Palaniswamy. The VTI team (G. Gynnerstedt, A. Brodin, and A. Carlsson) has acted as advisors and assisted in the development work. The project has received overall guidance from the World Bank group (C. Harral, P. Fossberg, and T. Watanatada). The valuable advice and encouragement of G. Singh and K.K. Sarin, directors general of road development, MOST; C.G. Swaminathan and M.P. Dhir, directors, CRRI; B. Stroem and H. Sandebring, directors general, and B. Thunberg, director, VTI; and S. Sampath, director IIT, Kanpur, are gratefully acknowledged.

REFERENCES

1. A. Carlsson, G. Gynnerstedt, and B. Westerlund. A Model for the Monte Carlo Simulation of Traffic along Two Lane Single Carriageway Rural Roads. Communication 43. VTI, Linkoping, Sweden, 1977.
2. G. Gynnerstedt. Systems Analysis of Road Traffic. Communication 44. VTI, Linkoping, Sweden, 1977.
3. A. Brodin, G. Gynnerstedt, and G.A. Levander. Program for the Monte Carlo Simulation of Vehicle Traffic along Two Lane Rural Roads. Communication 143. VTI, Linkoping, Sweden, 1979.
4. A. Brodin and A. Carlsson. VTI Trafiksimulerings-model-del I Berkrivning av modell och programsystem. Communication 321. VTI, Linkoping, Sweden, 1983.
5. Road User Cost Study in India. Final Report. Central Road Research Institute, New Delhi, India, 1982.
6. S.P. Palaniswamy. A Generalized Simulation Model for Vehicle Behavior Under Heterogeneous Traffic Conditions. Indo-Swedish Traffic Simulation Research Project, IIT, Kanpur, India, 1983.
7. B.R. Marwah. A Simulation Model of Two Lane and Four Lane Highways for Indian Conditions. Indo-Swedish Traffic Simulation Research Project, IIT, Kanpur, India, 1983.
8. G. Gynnerstedt. Indo-Swedish Traffic Simulation Research Project. Draft report. Central Road Research Institute, New Delhi, India, 1983.
9. A. Brodin. VTI Traffic Simulation Model, a Program for the Monte Carlo Simulation of Vehicle Traffic along Two Lane Rural Roads: An Application of JSP and SIMULA. Communication 322A. VTI, Linkoping, Sweden, 1983.
10. S.P. Palaniswamy and A. Brodin. A Generalized Simulation Model--A Program for the Monte Carlo Simulation of Heterogeneous Vehicle Traffic along Single, Intermediate and Narrow Two Lane Roads: An Application of JSP and SIMULA-67. Indo-Swedish Traffic Simulation Research Project, IIT, Kanpur, India, 1984.
11. R.J. Troutbeck. Overtaking Behavior on Australian Two Lane Rural Highways. Special Report 20. Australian Road Research Board, Numawading, Victoria, 1981.

Publication of this paper sponsored by Committee on Traffic Flow Theory and Characteristics.

Reduced-Delay Optimization and Other Enhancements in the PASSER II-84 Program

EDMOND CHIN-PING CHANG, CARROLL J. MESSER, and BLAIR G. MARSDEN

ABSTRACT

The development of a research study conducted by the Texas Transportation Institute entitled "Reduced-Delay Optimization and Other Enhancements to PASSER II-80" is summarized. The research was sponsored by the Texas State Department of Highways and Public Transportation (SDHPT) in cooperation with the FHWA, U.S. Department of Transportation. The brief 6-month research effort was directed toward several topic areas including development of a reduced-delay optimization procedure that could fine tune the offsets of traffic signals to reduce total arterial system delay and maximize arterial progression, development of methods that can better estimate vehicular delay in a nearly saturated traffic system, and development of methods to estimate fuel consumption for arterial traffic movements in an urban network. Significant enhancements have been made to the popular PASSER II program. This study also demonstrated the practical combination of the maximum bandwidth procedure and the minimum delay algorithm to effectively maximize progression and reduce delay, stops, and fuel consumption in optimizing arterial traffic signal operations. An enhanced version of the PASSER II-80 program, PASSER II-84, was programmed on Texas SDHPT's computer system. Program documentation and revised data-coding instructions were also prepared.

Continued demand for urban mobility requires that the highest degree of traffic service be obtained from existing urban arterial streets and intersections. The ability of signalized intersections to move traffic depends on the concurrent functioning of existing traffic control devices and proper signal timing settings on the street (1-3).

Traffic signal optimization is a complicated process that determines the cycle length, green time, phase sequence, and offsets between the signals. Optimization depends heavily on the relationships among the distances between signalized intersections, travel speed, cycle length, roadway capacity, and side friction along the arterial. Global optimization is time consuming and difficult to achieve without a thorough understanding of the interactions and sensitivities of the site-dependent variables. An alternative is to select proper independent variables, define relationships, and solve the optimization problem heuristically.

Computer techniques for off-line, fixed-time signal timing optimization have commanded widespread interest, but they can optimize merely a portion of the signal timing plan variables, one step at a time. Above all, the models involving a nonlinear formulation still cannot guarantee an optimal solution. The major development of a computerized signal timing optimization algorithm began in the early 1960s with the coordinated offsets of consecutive traffic signals for maximum throughput (1-3).

Currently, two major approaches to coordinating traffic signals along arterial streets are used: (a) the bandwidth maximization-based procedure and (b) minimization of disutility functions such as delay, stops, fuel consumption, or air pollution. The former includes Progressive Analysis and Signal System Evaluation Routine (PASSER), MILP, and MAXBAND (4-6). The latter includes TRANSYT-7F, MITROP, and SIGOP (7-12).

Because of the easily understood time-space diagram and the favorable progressive movement, several maximum bandwidth-based procedures were developed. Generally, relative progression efficiency depends on distances between signalized intersections, travel speed, cycle length, roadway capacity, and side friction along the arterial. On the other hand, delay is well recognized by traffic engineers as a useful tool for evaluating a traffic control system (13,14). However, the calculation with maximum bandwidth does not necessarily minimize the total delay due to the difference of objective functions. Appropriate traffic signal settings can help smooth the traffic flow through a street network, thereby reducing delay and stoppage (7,15-17).

Many traffic engineers still prefer maximum bandwidth settings because of the easily applicable time-space diagrams and the apparently verifiable progression along a major arterial street (4,5,7,10,18). The benefit of signal progression synchronization can be confirmed visually in the field, thereby minimizing complaints from a demanding public. In addition, several studies [e.g., Wagner (19); Wallace (20); Gerlough and Barnes, cited by Rogness (21); Rogness (21), and Cohen (14)] together with much practical user experience demonstrate that the bandwidth method does yield consistently good results on arterial progression systems.

Research by Huddart (22) indicated the possibility of arriving at a compromise between the maximizing bandwidth and minimizing delay method (using a stop penalty) in computing traffic progression performance. Wallace (12) also encouraged the use of PASSER II as a preprocessor for TRANSYT to minimize systemwide delay. Rogness (21) used a heuristic procedure to study the relative performance of PASSER II and TRANSYT programs under synthetic scenarios of cycle length, intersection spacing, and phasing sequence for single arterial street signal timing optimization. He further concluded that there is potential for obtaining good to optimal solutions by combining PASSER II and TRANSYT with some recommended enhancements. Cohen (14) suggested a similar heuristic using MAXBAND with TRANSYT.

Substantial improvement of the total arterial system operations could be achieved by combining the apparent advantages of maximum bandwidth and minimum delay (9,19-21). The maximum bandwidth solution, based on the time-space diagram calculation, is the most efficient way to provide optimal signal phasing sequences. It is less affected by travel demand fluctuation than are solutions of minimum delay.

The PASSER model was first developed by Messer et al. (4) and modified to an off-line computer program cooperatively by the Texas Transportation Institute and Texas State Department of Highways and Public Transportation (SDHPT) (23). PASSER II was designed primarily for high-type arterial streets with protected left-turn lanes and phases. It provides the timing parameters for modern eight-phase controllers, such as the phase sequences, cycle length, green splits, and offsets, to provide the minimum interference and maximum progression bandwidth efficiency. The theory, model structure, methodology, and logic of PASSER II have been evaluated and documented (4,23-25).

PASSER II is widely used because of its ability to select multiple phase sequences in an easy, understandable maximum progression solution format. However, the heavy reliance on bandwidth optimization to achieve maximum progression might somehow limit its optimal solution capability to minimize systemwide vehicular delay. To improve the PASSER II computer program, the Texas SDHPT sponsored a highway planning and research project entitled "Reduced-Delay Optimization and Other Enhancements to PASSER II-80." This study developed the fundamental procedures of fine tuning offset to minimize total arterial delay and preserve the convenience of bandwidth maximization for multiphase traffic signal timing optimization. By applying the enhanced reduced-delay algorithm and fuel consumption computations, improved signal timing can be expected for PASSER II users in the future.

STUDY PROCEDURE

This study was undertaken to find an efficient and usable delay-based search algorithm for selecting a reduced-delay, arterial signal timing plan based on a maximum bandwidth solution. Four major items were developed: delay calculation methodology, offset fine-tuning capability, offset optimization routine, and fuel consumption computations.

The delay reduction procedures have several assumptions:

1. Cycle length, green split, phase sequence, and progression speed are known for each signal;
2. The optimal time-space diagram, shown in Figure 1, a maximum bandwidth solution, is provided as the starting solution and constraint for arterial system delay-offset analysis; and
3. The interactions between two intersections depend on the signal phase pattern, traffic volumes, and offsets of neighboring intersections.

At first, specific enhancements to improve the performance of PASSER II-80 as a maximum bandwidth-based procedure were identified. Then, the existing PASSER II-80 program was extended to provide a maximum bandwidth-based minimum-delay solution and, at

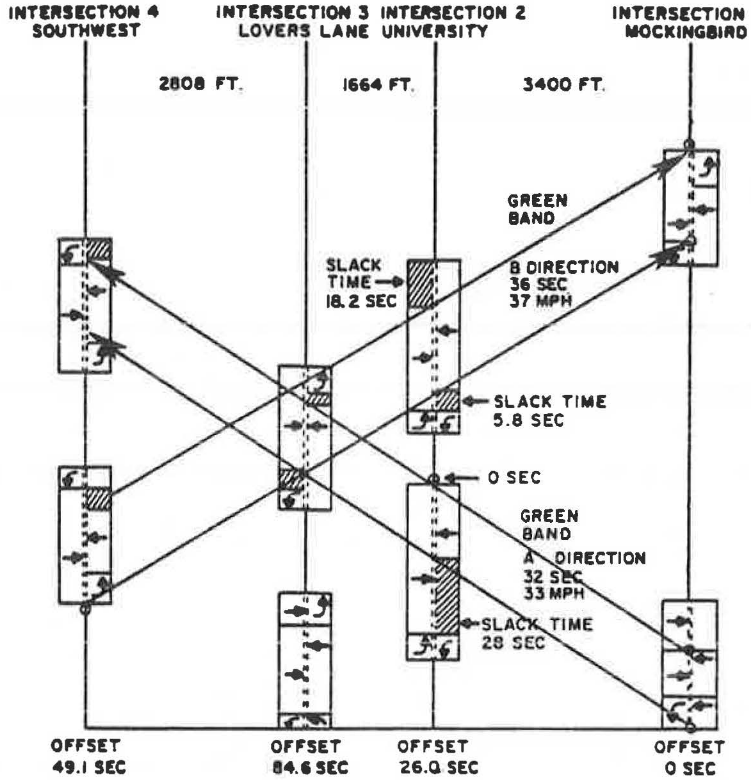


FIGURE 1 Example of slack time, slack-time allowance, and allowable offset range in PASSER II-80 time-space diagram (Skillman Avenue, Dallas, Texas).

the same time, to minimize delay, stops, and fuel consumption on arterial streets. Finally, the fuel consumption computations of TRANSYT-7F were enhanced for PASSER II-80 with the capability for future coefficient modifications by FHWA.

PASSER II ENHANCEMENTS

Efforts were made to improve the PASSER II-80 program to reflect users' working experience (24,25). The basic objective was to add a system offset fine-tuning optimization routine to PASSER II-80. The new extensions began with fine tuning the offsets starting from an existing progression solution in straightforward, deterministic, and noniterative approaches without affecting the major input and output structure.

Figure 2 shows a summary of the initial PASSER II-80 solution and enhanced PASSER II-84 program outputs. At first, the green splits are calculated by the modified Webster green split routine to equalize the specific volume-to-saturation flow ratios on critical movements. Then, optimal progression solutions are calculated by Brook's minimum interference theory to optimize phasing sequence and offset arrangements within coded preferable speed and optimal cycle length (26). The progression bandwidths are further adjusted to the sum of the total link volumes in both the A and the B directions.

After these calculations, the "best solution" and resultant time-space diagram, as in PASSER II-80, provide the initial solution to PASSER II-84. The enhanced PASSER II-84 can further provide the following capabilities:

1. Check the through progression band versus the actual green time interval. Detect any "plot through

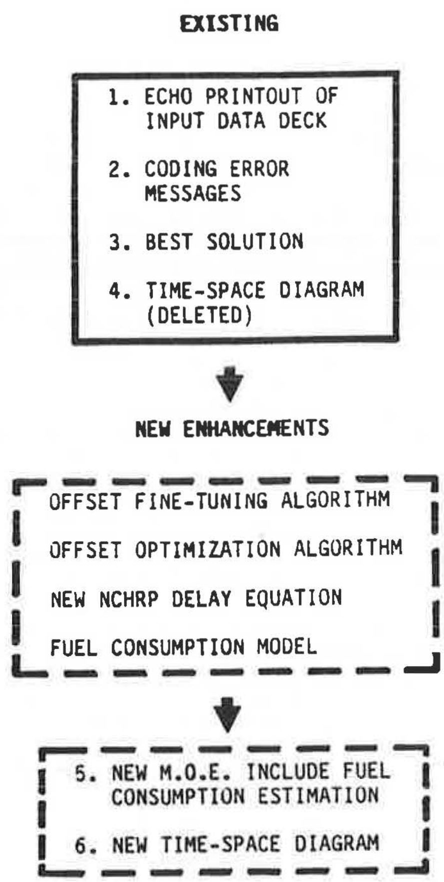


FIGURE 2 Schematic layout of elements in new PASSER II-84 output.

the red" and correct it, and then revise the available slack-time allowance in the time-space diagram.

2. Optimize offsets between intersections using delay-offset analysis. Adjust the time-space coordinate for a new time-space diagram.

3. Calculate the average delay per vehicle evaluation using the tentative NCHRP delay estimation equation to account for the oversaturated condition with saturation ratio greater than 1.0.

4. Estimate total fuel consumption (gal/hr) by the modified fuel consumption estimation model used in TRANSYT-7F.

5. As an option, compute the perfect one-way progression solution with the allowable design speed variations.

6. Provide the optional translation of the phase movement definitions of NEMA and PASSER II.

Finally, the result of the enhanced PASSER II-84 calculations will supply a reduced-delay best solution, including a fine-tuned time-space diagram and fuel consumption calculations.

Tentative NCHRP Delay Equation

Analytical delay estimates are commonly used in many computer models. The most widely used one is the Webster's model as plotted in Figure 3, which is based on Pignataro (2). However, because of the mathematical discrepancy, it is only applicable for a saturation ratio (or V/C ratio) up to about 0.95.

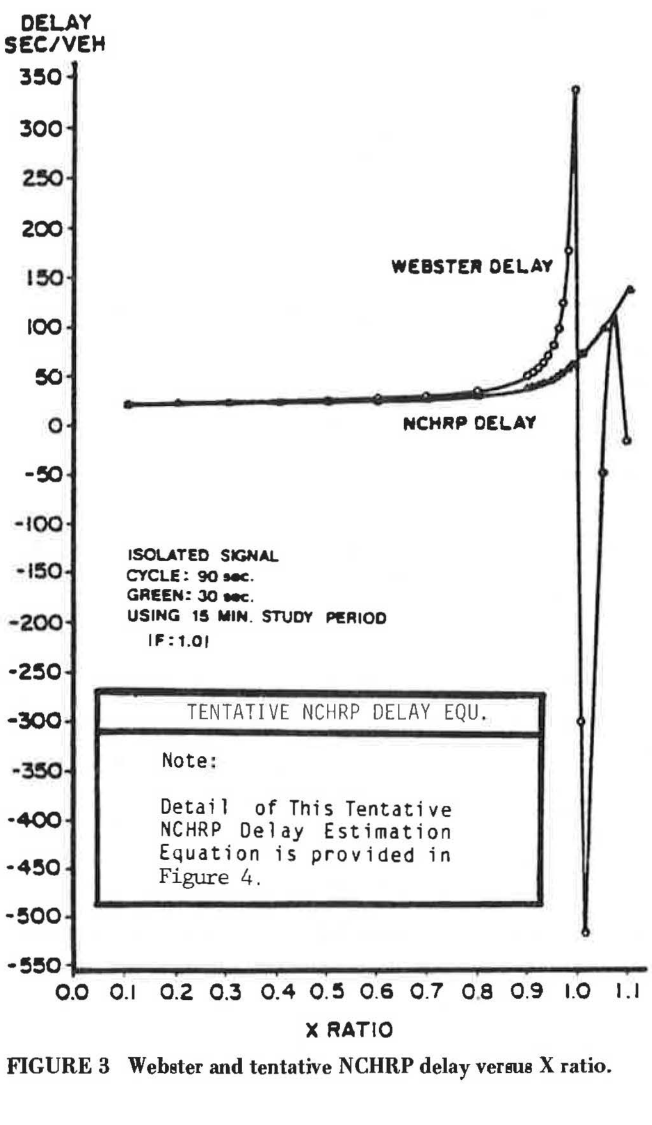


FIGURE 3 Webster and tentative NCHRP delay versus X ratio.

In updating the 1965 Highway Capacity Manual, National Cooperative Highway Research Program Project 3-28(2) developed a capacity and level of service method for urban signalized intersections. Specifically, a tentative delay estimation equation was developed to calculate delay and level of service for each lane combination (right, through, or left-turn lane), approach, and the overall intersection under normal, saturated, and oversaturated conditions. Summaries of the delay equations for the basic delay conditions are shown in Figure 4, which is based on Messer and Roess (27).

Uniform delay (UD) occurs in the period when all queued vehicles clear the approach on each cycle, assuming that none of the queued vehicles has to wait through more than one red period. The UD formula estimates the average stopped delay per approach vehicle for lane groups with a V/C ratio less than or equal to the overflow condition. The formula is based on uniform arrivals for various analysis period lengths (5 min to several hours). Overflow delay (OD) occurs when, on some cycles, all queued vehicles clear the approach while, on other cycles, some of the queued vehicles do not clear the approach due to variation of the traffic volume. Overflow delay is estimated according to the amount of the V/C ratio; that is, this empirically derived value adjusts the amount of the overflow delay according to the degree of oversaturation and randomness of traffic arrival patterns. The uniform delay component is not affected by the length of the analysis period. The overflow delay, because it is an estimate of arrival variations, is highly dependent on the analysis period. For convenience, a 15-min analysis period was assumed in PASSER II-84.

The tentative NCHRP delay estimation equation is valid for a V/C ratio above 1.0. However, the following guidelines should be noted when the V/C ratio is over 1.0:

1. Use the actual approach volumes. Check the analysis to assure that the volumes have not been adjusted to analyze the peak 15-min period or the worst lane;

2. Use the V/C ratio derived from the actual volumes, not the adjusted volumes; and

3. Use the time period that relates to the volumes and the V/C ratio.

Figure 3 indicates that the tentative NCHRP equation estimates the same or less delay than Webster's equation when V/C < 1.0 and provides a much better estimate of delay in oversaturated conditions. However, because the NCHRP delay equation was primarily designed for evaluation of uncoordinated signalized intersections, a version of this tentative NCHRP equation with a modified uniform delay term was added to the PASSER II-84 program by "platoon interconnection" adjustment as used in the existing PASSER II-80 program (28).

Offset Fine-Tuning Algorithm

To minimize total arterial system delay, efforts were made to find an efficient and applicable method to fine tune the offsets of individual intersections in an arterial system. It was determined that any new enhancements to PASSER II-80 should not conflict with the original maximum progression solution; such enhancements should, instead, fine tune this base solution by adjusting the relative offsets.

$$\text{NCHRP DELAY} = UD + OD$$

$$\text{WHERE } UD = 0.5 * \left[\frac{(C) * (1 - G/C)^2}{(1 - V/S)} \right]$$

$$OD = 225 * F * (X)^2 * \left[(X-1) + \sqrt{(X-1)^2 + \frac{16X}{V * F}} \right]$$

WHERE UD - UNIFORM DELAY
OD - OVERFLOW DELAY
C - CYCLE LENGTH
G - EFFECTIVE GREEN TIME
V - DEMAND VOLUME
S - SATURATION FLOW RATE
X - SATURATION FLOW RATIO
F - STUDY PERIOD ADJUSTMENT FACTOR
F = 1.0 WHEN STUDY PERIOD IS 15 MIN.
F = 4.0 WHEN STUDY PERIOD IS 1 HOUR

FIGURE 4 Tentative NCHRP delay estimation equation.

In the offset fine-tuning algorithm of PASSER II-84, subroutines FINTUN and PUSHUP first check through band versus actual green time, detect and correct the rare "plot through the red" condition, indicate the available slack-time allowance for the offset optimization, then reconstruct the time-space coordinates by travel time and distance calculations. The available slack-time allowance is the slack time, for a particular direction at each signal, that the offsets could be adjusted without losing the optimal progression solution and bandwidth.

Then, all the slack time is identified on both sides of the progression band for both travel directions at each traffic signal. The minimum value of the slack time that can be adjusted indicates the maximum amount of allowable green time available for adjusting the existing offset at each signal without affecting the bandwidth of the correct progression solution. This algorithm further reduces the need for manual adjustments on the final time-space diagram and provides a basic range of solutions for later constrained offset-optimization without searching through the entire cycle length as is done in the ordinary delay-offset analysis.

This offset fine-tuning algorithm is illustrated using the example time-space diagram of Skillman Avenue shown in Figure 1. At first, the slack time available for through movement but not used in the existing time-space diagram is indicated by hash marks. After the comparison of the relative magnitude of the slack time, the minimum values of slack time in each direction are identified as the allowable slack-time ranges at each signal for later offset fine-tuning optimization.

For example, in Figure 1, the slack times at the second signal are identified, respectively, as 28, 0, 5.8, and 18.2 sec on either side of the progression bands in both the A and the B directions. Because the A direction progression band is constrained by the zero slack time on the upper side of the A progression band for downward offset adjustment, the only allowable slack time available for upward offset adjustment, without affecting the width of both progression bands in either direction at intersection 2, is 5.8 sec on the lower end of the progression band in B travel direction. The resultant allowable slack-time range as found by this algorithm is 5.8 sec, and the resultant allowable offset adjustment range is, therefore, from the original 26 sec to a possible 31.8 sec.

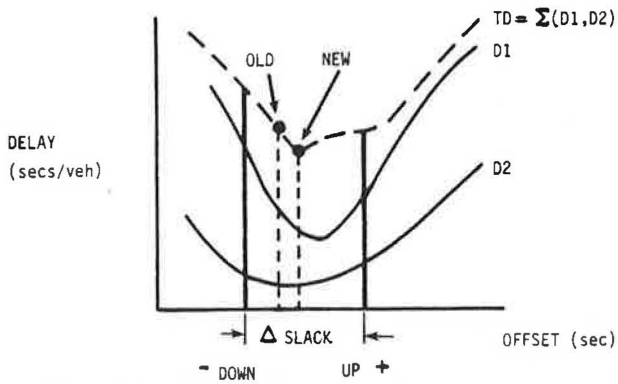
Offset-Optimization Algorithm

In PASSER II-84, subroutines OFSE2, OFSE3, and TSCORD provide an optimum progression offset between each signal. Further fine-tuning optimization would be obtained by adjusting the initial progression offset to some other fine-tuned offset within the allowable slack-time range to reduce the total two-way link delay from subroutines FINTUN and FKCDLY.

In this algorithm, progression remains the highest priority optimization objective and serves as the base for further optimization. The delay-offset analysis only fine tunes the offset within the allowable slack-time range. Operational performance is evaluated by average vehicle delay experienced by all vehicles. Because the total number of vehicles operated in the arterial street system during a fixed time period is a constant, adjusting signal settings can only redistribute the traffic and resultant delay on the network. Vehicular delays occurring between the intersections are calculated by a ver- sion of the deterministic delay-offset technique similar to that used in PASSER III for signalized diamond interchanges (24,29-31).

According to the combination method, where two or more links occur in parallel joining two nodes, the delay function of the individual links can be combined with reference to the same offset to yield an aggregate delay function. Then, the total delay function is calculated by combining all the individual delay-offset functions of the through links in both the A and the B directions. The average combined delay function is obtained by dividing the total delay of the adjacent signal pairs by the total link traffic volumes. An optimal offset, between the adjacent pair of signals, is obtained by searching for the minimal value of the combined delay-offset function.

Figure 5 shows the basic theory of the constrained delay-offset analysis in PASSER II-84. As indicated, the delay-offset curves D1 and D2 for each internal link are first developed. Then, the total delay-offset curve between a pair of signalized intersections is derived by accumulating the delays on each link at respective offset locations. The TD curve shown in Figure 5 is volume weighted instead of the sum of D1 and D2. The slack time allowance range (ΔSLACK) for each intersection is then identified by the range between -DOWN and UP+.



STEP 1. Calculate Average Delay-Offset Curves (D1 and D2),

STEP 2. Sum Up Individual Link Delay-Offset Curves to Obtain Total Systemwide Average Delay Per Vehicle Curve (TD),

STEP 3. Identify Slack Time Allowance Range (ΔSlack) on TD,

STEP 4. Obtain Reduced-Delay Solution (NEW) from Existing Progression Solution (OLD).

FIGURE 5 Delay offset analysis in PASSER II-84 offset-optimization algorithm.

Finally, the systemwide average delay per vehicle of the existing progression solution (OLD OFFSET) is calculated, and the offset optimization algorithm will search over the slack-time-allowance range (ΔSLACK) to obtain the reduced-delay solution (NEW OFFSET) as shown. Therefore, the optimization problem becomes:

> Find a new reduced-delay offset (NEW) within the slack-time allowance (-DOWN≤SLACK≤UP+) for a given combination of fixed cycle, phase sequence, green split, initial progression offset, and two delay curves (D1 and D2) of right-turn and through movements in both A and B directions.

In this algorithm, both the original maximum bandwidth procedure and the minimum delay algorithm are considered. The maximum bandwidth solution (OLD) in PASSER II-80 can be improved by this modified delay-offset algorithm to a reduced-delay solution (NEW) under multiphase operation in PASSER II-84. The detailed evaluation procedure and study results comparing the PASSER II-80 and the PASSER II-84 programs are discussed in another paper in this Record entitled "Minimum Delay Optimization of a Maximum Bandwidth Solution to Arterial Signal Timing."

Fuel Consumption Model

Faced with a fuel shortage and the increased fuel prices prevalent in the 1970s, traffic engineers became more and more sensitive to the consequences of delay and stops. To provide a more realistic evaluation of traffic signal alternatives, a fuel consumption estimation model was applied with the measure of effectiveness from PASSER II-84. It is capable of accepting any future modifications, by FHWA, to the fuel consumption equations.

After reviewing the available fuel consumption estimation models, the fuel consumption routine in TRANSYT-7F was modified and added to PASSER II-84. The model was developed from a series of stepwise multiple regression analyses of data collected and programmed by the Transportation Research Center of the University of Florida (8). The basic model estimates the total arterial system fuel consumption (gal/hr) as a function of total travel (veh-mile/hr), total delay (veh-hr/hr), total stops (veh/hr), and cruise (free) speed (mph).

Among these variables in the fuel consumption model, the total stops in vehicles per hour was the only variable not available in PASSER II-80. Therefore, a modified formula, developed by Akcelik and Miller, was applied in PASSER II-84 to estimate the total stops for coordinated multiphase traffic signals operated on arterial streets (8,17). In summary, the formula for estimating total number of stops per hour is calculated directly as

$$H = (3240/C) \cdot [(vr/1 - g/s) + N_o]$$

where

v = arrival flow rate (veh/sec),
C = cycle time (sec),
g = effective green time (sec),
s = saturation flow rate (veh/sec), and
N_o = average overflow queue (veh/sec)
where

$$N_o = \exp\left(\{1.33 \cdot [(1 - vC/gs)/(vC/gs)] \cdot (s \cdot g)^{1/2}\}/(2 - vC/gs)\right).$$

Perfect One-Way Progression

Because of the physical restrictions and unique traffic characteristics of the urban street network, the PASSER II program may sometimes be used to provide one-way progression. This option can provide the optional time-space diagram for a one-way street or for an arterial street system with heavy directional peak-hour travel.

Subroutine ONEWAY, similar to the one in PASSER III, calculates the offsets and overwrites the time-space coordinates providing "perfect" one-way progression along a two-way arterial street (26,p.27). The "perfect" one-way progression solution in either the A or the B direction can be obtained by specifying a 1 or a 99 in the optional "min. B direction band split" of the PASSER II-84 input data set. Figure 6 shows an example of the result from the subroutine when 1 is specified for the "perfect" one-way progression option in the A direction.

As indicated, a "perfect" progression band that uses the whole amount of the available green time for progression movement in the A travel direction is provided as specified. Similarly, the "perfect" one-way progression band can be provided for the progressive movement in B travel direction by specifying 99 in this one-way progression option. In both cases, the traffic signal settings optimized

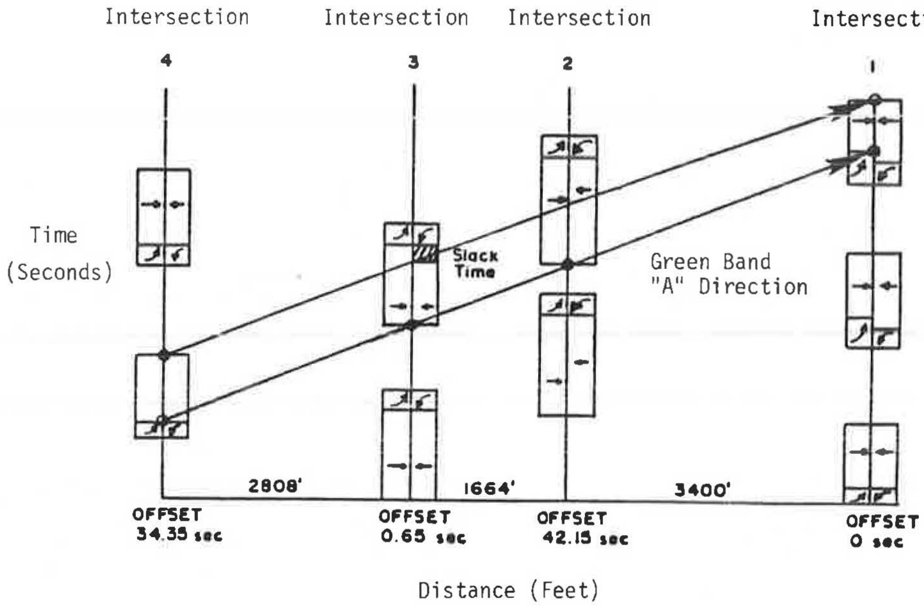


FIGURE 6 Time-space diagram of the perfect one-way progression in A direction.

for the original two-way progression solution of the PASSER II program are used with the fine-tuning offsets.

Phase Movement Translations in NEMA and PASSER

Two widely accepted phase movement designations have been used in PASSER II-80: National Electrical Manufacturers' Association (NEMA) and PASSER phase definitions. As shown in Figure 7, the NEMA designation could be considered as swapping the major street movements 3 and 4 with the minor street movements 5 and 7 compared to PASSER's designation.

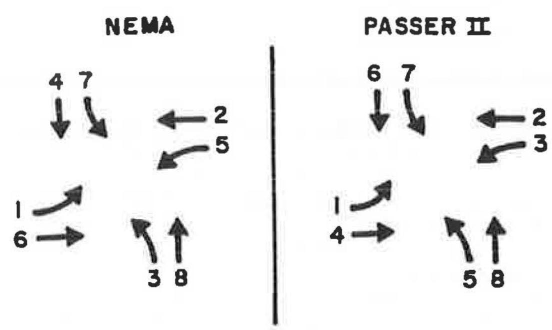


FIGURE 7 Movement definitions in NEMA and PASSER II.

As the data in Table 1 indicate, PASSER II-80 uses PASSER's phase designation as default input with the option of using the NEMA movement definition as an alternative. As indicated, PASSER II-84 still has the existing PASSER II-80 options to choose between: the NEMA (option 1) and the PASSER phase definition (option 0). In addition, if the user wants to use PASSER's phase definition as input but chooses the NEMA phase definition as output, a 2 may be entered. If the user prefers to use the NEMA phase as input but desires PASSER's movement numbering definition for output, 3 may be entered in the

TABLE 1 Movement Translation Codes for NEMA and PASSER II

OUTPUT OPTION \ INPUT OPTION		INPUT	ECHO
		P2	NEMA
OUTPUT	P2	0	3
	NEMA	2	1

data field. PASSER II-84 recognizes the options selected (or default) and provides proper phase movement designations in both the echo printout of input data deck and the final printout of the PASSER II-80 "best solution."

Summary

In summary, significant programming efforts have been completed using ANSI FORTRAN 77 standard on the Amdahl Computer System at Texas A&M University. The results comprise the revised PASSER II-84 program with the new delay calculation and offset optimization routine, as shown in Figure 8. These efforts permit the user to determine the optimal signal settings for progression operation on signalized arterial streets without having to manually adjust the offsets of the final time-space diagram for reduced-delay operation.

CONCLUSIONS AND RECOMMENDATIONS

The enhanced reduced-delay optimization in PASSER II-84 guarantees minimizing total arterial system delay within the slack-time allowance of the original PASSER II solution. However, the general improvement that can be achieved by PASSER II-84 relies mainly on the quality of the original answer. If the green times were intentionally constrained,

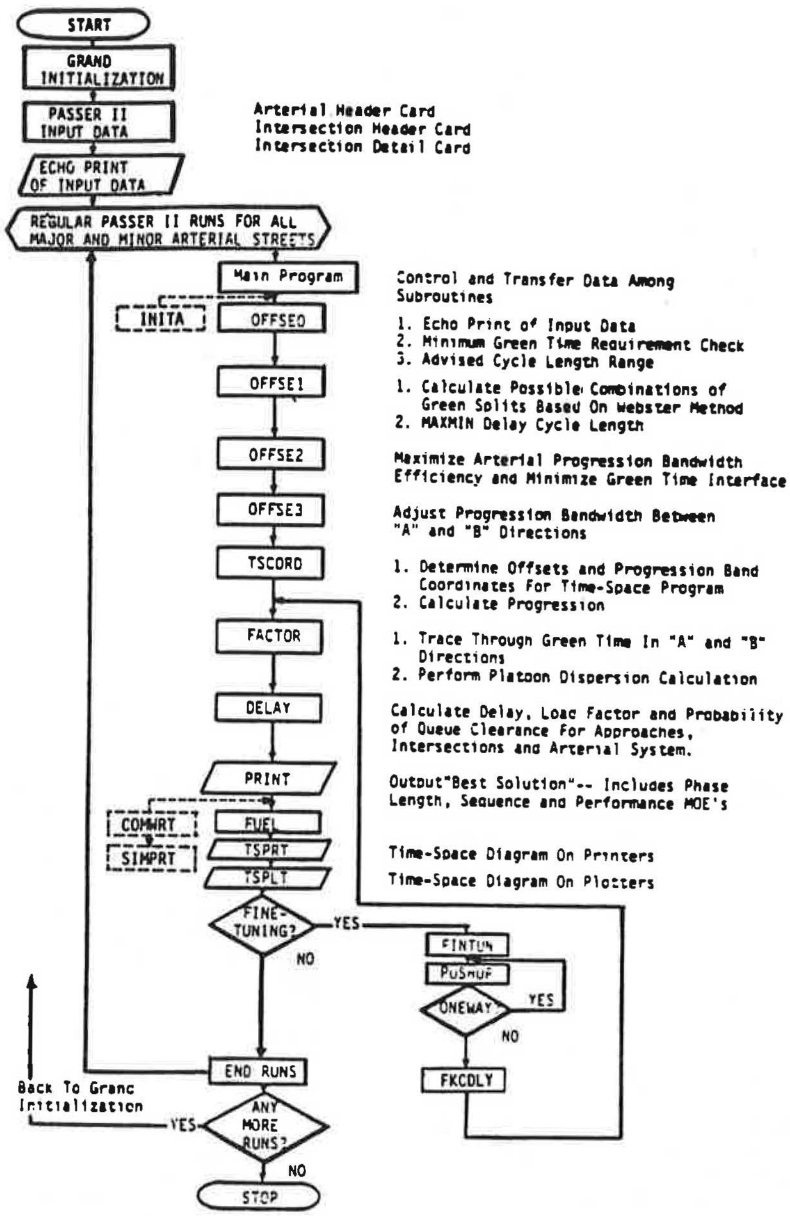


FIGURE 8 Functional flowchart for PASSER II-84.

or had been engineered in an expert manner, the improvements would not be as significant as they would be for ordinary PASSER II solutions.

This study and several other related studies have also found that trading off progression bandwidth in either arterial travel direction, instead of using the total directional traffic volume ratios and minimum green as constraints, may further improve the total system performance. Because the enhanced PASSER II-84 program does not have a microscopic simulation model to predict actual platoon dispersion effects on the downstream signals, the accuracy and estimation ability of the "platoon projection model" or the "platoon interconnection effect" is constrained by site-dependent travel behavior, vehicular mixes, and travel speeds.

Therefore, further research is recommended on field validation of the reduced-delay offset-optimization algorithm, the calibration of platoon dispersion models, alternative strategies for allocating the directional bandwidths, revision of green split routine to account for the impact of green time adjustment on overall system delay, and trade-offs of local and system optimization problems in arterial signal optimization.

Documentation of research results in the development of PASSER II-84, the latest version of arterial traffic signal timing computer model of the Texas State Department of Highways and Public Transportation, is available elsewhere (32). A comparison of the basic features in existing PASSER II-80, enhanced PASSER II-84, TRANSYT-7F, and MAXBAND computer models is given in Table 2. No modifications to the existing user's manual or data coding are required in the enhanced PASSER II-84. The basic program is currently operational on the Texas SDHPT district remote computer terminals.

ACKNOWLEDGMENTS

The paper is based on research conducted for the Texas Department of Highways and Public Transportation in cooperation with the FHWA, U.S. Department

TABLE 2 Comparison of PASSER II-80, PASSER II-84, TRANSYT-7F, and MAXBAND Computer Programs

	PASSER II (NEW)	PASSER II (OLD)	MAXBAND (MITROP)	TRANSYT-7F
Control Variables	Cycle Offset ϕ-Sequence ϕ-Length	Cycle Offset ϕ-Sequence ϕ-Length	Cycle Offset ϕ-Sequence ϕ-Length	Cycle Offset ϕ-Length
Optimization	Max. Bandwidth Min. Interference Delay-Offset	Max. Bandwidth Min. Interference	Max. Bandwidth MPCODE	Min. Delay
Solution	Local Optimum	Local Optimum	Global Optimum	Local Optimum
Objective Function	Max. Efficiency Min. Link Delay (Interior)	Max. Efficiency	Min. (Flow × Cost) Offset Split	Min. PI = (Delay + k × stops)
Delay Measurement	Mod. Webster NCHRP-TTI-PINY	Mod. Webster	Link Performance Saturation Deterrence	Platoon Representation by Flow Profile
Delay Component	1. Uniform Delay 2. Overflow Delay	1. Uniform Delay 2. Random Delay 3. Empirical Adj.	1. Deterministic Queue 2. Stochastic Overflow	1. Uniform Delay 2. Random Delay 3. Saturation Delay
Fuel Consumption	Yes	No	No	Yes
Data Input Base	Node	Node	Node	Link
Phase Selection	PASSER NEMA or Combinations	PASSER NEMA (A/B Dir.)	Inbound Outbound	Link Movements

of Transportation. The technical input and constructive comments from Texas SDHPT and FHWA officials during the conduct of this research are greatly appreciated.

REFERENCES

1. Manual of Traffic Engineering, 2nd ed. Institute of Traffic Engineers, Washington, D.C., 1976.
2. L.G. Pignataro. Principles of Traffic Engineering--Theory and Practice. Prentice-Hall, New York, 1976.
3. P. Ross and D. Gibson. Review of Road Traffic Network Simulation Models. In Transportation Research Record 644, TRB, National Research Council, Washington, D.C., 1977, pp. 36-41.
4. C.J. Messer, R.H. Whitson, C.L. Dudek, and E.J. Romano. A Variable Sequence Multiphase Progression Optimization Program. In Highway Research Record 445, HRB, National Research Council, Washington, D.C., 1973, pp. 24-33.
5. J.D.C. Little and M.D. Kelson. Optimum Signal Timing for Arterial Signal Systems, Vol. 1: Summary Report. Operations Research Center, Massachusetts Institute of Technology, Cambridge, April 1980.
6. M.D. Kelson. Optimal Signal Timing for Arterial Signal Systems, Vol. 3: MAXBAND Programmer's Manual. Operations Research Center, Massachusetts Institute of Technology, Cambridge, May 1980.
7. D.I. Robertson. TRANSYT: A Traffic Network Study Tool. TRRL Report 253. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1969.
8. Transportation Research Center, University of Florida. TRANSYT-7F--User's Manual. FHWA, U.S. Department of Transportation, Feb. 1983.
9. J.D.C. Little, N.H. Gartner, and H. Gabby. MITROP: A Computer Program for Simultaneous Optimization of Offsets, Splits, and Cycle Time. Traffic Engineering and Control, Aug. 1976, pp. 355-362.
10. E.B. Lieberman and J.L. Woo. SIGOP II: A New Computer Program for Calculating Optimal Signal Timing Patterns. In Transportation Research Record 596, TRB, National Research Council, Washington, D.C., 1976, pp. 16-21.
11. R.O. Rogness. Possible PASSER II Enhancements. In Transportation Research Record 881, TRB, National Research Council, Washington, D.C., 1982, pp. 42-48.
12. C.E. Wallace and K.G. Courage. Arterial Progression--New Design Approach. In Transportation Research Record 881, TRB, National Research Council, Washington, D.C., 1982, pp. 53-59.
13. D.W. Whitehead, K. Ross, and B.D. Miller. The Use of Empirical Platoon Profiles to Minimize Signal Network Delay. Traffic Engineering and Control, Vol. 17, No. 1, Jan. 1976, pp. 10-13.
14. S.L. Cohen. Concurrent Use of the MAXBAND and TRANSYT Signal Timing Programs for Arterial Signal Optimization. In Transportation Research Record 906, TRB, National Research Council, Washington, D.C., 1983, pp. 81-84.
15. N.H. Gartner, J.D.C. Little, and H. Gabby. Optimization of Traffic Signal Settings by Mixed-Integer Linear Programming, Part I: The Network Coordination Problem. Transportation Science, Vol. 9, No. 4, Nov. 1975, pp. 321-342.
16. C.J. Messer, D.B. Fambro, and D.A. Anderson. Effects of Design on Operational Performance of Signal Systems. Research Report 203-2F. Texas Transportation Institute, Texas A&M University, College Station, Aug. 1975.
17. R. Akcelik. Time-Dependent Expressions for Delay, Stop Rate and Queue Length at Traffic Signals. Internal Report AIR 367-1. Australian Road Research Board, Numawading, Victoria, Australia, Oct. 1980.
18. L.P. Rach et al. Improved Operation of Urban Transportation Systems, Vol. 1: Traffic Signal Control Strategies--A State-of-the-Art. Corporation of Metropolitan Toronto, Ontario, Canada, March 1974.
19. F.A. Wagner, D.L. Gerlough, and F.C. Barnes. Improved Criteria for Traffic Signals at In-

dividual Intersections. NCHRP Report 32. HRB, National Research Council, Washington, D.C., 1967.
20. C.E. Wallace. Development of a Forward Link Opportunities Model for Optimization for Traffic Signal Progression on Arterial Highways. Ph.D. dissertation. University of Florida, Gainesville, 1979.
21. R.O. Rogness. Evaluation of a Heuristic Programming Approach to Arterial Street Signal Timing Operation. Ph.D. dissertation. Texas A&M University, College Station, 1981.
22. K.W. Huddart. The Importance of Stops in Traffic Signal Progression. Transportation Research, Vol. 3, No. 1, April 1969, pp. 143-150.
23. C.J. Messer, H.E. Haenel, and E.A. Koeppe. A Report on the User's Manual for Progression Analysis and Signal System Evaluation Routine--PASSER II. Research Report 165-14. Texas Transportation Institute, Texas A&M University, College Station, Aug. 1974.
24. C.J. Messer, D.B. Fambro, and E.C. Chang. Signal Timing Optimization to Maximize Traffic Flow--A 2-Day Workshop. Texas Transportation Institute, Texas A&M University, College Station, April 1983.
25. PASSER II-80 User's Manual. Texas State Department of Highways and Public Transportation, Austin, Dec. 1982.
26. W.D. Brooks. Vehicular Traffic Control, Designing Arterial Progression. IBM Document. Armonk, N.Y., 1966.
27. C.J. Messer and R. Roess. Signalized Intersections. Draft. NCHRP Project 3-28 to Update the 1965 Highway Capacity Manual. TRB, National Research Council, Washington, D.C., July 1984.
28. C.J. Messer and D.B. Fambro. A Guide for Designing and Operating Signalized Intersections in Texas. Research Report 203-1. Texas Transportation Institute, Texas A&M University, College Station, Aug. 1975.
29. F.V. Webster and B.M. Cobbe. Traffic Signals. Technical Paper 56. Road Research Laboratory, London, England, 1966.
30. J.C. Tanner. A Problem of Interface Between Two Queues. Biometrika, Vol. 40, 1953.
31. P.J. Tarnoff. The Results of FHWA Urban Traffic Control Research: An Interim Report. Traffic Engineering 45, April 1975, pp. 27-35.
32. E.C. Chang, C.J. Messer, and B.G. Marsden. Analysis of Reduced-Daily Optimization and Other Enhancements to PASSER II-80--PASSER II-84--Final Report. Research Report 375-1F. Texas Transportation Institute, Texas A&M University, College Station, April 1984.

The opinions and conclusions expressed are the authors' and are not necessarily those of Texas SDHPT and FHWA.

Publication of this paper sponsored by Committee on Traffic Flow Theory and Characteristics.

Abridgment

Minimum Delay Optimization of a Maximum Bandwidth Solution to Arterial Signal Timing

EDMOND CHIN-PING CHANG and CARROLL J. MESSER

ABSTRACT

This study indicated the advantages and drawbacks of combining the two major state-of-the-art traffic signal control strategies: the bandwidth maximization procedure and the delay minimization technique. The enhanced reduced-delay optimization model provided in PASSER II-84 guarantees minimum total arterial system delay within the slack-time allowance range of the original PASSER II-80 maximum progression solution. Modifications to the PASSER II signal timing plan for an arterial street system, using both a maximum bandwidth procedure and a minimum delay signal timing optimization algorithm, are evaluated. An efficient and usable delay-based search algorithm to assist traffic engineers in selecting a minimum delay arterial street signal timing plan that optimizes phasing sequence, cycle length, and offsets based on maximum bandwidth calculations in an urban network is demonstrated. The maximum bandwidth procedures are based mainly on calculations of distance, travel speed, and continuity of available green time for progressive movements without direct relationship to delay. The minimum delay algorithm minimizes total system delay endured by all traffic in the analysis network. Resulting offsets confirmed the feasibility of minimizing delay by the optimal offsets from the maximum bandwidth algorithm. When minimum delay and maximum progression are used, as calculated by the enhanced PASSER II-84, an improved level of service results thereby providing maximum progres-