted in single step increments, if desired.

4. At each increment any improvement is recorded as the current optimum, or if no improvement was noted, the earlier solution is retained. The optimal solution is the minimum PI resulting from this iterative search.

Recommended signal timings and offsets are those which produced the minimum PI.

Measures of Effectiveness (MOE)

TRANSYT6C produces virtually all important MOE needed by the traffic engineer in evaluating design alternatives.

Delay. Both uniform and random delay are calculated using a modified version of Webster's (1958) method. The uniform delay is the recurring delay due to an estimated arrival pattern over the cycle and is equal to the average queue length over the cycle times the cycle length, where the average queue length is the IN pattern minus the OUT pattern (as discussed earlier).

Random delay, d_r, is calculated to account for the stochastic variation in arrivals by a formula which Robertson (1969) found to closely simulate field data, namely,

$$d_r = X^2/4(1-X); \qquad (B.5)$$

where X = degree of saturation, or the ratio of demand to available capacity.

Stops and maximum average queue. The number of stops is calculated from the IN/OUT patterns, where (initially) any excess IN-flow is considered stopped, and delayed, of course. TRANSYT has a facility to adjust for small delays which can be considered slow-downs, but not stops. This is the situation where vehicles arriving at the end of a queue may

have to decelerate, but not actually stop. The user specifies on a parameter card what fraction of traffic incurring delays in steps of one, two etc., up to a maximum value, are to be considered actually stopped. The percentage of vehicles stopped is also calculated.

The maximum average queue length is derived from the same calculation of stops, and is simply the longest recurring uniform queue, excluding random arrivals.

Degree of saturation. The degree of saturation is calculated by the common v/s, where s is the saturation flow based on effective green times, see Eq. (A.5).

Total travel. The total travel in vehicle-miles is simply the total flow on a link times the link length, aggregated over all links.

Total travel time. The total vehicle-hours is composed of three components. First is the free travel time, based on total flow, times the individual travel time input by the user. The last two components are the uniform and random delays calculated previously.

Fuel consumption. The fuel consumption MOE was added to TRANSYT by Jovanis et al., (1977) and is based on fuel consumption tables developed by Claffey (1971). Calculations are made for traffic on links to obtain the fuel consumed due to traversing the links as well as stops and delays. The fuel consumption on links is based on cruise speed on a link, the total travel time and the delay. The initial fuel consumption is drawn from a table and is then adjusted for road surface condition and curvature. Next, a correction is made for the degree of saturation. Fuel consumption is not considered in the present research.

Vehicle emmissions. Vehicle emissions are based on studies by Kunselman et al. (1974). These MOE are also not considered in the present research.

Average speed. This MOE is only output for the entire network, rather than by individual link. It is simply the ratio of total travel (vehicle-miles) to total travel time (vehicle-hours). This is a common MOE for "system" evaluation.

Input Requirements

Inputs to TRANSYT are relatively extensive and require a great deal of manual preparation. Like the PASSER II model, the field data requirements consist of traffic demands and free speeds. The detail is greater than that of PASSER II, however. TRANSYT requires that inputs from upstream links be specified for each adjacent downstream link. To be totally accurate, this would require considerably more detailed traffic counts (or origin-destination studies) and travel time studies as well.

A complicated input format is required to establish signal phasing (which is fixed for a given run). Initial signal timing may be input by the user, or a subroutine (STAR1) may be used to generate initial settings.

The remaining inputs are control options and traffic parameters, such as capacities, minimum greens, etc., and (if used) parameters for the demand response analysis. The latter are not considered in this research. Detailed specifications for the inputs are contained in the user's manuals (Robertson and Gower, 1977 and Jovanis et al., 1977).

All input card images are labeled by type of card. A summary of the card types is given in Table B.1.

Input data are stored in arrays keyed generally to an internal indexing of nodes or links, as appropriate. Many variables are

TABLE B.1 INPUT REQUIREMENTS FOR THE TRANSYT6C MODEL

CARD TYPE[a]	INPUTS	DESCRIPTION
1	Cycle length	Cycle length in seconds and in steps.
	Stop penalty	The value of k in the PI (see Card Type 6, if the PI card is included, this value is ignored).
	Time	Length of study period (min.) for purposes of reporting oversaturated delays.
	Lags	Lag times for start of green (called lost time, usually 4 sec.) and end of green, usually zero.
	STAR1	Option to use STAR1 subroutine to calculate initial timings.
	Options	Specify whether timing inputs are in steps or seconds, whether speeds are input as speeds or travel time, output level, and number of copies of final results.
	Flow scale	A multiplier to allow variation of all volumes.
2	Node list	The numbers of all nodes, in the order to be optimized.
3	Link list	The numbers of all links, in the order to be optimized.
4	Hill climb step sizes	The numbers of steps at each stage of the hill climb optimization process. A negative one (-1) specifies split variation.
5	Stop per delay	A filtering function whereby small amounts of delay are not counted as stops.
6	Performance Index	Coefficients of the objective function, see Eq. (8.4). If omitted, no optimization is done, but initial timings are analyzed.

TABLE B.1 (CONTINUED)

CARD TYPE[a]	INPUTS	DESCRIPTION
1X	Timings	The initial start time of each phase (if input, otherwise must be calculated by STAR1), and the minimum greens. The 'X' in the card type refers to the number of phases.
2X	Timings	Same as 1X, except for double cycled signals.
28	Offsets	Initial offsets for the starts of phase one at each node.
30	Flow-speed multiplier	Individual variations in flow or speed, to permit changes or sensitivity studies.
31	Link parameters	For each link, the phase numbers in which the link switches to green, then to red; the link length and capacity (veh/hr of green); and individual variations in stop penalty, delay weights and Platoon Dispersion Factor.
32	Volumes	For each link, the total demand (veh/hr) and its components; which are any uncontrolled, uniform inputs and inputs from all upstream links (with link numbers identified).
33	Fuel consumption parameters	Parameters to influence fuel consumption calculations: curvature, grades and percentages of trucks and buses.
35	Plots	Specify which links are to have stopline flow patterns plotted.
36	Demand response	Options to control the demand response analysis (not used in this research).
37	Segment demand response	Options to establish priority segments for buses and carpools (not used in this research).
40/41	End	Specify whether end of run or a second data set to follow (used only for demand response analysis).

a. TRANSYT6C requires that data cards be numbered as indicated in this column.

transformed for internal purposes; thus, many items of data are not readily accessible. As discussed in Appendix C, it was found to be more convenient to establish new arrays to store the data needed for the forward link opportunities analysis rather than directly accessing the data in existing arrays.

Program Outputs

Input Data Report

This report echoes all input data exactly as supplied to the program. TRANSYT6C has an extensive error checking capability. When errors are detected, the offensive value is underlined in this report and execution of the run is cancelled. Data checking continues until all inputs have been processed.

Performance Tables

At each stage of the hill climb process, a table is output which contains all the MOE in a link-by-link listing. This table may be suppressed for intermediate settings if desired. If a link is oversaturated, a message is printed to alert the user to the problem.

Performance Index Summary

At each stage of the hill climb process, a summary of the MOE making up the performance index is output, see Eq. (B.4). The actual values of each MOE are printed, as well as their relative contribution to the PI. Additionally, system total travel, total travel time and average speeds are included.

Flow Pattern Diagrams

For each link requested, a diagram of the "stop line flow pattern" is printed. An example is shown in Figure B.1. The time scale (abscissa) is always in steps of the cycle. The flow rate scale always has as its

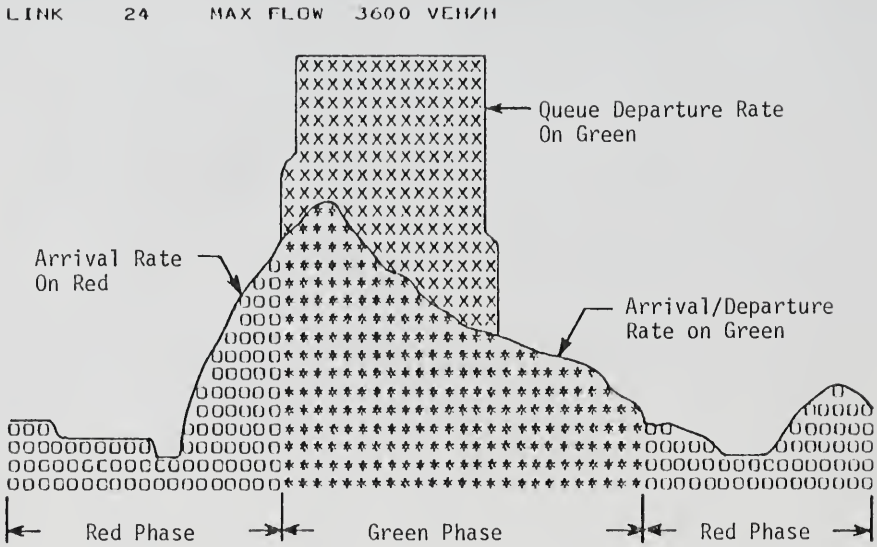


FIGURE B.1 EXAMPLE OF STOPLINE FLOW PATTERN PRODUCED BY TRANSYT6C

maximum (24 lines on the plot) the maximum flow rate experienced at the intersection; thus, the flow scale varies among plots. As seen in the example, the 'O' characters depict arrivals during the red phase, the '*' characters depict arrivals and departures during the green phase, and the 'X' characters depict departures of the queue. These plots are generated by the estimates of 'IN', 'OUT' and 'GO' patterns discussed earlier.

APPENDIX C

MODIFICATIONS TO TRANSYT6C TO IMPLEMENT THE FLOS MODEL

General

The TRANSYT6C model, described in Chapter 2 and Appendix B, was modified substantially to implement the FLOS concept as an effectiveness function. Additionally, other modifications were undertaken to effect the following:

1. Certain outputs of the existing model were incompletely or incorrectly labeled. These were corrected.
2. The performance tables output by the existing program were modified to produce more usable information (e.g., phase lengths in lieu of phase-end times).
3. A new measure of effectiveness was added to express the percentage of arrivals at the stop line during the red display.
4. A time-space plot routine was added.

Description of Additions/Modifications

Table C.1 briefly describes the TRANSYT6C/FLOS model specifications. The modifications to existing subprograms and the added subprograms are given below. For more information on the original TRANSYT6C program see Appendix B.

MAIN

No changes were made to the executive calling program.

TABLE C.1 TRANSYT6C/FLOS PROGRAM SPECIFICATIONS

ITEM	SPECIFICATION
Computer System	IBM 370-compatible
Language	FORTRAN IV
Program Length (including comments)	9300 lines (approx.)
Recommended Compiler	FORTRAN H, extended
Core Requirements (compile)	550k bytes
Core Requirements (execute)	384k bytes
Execution Time (FLOS optimization)	60 sec. (approx. for 20 intersections)

BLOCK DATA

Common block FLO7 was added to this set of constant data values and symbols (see added COMMON BLOCK descriptions below).

TINPUT

This is the input data processing routine. A new card (Type 7) was added to input options and parameters pertinent to the FLOS analysis and the time-space plot. The new card is checked, and errors marked, consistently with the existing input data checks. The inputs on this card are described in Table C.2.

A new link-related vector variable, LKLEN, was added to store link lengths. Various improvements were made to correct errors in the input data report, and common blocks FLO1 and FLO4 were added.

KRIMP and FUEL

No changes were made to these function subprograms.

TABLE C.2 ADDITIONAL INPUT REQUIREMENTS FOR THE TRANSYT6C/FLOS MODEL--CARD TYPE 7

INPUTS/NAME	DESCRIPTION
FLOS analysis option IFLGN1	Specify the type of analysis as follows: 0 = no FLOS analysis (same as leaving the card out, in which case a normal TRANSYT6C analysis is done), 1 = FLOS analysis by optimization based on Performance Index, and 2 = FLOS optimization.
Type weighting IFLGN2	Specify the type of weighting to be applied to the FLOS, as follows: 0 = none, normal FLOS, 1 = link length, 2 = total demand, 3 = in-flow pattern, and 4 = Platoon Dispersion Factor.
Weighting factor IWFCT	Specify a multiplier to effect the magnitude of the FLOS objective function.
Time-space plot IFLGN3	Specify whether the time-space plot is to be printed as follows: 0 = none, 1 = final settings only, and 2 = initial and final settings.

TABLE C.2 (CONTINUED)

INPUTS/NAME	DESCRIPTION
Scale factors ITIMSC,IDISSC,INCREM	Specify the time and distance scales and the grid dimensions for the time-space plot.
Objective function IFLGN5	Specify the FLOS objective function as follows: 1 = normal FLOS, 2 = FLOS/CFLS, 3 = not used, 4 = (W_1 x FLOS) + (W_2 x TFLS), 5 = bandwidth, and 6 = FLOS/PI.
Coefficients FLOWT(1),FLOWT(2)	Specify W_1 and W_2 where, for all objective functions except number 4, OBJ. FTN. = W_1 x right-bound value + W_2 x left-bound value.
Trace ITRACE	A debugging tracer option which permits specified calculations to be output. Also used for several other specialized functions.

STAR1

No change was made to this routine that (optionally) sets initial timings.

TOUTP

This is the output subroutine of TRANSYT6C. Several changes were made to the performance table to facilitate interpreting outputs. Phase lengths are now output in lieu of phase-end times. Link numbers are printed on the right side of the table, in addition to the left side. Messages were changed to be more appropriate and the table formats were improved.

During FLOS optimization, outputs on intermediate hill climb steps are restricted to summary reports.

HILLCL

This routine performs the hill climbing optimization algorithm. Conditional branches were added to enable the hill climbing algorithm to test the value of FLOS if FLOS optimization were requested. Calls to outputs were modified to reflect the addition of FLOS analysis or optimization and the time-space plot.

A call is made to the added routine XFORM to initialize variables peculiar to the FLOS analysis. Calls are made to FLOUT and TSPLOT, as required, to output the FLOS results and the time-space plot.

SUBPT

This is the simulation subroutine which calculates TRANSYT6C flow patterns and measures of effectiveness. It was revised to permit storing of the signal timings and in-flow patterns in formats consistent with the added FLOS-related routines. When FLOS optimization is being performed, most of this subroutine is usually bypassed and CFLOS is called

instead. These portions are not bypassed on the first and last iterations or if the alternative objective function which is a ratio of FLOS to the TRANSYT6C Performance Index is specified. Complete calculation of the TRANSYT6C measures of effectiveness is permitted for such cases in order to obtain reports on these MOE.

Common blocks FL01, FL02, FL03, FL05 and FL06 were added.

SPLOT

This routine performs the arrival/departure pattern plots. A call to added subroutine PERCNT was inserted to obtain the calculations of the percentage of red arrivals.

SSHIFT

No change was made to this routine, which calculates various demand responses. Furthermore, this routine is presently superfluous to the TRANSYT6C/FLOS model.

ADJFLOW

No change was made to this routine that supports SSHIFT, and it is also superfluous to the new model.

OECS, RECS, and WECS

No changes were made to these routines which simulate the extended core storage which was used in the original CDC version of TRANSYT6C.

XFORM (added)

This subroutine is called by HILLCL immediately upon entry (one time only) to transform certain variables from the storage format used in TRANSYT6C to a more convenient format used in the added FLOS-related subroutines. No numerical changes are made, but variables are simply re-stored in a structured set of arrays. This does impose constraints on how the link-node coding is assigned (as discussed in Chapter 3), but

the method of coding is consistent with guidelines suggested in the TRANSYT6C users' manuals (Robertson and Gower, 1977, and Jovanis, et al., 1977). Additionally, the coding scheme is consistent with the required movement assignments for PASSER II. The coding scheme is summarized as follows (see Figure C.1):

1. Nodes (intersections) are numbered consecutively in the direction selected as the "A-direction" in a PASSER II run.
2. About each node the links are numbered such that the first digit(s) is the node number and the units digit corresponds to the PASSER II scheme.

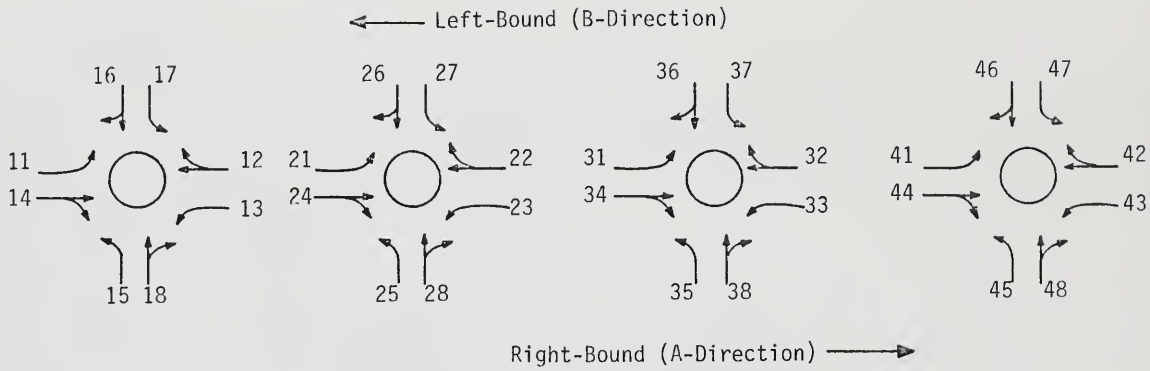
To code a system, the artery should be laid out left to right in the "A-direction", regardless of the actual directional orientation, thus outputs refer to right-bound and left-bound.

CFLOS (added)

This is the main subroutine which calculates the forward link opportunities. Called by SUBPT at each iteration of the hill climb process of a FLOS optimization, it calculates all variations of FLOS (e.g., CFLS, TFLS and normal FLOS) and calls WEIGHT to perform any required weighting of these measures. The objective function is calculated and returned to HILLCL via SUBPT.

The logic of this subroutine is described briefly below.

1. Given the signal timings for the green starts in each direction (from SUBPT) the start time of each green is adjusted for travel time over the link. The phase is scrolled about the cycle if necessary to insure that the current start time is between zero and the cycle length. Start times are also scrolled back until the earliest start is at time zero.



Conventions:

1. Nodes numbered consecutively, left to right.
2. Links numbered 'nm' or 'nnm', where 'n' or 'nn' is the node number and 'm' is as follows:

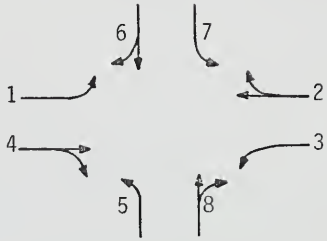


FIGURE C.1 TYPICAL ILLUSTRATION OF LINK-NODE CODING SCHEME FOR TRANSYT6C/FLOS

2. A signal status matrix having node numbers as columns and steps (time) as rows is completed to indicate negative unity (-1) when the signal is red and zero (0) when green.
3. The signal status matrix is scanned to determine how many adjacent downstream signals are green. The number, if any, is substituted for the zero in the appropriate cell of the matrix. The raw FLOS are thus accumulated.
4. The matrix is scanned to locate the through band if any.
5. A second scan locates any second band, but more significantly, determines if the through band overlaps the cycle length. If the latter is the case, the parts of the through band are combined. In the (extremely rare) event that a second through band is detected, the two bandwidths are added together (per direction), but the larger of the two is referenced as the pertinent through band.
6. The various MOE (CFLS, TFLS and FLOS) are calculated in a call to WEIGHT, where any requested weighting factors are applied. The MOE related to PASSER II (bandwidth efficiency and attainability) and the progression quality ratios are also calculated in CFLOS.
7. The objective function is calculated as specified on Card Type 7 in variable IFLGN5. If IFLGN5 is coded as a negative number, the original bandwidths must be maintained as a minimum. If this constraint is violated, an objective function value of zero is returned by CFLOS to ensure further search in the hill climb.

The available objective functions are summarized below.

1. Unweighted FLOS. The forward link opportunities (raw, unweighted) are maximized.
2. Progression quality ratio. The PQR is the ratio of normal FLOS to cycle forward link (CFLS). This is similar to the MOE referred to as efficiency in the PASSER II model, in that it expresses the proportion of the total cycle length available for progression. Optimization using this ratio is, in effect, no different than optimization of normal FLOS.
3. Normal FLOS and through FLOS. A combination of normal FLOS and through forward links (TFLS) permits the assurance of maintaining through bands while improving FLOS elsewhere. This is a special objective function which should be used when optimization of normal FLOS tends to degrade the through bands in one direction or the other. The function is a weighted linear sum of the two measures.
4. Normal FLOS and Performance Index. When FLOS optimization results in an unacceptable degradation of delay and stops, the two can be combined as follows:

$$\text{Obj. Ftn.} = [(W_1 \times FLOS_1) + (W_2 \times FLOS_2)]/PI; \qquad (C.1)$$

where W = Coefficients to assign directional priorties (see the discussion of subroutine WEIGHT),

FLOS = normal forward link opportunities, in the right (1) and left (2) directions, respectively, and

PI = the TRANSYT6C Performance Index, a linear combination of stops and delay (or, for that matter, also fuel consumption and vehicle emissions)

By properly setting the coefficients, priority can be granted to one direction or the other.

5. Special constraint on objective function. In certain cases an optimal solution will result in progression being shifted to one direction. If this is not desired, the objective function can be constrained to disallow depletion of the initial through bands in both directions. Presently, this requires initial timings which contain reasonable bands (e.g., from a PASSER II optimization). The constraint is evoked by entering the negative of the corresponding code for the desired objective function.

7. Bandwidth. Total bandwidth, similar to the PASSER II model, is included as an explicit objective function.

WEIGHT (added)

This subroutine applies weights to the various FLOS values as specified on Card Type 7 by the variable IFLGN2. The available weights are applied as follows:

1. No weight. Normal FLOS-related values (e.g., CFLS, TFLS and FLOS) are reported without alteration.

2. Distance weight. All FLOS-related values are multiplied by the length of the appropriate link. This weighting tends to favor longer links.

3. Total volume weight. All FLOS-related values are multiplied by the total demand on the appropriate link, in vehicles per cycle. This weighting favors links (and more particularly, the direction) with heavier demands.
4. In-flow pattern weight. TRANSYT6C disperses traffic departing one link to the downstream link. When several inputs are merged, the arrival pattern at the downstream signal is defined (see next item). Weighting of individual FLOS (by step) favors platoon arrivals at the signals.
5. Platoon dispersion factor weight. All FLOS-related values are weighted by the platoon dispersion factor defined below.

$$F = (1 + kt)^{-1} ; \qquad (C.2)$$

where F = platoon dispersion factor,

t = link travel time, and

k = an adjusting coefficient.

This factor has been shown to reflect the dispersion of traffic departing as a platoon from an upstream link over a downstream link (Robertson, 1969, and Hillier and Rothery, 1967). The factor is applied as follows:

$$q'_{i+t} = F \times q_i + (1-F) \times q'_{i+t-1}; \qquad (C.3)$$

where q'_{i+t} = flow in the ith time interval of the predicted platoon, and t is 0.8 times the link travel time over the downstream link, and

q_i = flow in the initial platoon.

The appropriate value for k in Eq. (C.2) was determined by Robertson (1969) to be 0.5. This platoon dispersion technique is that which predicts the in-flow patterns discussed in the previous item.

Weighting by this factor is, in essence, the reciprocal of distance weighting (item 2 above) and tends to favor shorter links. The rationale is that forward link opportunities over closely spaced signals are perceived by the motorist as more beneficial.

These weights may be applied in any of the objective functions discussed earlier. FLOS-related MOE can be further weighted by the input parameters FLOWT(1) and FLOWT(2) on Card Type 7. These coefficients may be used to imply preference by direction (e.g., for FLOS, PQR, bandwidth, etc.) optimization, or to adjust combinational components of the objective function (e.g., FLOS and TFLS). Finally, a scalar parameter (WTFCT) may be used to adjust the numerical magnitude of the FLOS MOE to limit their sizes. WTFAC is set to ten to the power of IWFCT input on Card Type 7.

FLOUT (added)

This subroutine first outputs a table giving results of all FLOS calculations, the FLOS objective function and percent change in the objective function. There is no significant computational logic to this section of the subroutine. An example is shown in Figure C.2.

The travel time normalized plot of FLOS is also produced by this routine as required. An example of this plot is shown in Figure C.3, which may be compared with the time-space plot in Figure C.4. When offsets are corrected for travel time, the distances between nodes are

FORWARD LINK OPPORTUNITIES ANALYSIS

CONDITION: GAINESVILLE S.R. 26 DSN=T.SR26B

TYPE OF FLOS WEIGHTING: NONE

	RGHT DIRECT	LEFT DIRECT	BOTH DIRECT	
CFLS	2744.0	2744.0	5488.0	
AFLS	1285.4	1594.1	2879.6	
TFLS	640.3	823.2	1463.5	
FLOS	834.6	1296.8	2131.5	
BANDWIDTH	22.9	29.4	52.3	SEC
EFFICIENCY	23.3	30.0	26.7	%
ATTAINABILITY	100.0	100.0	100.0	%
PQR=FLOS/CFLS	30.4	47.3	38.8	%
PQR=FLOS/AFLS	64.9	81.4	74.0	%
PQR=FLOS/TFLS	130.4	157.5	145.6	%

CRIT. INTERS. 1 8

THE FLOS OBJECTIVE FUNCTION IS: NORMAL FLOS

THE COEF. OF THE OBJ. FTN. ARE 1. (R-BOUND) AND 1. (L-BOUND)

CURRENT VALUE = 2131.5 LAST VALUE = 2131.5 CHANGE = 0.0 %

FIGURE C.2 EXAMPLE OF THE FLOS MOE OUTPUT TABLE

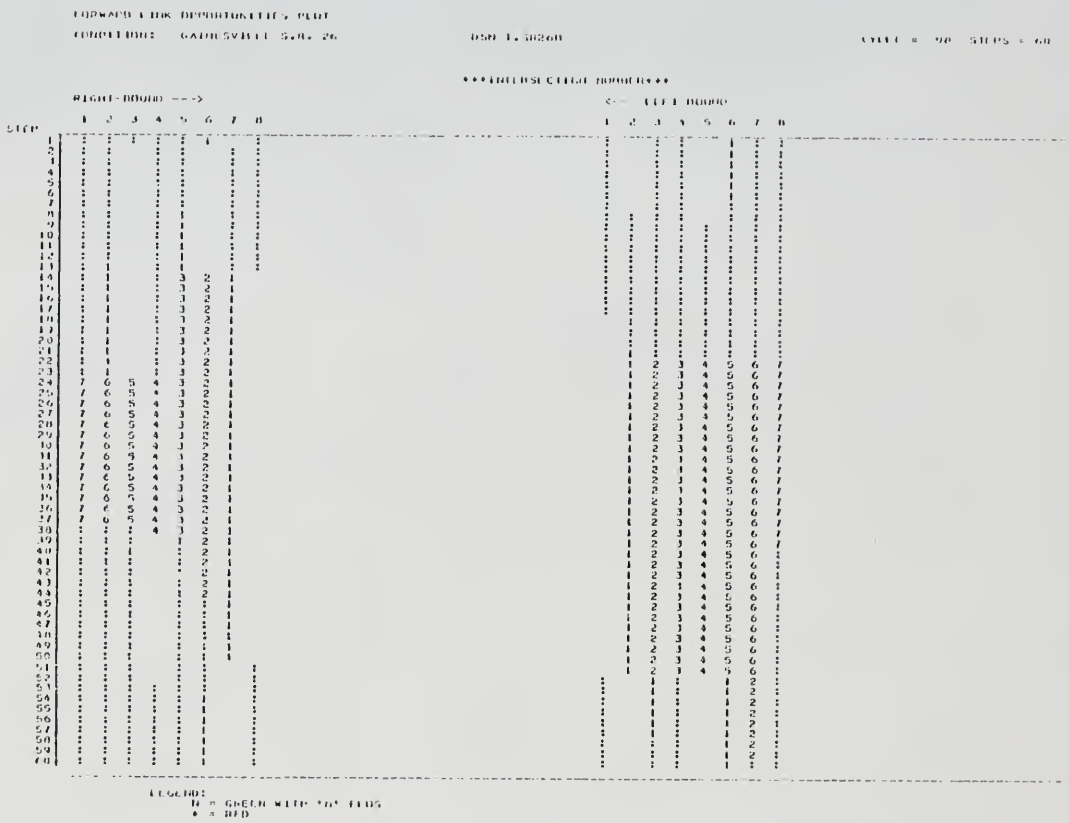


FIGURE C.3 TYPICAL TRAVEL TIME-NORMALIZED PLOT OF FORWARD LINK OPPORTUNITIES

FIGURE C.4 TYPICAL TIME-SPACE DIAGRAM

no longer relevant; thus, the intersections may be collapsed into a non-dimensional scale. The time scale of this plot is in steps of the cycle (see Appendix B for an explanation of steps vs. seconds of the cycle).

The only significant logic in this section of FLOUT is to scroll the cycle to center the through band in each direction. This facilitates interpreting the plot and has no effect on the quantitative MOE. It must be realized, however, that the offsets implied in the plot are, therefore, generally not numerically the same as those output in the TRANSYT6C performance and timing tables, since they are relative to a different base time.

PERCNT (added)

This subroutine calculates the percentage of arrivals at the end of each link that arrive during the red signal. The subroutine is called by SPLOT for each link for which a stopline pattern plot is being produced. The logic (developed by Courage and Parapar, 1977) is simply the arrival rates during the red display divided by the total arrival rate over the cycle, using the "IN" flow pattern distribution discussed in Appendix B.

TSPLOT (added)

This subroutine generates a space-time diagram of the arterial signal timing. TSPLOT is called by HILLCL for the initial and final settings only (if desired, see variable IFLGN3 on Card Type 7). The logic is described below.

1. Scale factors are set from the inputs (ITIMSC, IDISSC and INCREM) on Card Type 7. Signal timings from SUBPT are converted from steps to percentage of the cycle length.

2. Comparing relative start and end times of the two directions, the initial and final directions are determined. If a through and left-turn in one direction precedes a different display, that direction is said to lead. Naturally, through in both directions may also lead, or trail.
3. Once the leader and trailer displays are determined, the display in the middle is identified.
4. Start and end times (expressed in percentages of the cycle) are set for each interval at each signal and an expanded row of appropriate display symbols is printed whenever the proportionate distance between intersections has been reached.

The time-space plot does not presently locate through bands. The slope of the bands may be conveniently computed, and located on the plot using the time scale legend, by the following formula:

$$D = 100\ L/(u \times TS \times C \times CF)\ ; \qquad (C.4)$$

where D = the displacement of the progression bands from the first to the last signal, in terms of the number of columns on the plot;

L = the total length of the system;

u = the speed in the direction of interest;

TS = time scale in percent of cycle per column;

C = Cycle length in seconds; and

CF = conversion factor (5,280 ft/mi/3,600 sec/hr).

An example of the time-space diagram produced by TRANSYT6C/FLOS has been shown in Figure C.4.

Labeled Common Blocks

Several labeled common blocks were added to various existing and added subroutines to store and pass data among these routines. Their contents are not of sufficient interest in this discussion to describe the variables in detail. Briefly, they contain the following:

1. FL01 - values from the new Card Type 7 (see Table C.2).
2. FL02 - the current and old values of the objective function and a pointer to identify initial, intermediate and final signal settings.
3. FL03 - link specific characteristics (e.g., internal link numbers, link lengths, travel times and volumes).
4. FL04 - link lengths in an array peculiar to TRANSYT6C. These are transformed by XFORM and further passed in FL03.
5. FL05 - phase start, duration and end times and in-flow patterns.
6. FL06 - the FLOS-related MOE.
7. FL07 - plot symbols used by FLOUT and TSPLOT, defined in BLOCK DATA.

Comment on Program Structure

The TRANSYT6C/FLOS model was created by merging the existing TRANSYT6C program and separate programs written by the author to calculate FLOS and perform the time-space plot. Conventions regarding variable naming and logic coding are quite different. There is no doubt that a professional computer programmer could improve the coding to produce a more efficient model. As the present model exists, however, run times of the new model are approximately 50% lower than an equivalent normal TRANSYT6C run. The time savings are due to the simplified calculations for FLOS which are made for the vast majority of hill climb iterations for FLOS

optimization. When the PI is included in the objective function (eg., FLOS/PI) the execution time is approximately 20% longer than a normal TRANSYT6C optimization. More complicated combinations, such as in-flow pattern-weighted FLOS/PI, increase run time even further. The additional core storage is insignificant in a large system, but this, too, could be reduced by better use of shared space.

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BIOGRAPHICAL SKETCH

Charles Edward Wallace was born in Cuero, Texas, on June 17, 1943. He attended public schools in the neighboring area until his father was recalled to armed services. Subsequently, he attended both military and public schools in Japan, Arkansas, Italy, New York and Texas. He graduated from Thomas Jefferson High School in San Antonio, Texas, in 1961.

In September, 1961, he enrolled at Texas A & M University where he studied Civil Engineering and participated in the Reserve Officer's Training Corps. He was awarded the Bachelor of Sciences in January, 1966, and was commissioned a Second Lieutenant in the United States Army.

He continued his studies in civil engineering at Texas A & M University, specializing in Transportation Engineering and was awarded the Master of Engineering in August, 1967. During the course of his studies, he was a Research Assistant with the Texas Transportation Institute and held a responsible position on a major research project in Detroit, Michigan.

Following graduation, Mr. Wallace entered active military duty where he served for almost four years as an engineer company commander and as an engineering staff officer in Thailand and West Germany, respectively. He also held a civilian engineering position with the Army Corps of Engineers in Germany.

In 1972, he entered the Graduate School of the University of Florida where he pursued the degree of Doctor of Philosophy in civil engineering, specializing in transportation.

During the course of his academic training, he was engaged in a number of transportation research projects as a Graduate Research Associate in the Department of Civil Engineering, including over three years as director of a remote research office in Miami, Florida.

Mr. Wallace is married to Patricia Anne Ryan and has one son, Ryan David, and one daughter, Shannon Kathleen. He is a member of the National Society of Professional Engineers, the Institute of Transportation Engineers and the Transportation Research Board, and he is a registered Professional Engineer in the State of Texas.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

J. A. Wattleworth, Chairman
Professor of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

J. H. Schaub
Professor of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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G. Long
Associate Professor of Civil Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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December 1979

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