PASSER IV: A Program for Optimizing Signal Timing in Grid Networks

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The development of PASSER IV, a practical state-of-the-art program for simultaneously optimizing progression bandwidth in multiarterial traffic signal networks, is described. PASSER IV is efficient and is being developed for use on personal computers. A user-friendly mouse-driven graphic interface that provides data entry and file management functions makes the program extremely easy to use. However, the main core of the program, written in FORTRAN 77 using structured programming techniques, is usable on virtually any type of computer. The existing version of PASSER IV determines all four signal timing parameters: cycle length, green split, offset, and phasing sequence. The program optimizes cycle lengths, offsets, and phasing sequences to maximize progression bandwidth. The green splits, however, are determined in a preprocessor using Webster's method. In addition, PASSER IV is capable of minimizing cycle length and can report signal timings for several alternative optimal solutions. Also described is ongoing research to enhance the capabilities of PASSER IV. This research includes optimization of green splits, optimization of two additional main-cross split (circular) phasing sequences, delay calculation procedure, and the capability to generate data files for TRANSYT 7F to facilitate fine-tuning of bandwidth solutions through bandwidth-constrained delay optimization. The final version of PASSER IV will be available in mid-1994.

Optimal traffic signal timing in urban and suburban networks is essential for the full utilization of existing roadways. The objective of signal timing optimization in undersaturated networks is to determine four signal timing parameters, namely, signal cycle lengths, offsets, phasing sequences, and green splits, that optimize (*a*) progression bandwidth, (*b*) a combination of delay and stops, or (*c*) a compromised function based on bandwidth and delay. The existing technology, however, has limitations that do not allow the full achievement of desired objectives.

MAXBAND 86 (*1*,*2*), the only program now generally available for progression bandwidth maximization in multiarterial networks, does not optimize green splits, has a very simplistic traffic model, and is extremely inefficient for practical computations. In addition, it has no capability for reporting traffic measures such as delay, stops, and level of service. TRANSYT 7F (*3*), a program for delay minimization in traffic networks, is the most widely used network signal timing optimization program. TRANSYT 7F, however, is incapable of phasing sequence optimization. Further, its final solution is dependent on the quality of the starting solution, which is not always available.

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Recent research has shown that concurrent use of MAXBAND 86 and TRANSYT 7F produces signal timings better than those produced by either program alone (*4*,*5*). This approach suggests that the initial starting solution for TRANSYT 7F should be obtained using a bandwidth maximization program and fine-tuned using the bandwidth-constrained delay minimization capability in TRANSYT 7F. However, unlike Arterial Analysis Package (AAP) (*6*) for arterial problems, no program currently exists that provides traffic engineers an automated capability for employing this coordinated approach to multiarterial network optimization problems.

PASSER IV is being developed to overcome many of the above limitations in the existing programs for optimizing signal timing in traffic networks. The focus of this paper is the undersaturated traffic control problem. PASSER IV has evolved from MAXBAND 86 over a period of several years, and all the basic features of MAXBAND 86 have been retained in PASSER IV. However, several enhancements and additional features make the new program easier and more practical to use by traffic engineers. In the following sections, key features of PASSER IV and the current developmental work are described. To begin, the network data sets used for illustrating computational results in the remainder of the paper are described.

DESCRIPTION OF TEST DATA

Thirteen network data sets are used for illustrating computational results described in this paper. Table 1 describes these network problems. The information includes network name and location and the number of arterials, signals, links, and closed loops in the network. More detail and extensive computational experience with these specific problems are described by Chaudhary et al. (*7*).

DESCRIPTION OF PASSER IV PROGRAM

PASSER IV is an advanced network signal timing optimization program. It currently is the only practical personal computer (PC)-based computer program that can optimize signal timings for large multiarterial networks based on maximizing platoon progression. PASSER IV simultaneously maximizes progression bandwidth on all arterials (one-way and two-way) in closed networks such as that shown in Figure 1. PASSER IV explicitly handles one-way streets. It calculates green splits

TABLE 1 Description of Network Problems

NO.	NETWORK NAME	NETWORK GEOMETRY ARTERIALS	SIGNALS	LINKS	LOOPS
1.	University/Canyon/12th/ Street	3	11	11	1
2.	Wisconsin/Massachusetts/Garfield	3	15	15	1
3.	Pennsylvania/Connecticut/K Street	3	17	17	1
4.	Hawthorne Blvd. mini network, California	5	9	10	2
5.	Walnut Creek Network, California	6	13	15	3
6.	Daytona Beach Network, Florida	7	12	17	6
7.	Post Oak Network, Houston, Texas	8	13	18	6
8.	Ogden Network, Utah	8	13	18	6
9.	Ann Arbor Michigan	8	14	20	7
10.	Los Angeles, California	8	15	21	7
11.	Owosso, Michigan	8	16	18	3
12.	Bay City, Michigan	8	16	20	5
13.	Downtown Memphis Network, Tennessee	8	17	22	6

(from volume and saturation flow data) using Webster's method (*8*) and then optimizes cycle length, offsets, and National Electrical Manufacturers Association (NEMA) phasing sequences with overlap. In addition, PASSER IV allows link-to-link speed variations together with arterial and directional priority options.

PASSER IV is the result of several years of research at Texas Transportation Institute on methods to improve the mathematical model for optimizing progression bandwidth in networks together with the computational efficiency of the underlying mixed-integer linear programs for simultaneously maximizing progression bands on all arterials in the network. The program is being developed with a focus on PC users; however, the core of PASSER IV is adaptable for use on any computer with a FORTRAN compiler. Two PC versions of PASSER IV have been developed and are being enhanced. The standard PC version can be used with any IBM-compatible PC with 640K of random access memory (RAM) and can handle networks having up to 20 arterials and 35 intersections. The advanced PC version is designed for use on 80486 and 80386 (with math coprocessor) based PCs with at least 8 megabytes of RAM. This version can handle larger networks with up to 50 intersections. The advanced version is also twice as fast as the standard PC version. In the following sections, key features of PASSER IV, additional options currently being implemented in PASSER IV, and future plans for enhancing the program are described. The final version of PASSER IV with all these features, PASSER IV-94, will be ready for distribution in mid-1994.

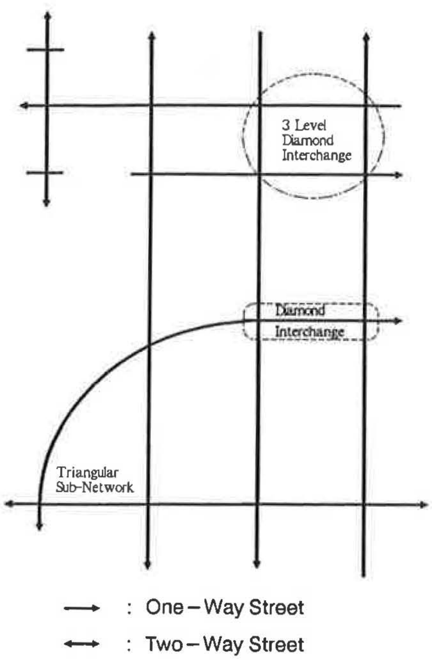

FIGURE 1 Example network with possible subcomponents.

KEY FEATURES OF PASSER IV

Graphic User Interface

PASSER IV's menu-driven graphic user interface (GUI), with pull-down menus and mouse support, makes the program extremely easy to use. Data are entered arterial by arterial until the total network is described. Arterial data can be entered in any order. However, data for intersections on an arterial must be entered in sequential order. This format is slightly restrictive as compared with other programs, but it reduces the linkage data coding requirements to only link distances and travel speeds. The other linkage information is automatically obtained by the program. The program requires that each intersection be assigned a unique (node) identification number. This allows the program to determine the network structure. In addition, this scheme permits the data for a signal (which falls on two intersecting arteries) to be entered only once. Figures 2 and 3 shown two video screens of the GUI.

Computational Efficiency

In the past, some researchers have speculated that MAXBAND's optimization routine MPCODE (*9*) was inef-

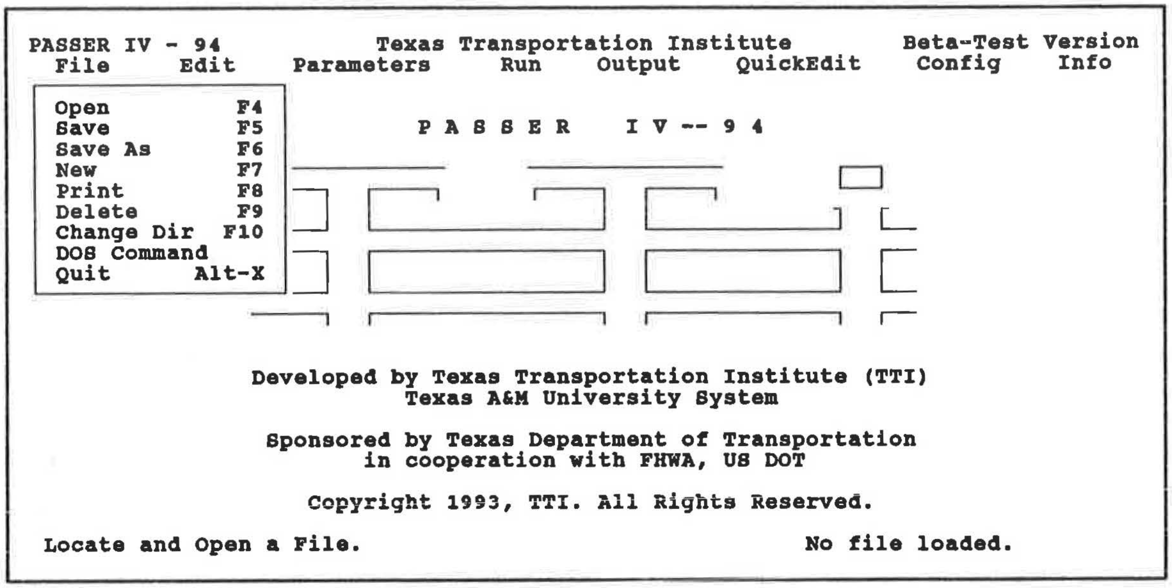

FIGURE 2 Pull-down menus.

ficient and recommended that it be replaced by a more efficient routine (*10,11*). Experimental work by Chaudhary et al. and comparison of MPCODE with LINDO (*12*) (a fairly recent efficient optimization package), however, demonstrated that MPCODE is as efficient as LINDO for signal timing optimization problems (*13*). Chaudhary et al. further concluded that the underlying mixed-integer linear programming (MILP) problem formulations for signal synchronization in networks are inherently difficult, requiring the need to develop efficient heuristic optimization procedures. Therefore, MPCODE is retained in PASSER IV and the optimization efficiency of PASSER IV is increased by implementing the following techniques:

1. The simultaneous optimization method of MAXBAND 86 has been retained in PASSER IV. In addition, two heuristic optimization techniques developed by Chaudhary et al. (*7,14*) have been implemented in PASSER IV. The two-step heuristic method is 10 times faster than the simultaneous optimization (SO) of all variables and produces the same results as the SO method. The three-step method is up to 99 percent faster than the SO approach, but it does not guarantee the absolute maximum bandwidth, although it produces the best possible solution in many cases. For large network problems, however, the three-step method seems to be the only feasible approach from a practical point of view.

2. In PASSER IV, one-way arterials are explicitly modeled as compared with the approach used in MAXBAND 86. This reduces the MILP size and computational complexity of network problems with one-way arterials. As a consequence, the central processing unit (CPU) time is reduced and wider bands are produced (*7*).

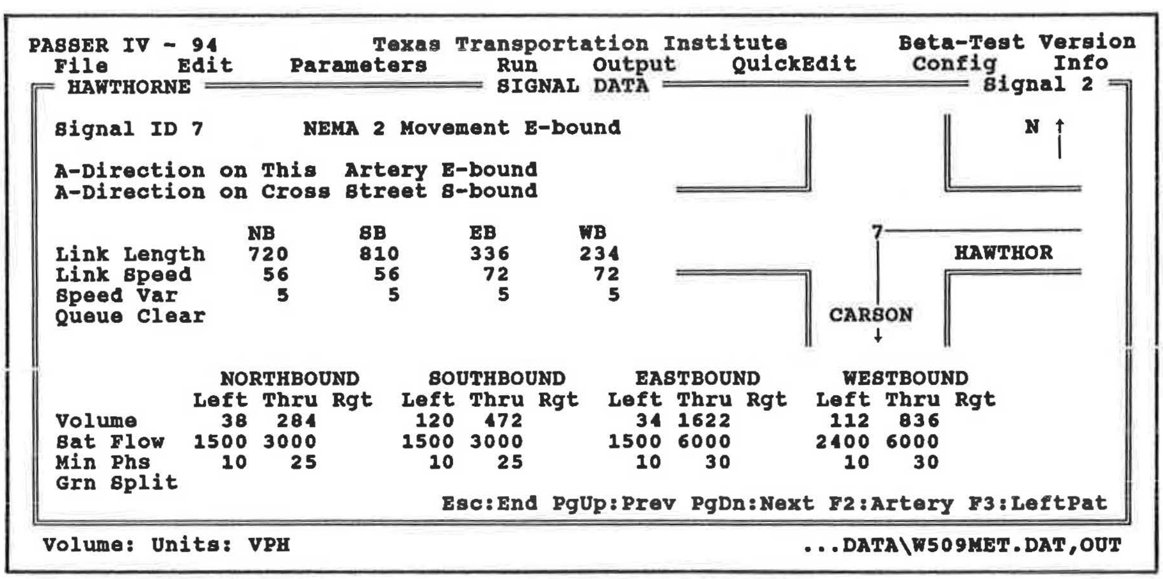

FIGURE 3 Signal data entry screen.

3. Chaudhary et al. (*7*) demonstrated that the use of tighter bounds for link synchronization variables significantly enhanced the computational efficiency of MILPs for progression bandwidth optimization. However, this approach is not practical since the results were based on the usage of bounds obtained through observation of only a few test problems. Recently, a formal, data-specific scheme for calculating tighter bounds for these variables was developed by Chaudhary et al. (*14*). This scheme has been implemented in PASSER IV. The use of tighter bounds reduces the search region. In addition, integer variables having the same lower and upper bounds are eliminated from the MILP. As a consequence, PASSER IV produces solutions much faster than MAXBAND 86.

Table 2 provides a summary of optimization results for the test problems using the advanced version of PASSER IV on a 80486-based PC. The three-step heuristic method was selected for optimizing all the test network problems. Information given in Table 2 includes total bandwidth as a fraction of cycle length (entries in parentheses give the best possible total bandwidth as a fraction of cycle length using simultaneous optimization), average total arterial bandwidth obtained by dividing numbers in the previous column by the number of arterials in the network, and the CPU run time in seconds required on the PC. Observations of the results are summarized as follows:

1. Except for the second problem, all total bandwidths obtained were within 95 percent of the best possible bandwidths. Further, total bandwidths for eight problems were within 99 percent of the best possible bandwidths. These results demonstrate that the three-step method provides good (sometimes the best) solutions for network problems.
2. None of the problems required more than 8 min of CPU time for optimization. In contrast, the same problems required several (sometimes up to 10) hours of CPU time when optimized using MAXBAND 86 (7).

In summary, the three-step optimization capability in PASSER IV makes the program feasible for use even on a PC. Given the fact that the traffic data used in the optimization program are never 100 percent accurate, this heuristic strategy is more than sufficient for practical purposes. However, for those users who wish to obtain absolutely the best solutions, PASSER IV is equipped with two-step and simultaneous optimization capabilities.

Minimization of Cycle Length

Often a signal timing optimization problem has multiple optimal solutions with the same bandwidth efficiency but different cycle lengths. PASSER IV has an optional capability to select the solution with the lowest cycle length. The user can activate this capability by setting the cycle length optimization switch and specifying the weight to be given to cycle length optimization. The higher the weight, the better the chance of finding a solution having a lower cycle length. However, care should be taken because too high a weight may result in a nonoptimal bandwidth solution.

To illustrate the fact that same best bandwidth (as a fraction of cycle length) may result at various cycle lengths, an actual arterial (12th Street) is used (Figure 4). Two volume conditions, a.m. peak and off peak, were examined. Multiple bandwidth solutions using the simultaneous optimization method for these problems were obtained and analyzed using TRANSYT 7F. Tables 3 and 4 summarize the results. The following is a discussion of the results:

1. For the a.m. peak case, four alternative optimal solutions having the best bandwidth of 0.37564 (fraction of cycle length) were found. For the off-peak volume conditions, two solutions with the best total bandwidth equal to 0.4223 (fraction of cycle length) were found.
2. For the a.m. peak condition, neither the lowest nor the highest cycle length resulted in the least delay. In fact, the

TABLE 2 Summary of PASSER IV Runs

NO.	NETWORK NAME	Total Bandwidth Efficiency	Average Arterial Bandwidth Efficiency	CPU Run Time (seconds)
1.	University/ Canyon/ 12th/ Street	1.281(1.304)	.427	10
2.	Wisconsin/ Massachusetts/ Garfield	1.182(1.371)	.394	27
3.	Pennsylvania/ Connecticut/ K Street	1.051(1.051)	.350	36
4.	Hawthorne Blvd. mini network, California	3.996(3.996)	.799	14
5.	Walnut Creek Network, California	2.770(2.771)	.462	84
6.	Daytona Beach Network, Florida	2.910(2.911)	.416	403
7.	Post Oak Network, Houston, Texas	2.715(2.816)	.339	161
8.	Ogden Network, Utah	3.099(3.156)	.387	186
9.	Ann Arbor Michigan	3.868(3.869)	.484	202
10.	Los Angeles, California	3.609(3.609)	.451	479
11.	Owosso, Michigan	4.196(4.196)	.525	137
12.	Bay City, Michigan	3.576(3.732)	.447	147
13.	Downtown Memphis Network, Tennessee	3.408(3.418)	.426	131

Note: Entries in parentheses give the best possible total bandwidth as a fraction of cycle length using simultaneous optimization.

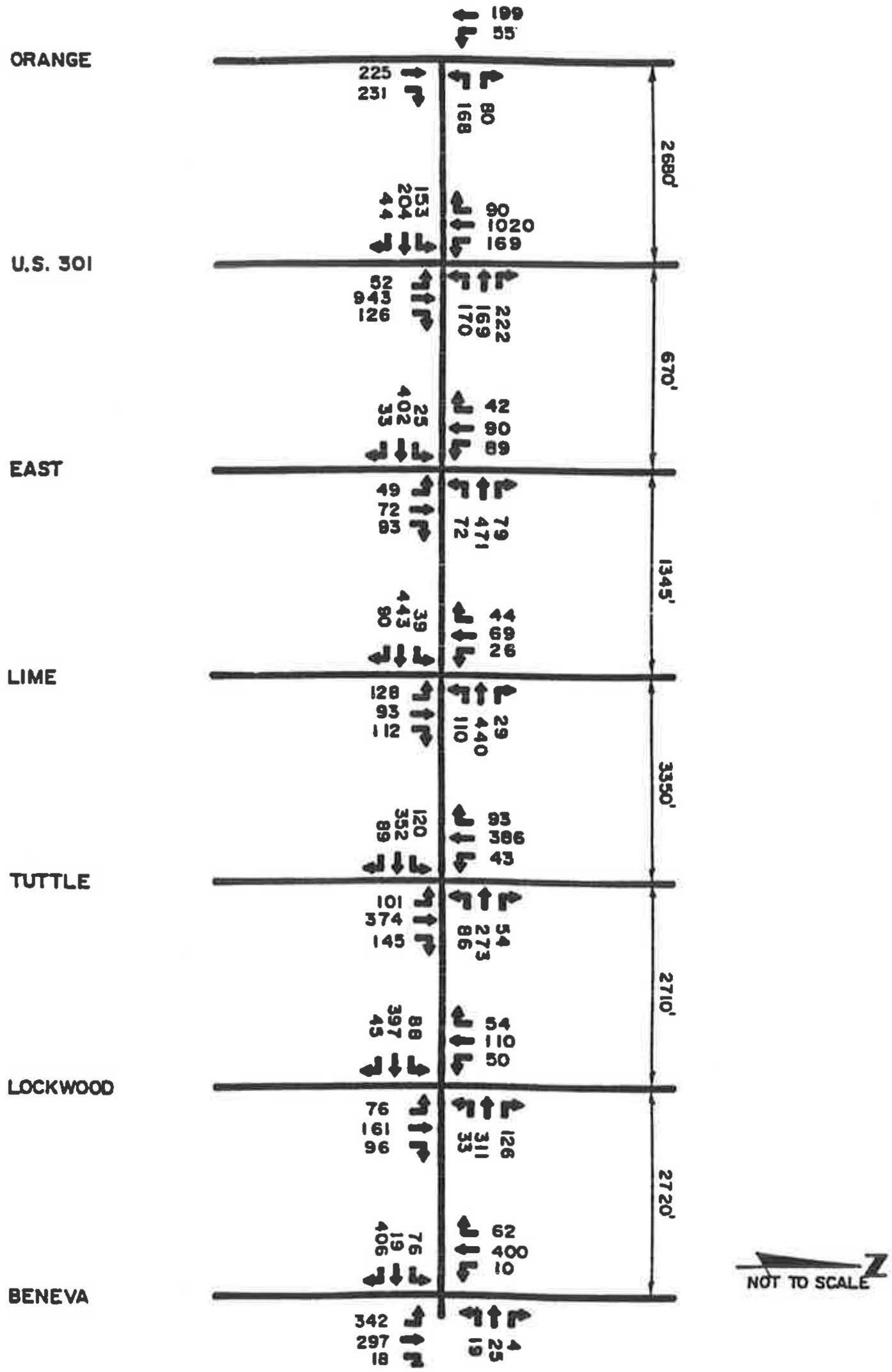

FIGURE 4 Off-peak turning movements for 12th Street.

solution with a cycle length of 79 sec (19 sec more than the lowest cycle length) had the lowest TRANSYT performance index (PI). Similarly, for the off-peak period, the solution with the lowest cycle length had a higher (delay and stops) TRANSYT PI.

In summary, it may be seen that the lowest cycle length solution is not necessarily the minimum delay solution. The cycle length range chosen for given traffic conditions may be the biggest factor affecting delay. However, it is not the only factor, since the authors' experience with arterial problems has shown that even two alternative solutions with the same cycle length may exhibit significantly different delay measures. More research is needed to understand the effects of other signal timing variables on delay. Despite the need for more research, the cycle length minimization capability in PASSER IV is a useful tool that can enable the generation of alternative solutions for the same problem.

Output Reports for Multiple Solutions

As mentioned earlier (and demonstrated above for the arterial cases), multiple optimal or very good suboptimal solutions may exist for a network problem. These solutions may have

TABLE 3 TRANSYT Delay Comparison of Alternative Solutions for 12th Street: A.M. Peak Case

	Total Delay (veh-hr /hr)	Average Delay (sec/ veh)	Number of Stops Per Trip	Average Speed (mph)	Transyt. P.I.	Cycle Length (Sec)
Solu 1	222	53.9	12125	14.6	229.2	60
Solu 2	181	44.0	12102	17.2	199.3	71
Solu 3	168	40.7	12050	16.6	189.1	79
Solu 4	207	50.4	11915	14.9	217.5	88

Note: All solutions have the same optimum bandwidth, 0.37564.

significantly different estimates of delay and stops. In maximizing progression bandwidth, a traffic engineer would probably want to select an alternative solution (if more than one solution is available) that results in the lowest delay and stops. PASSER IV has been equipped to allow printing of signal timing reports for a specified number of multiple solutions. The maximum number of solutions that can be printed is 5 and 10 for the standard and advanced PC versions, respectively.

A delay analysis was performed of the six best bandwidth solutions for each of the test networks. Since PASSER IV does not currently have the capability to estimate traffic performance measures such as delay, stops, and fuel consumption, TRANSYT 7F was used to evaluate each solution on the basis of PI (a linear combination of stops and delay). In addition, for each alternative solution, TRANSYT 7F was used to perform a bandwidth-constrained delay minimization with the option to minimize fuel consumption. TRANSYT results showed that bandwidth-constrained delay optimization (BCDO) further reduces delay. In order to perform an unbiased comparison, five replications of microscopic simulation using TRAF NETSIM (*15*) were performed to analyze each PASSER IV and TRANSYT 7F solution. It was discovered that NETSIM results do not always match those of TRANSYT. For many cases, TRANSYT BCDO results were worse than those of PASSER IV. A surprising finding was that for many cases, PASSER IV solutions had lower fuel consumption than TRANSYT BCDO solutions, even when TRANSYT solutions had lower delay and stop estimates. More research is needed to pinpoint and correct this discrepancy between TRANSYT and NETSIM. Also, the amount of work involved to code data and to perform all TRANSYT and NETSIM computer runs warrants that an automated capability be developed for such work. This issue is discussed later.

PASSER IV Output

PASSER IV prints an extensive signal timing solution report. The solution report includes a section summarizing the input data and calculations done in the preprocessor, a section showing the performance at each step during optimization, signal timings for each arterial in the network, time-space diagrams, and a section giving timings for each signal in the network. PASSER IV GUI allows the user to view or print the complete output or selected portions of the solution report. Figure 5 shows a network solution being viewed through the GUI. Figure 6 shows a time-space diagram and a signal setting table.

Data Requirements

PASSER IV requires the following network data: a unique identification number for each signal, link lengths, saturation flow rates, traffic volumes, average travel speeds on links, and cycle length range. The green splits are calculated internally from volume and saturation flow data using Webster's equation. Optionally, the user can directly specify green splits, which are used by the program without modification. However, the data input is relatively simple as compared with other network optimization/simulation programs.

TABLE 4 TRANSYT Delay Comparison of Alternative Solutions for 12th Street: Off-Peak Case

	Total Delay (veh-hr /hr)	Average Delay (sec/ veh)	Number of Stops Per Trip	Average Speed (mph)	Transyt. P.I.	Cycle Length (Sec)
Solu 1	97	28.1	9780	19.3	124.6	60
Solu 2	90	26.2	9667	19.6	119.2	70

Note: Both solutions have optimum bandwidth, 0.4223.

```
PASSER IV - 94           Texas Transportation Institute          Beta-Test Version
  File      Edit      Parameters     Run     Output    QuickEdit    Config      Info
                              C:\P4\DATA\W509MET.OUT                  Page: 36/ 56
      ARTERIES  2 AND  3 INTERSECT AT SIGNALS  5 AND  2, RESPECTIVELY.
      ARTERIES  3 AND  5 INTERSECT AT SIGNALS  1 AND  2, RESPECTIVELY.
      ARTERIES  4 AND  5 INTERSECT AT SIGNALS  1 AND  1, RESPECTIVELY.


                         **** NETWORK SOLUTION ****

    NETWORK WIDE CYCLE TIME:     90.00 SECS

              BANDWIDTHS - PERCENTAGE OF CYCLE LENGTH (SECONDS)
              -------------------------------------------------
    ARTERY 1:       EASTBOUND:  .5556 (50.00)     WESTBOUND:   .5556 (50.00)
    ARTERY 2:       EASTBOUND:  .3225 (29.03)     WESTBOUND:   .3225 (29.03)
    ARTERY 3:      SOUTHBOUND:  .2778 (25.00)    NORTHBOUND:   .2778 (25.00)
    ARTERY 4:      SOUTHBOUND:  .2777 (24.99)    NORTHBOUND:   .2777 (24.99)
    ARTERY 5:       EASTBOUND:  .5211 (46.90)     WESTBOUND:   .5211 (46.90)

    TOTAL BANDWIDTH:          3.909355

  PgUp:PrvPg PgDn:NxtPg ↑:ScrlUp ↓:ScrlDn F5:Search F6:Goto F7:Print Esc:End
```

FIGURE 5 Section of output from PASSER IV GUI.

Computer Hardware Requirements

PASSER IV is developed specifically for IBM PCs and compatible computers. However, the core of the program, its signal timing optimization program, can be compiled and used on virtually any machine that has a FORTRAN compiler available. This capability will permit the program to be used for large urban networks controlled by existing traffic management systems and future intelligent vehicle-highway (IVHS) systems.

ADDITIONAL FEATURES TO BE IMPLEMENTED

Research is currently under way to add more options to PASSER IV. The new options will further enhance the program and provide better signal timing solutions. Some of these enhancements are described in detail in the following sections.

Green Time Optimization

Recently, Chaudhary et al. developed the necessary mathematics to allow the simultaneous optimization of cycle length, offsets, signal phasing sequences, and green splits for arterial problems (*16*). The enhanced arterial formulation produced wider progression bands as compared with those produced by all the existing programs (including PASSER IV) for arterial bandwidth optimization. These enhancements were applied to some network optimization problems. The results of the enhanced network formulation showed significant improvement in total bandwidth. However, from a practical viewpoint, the increase in MILP formulation size and an exponential increase in the CPU time make this formulation impractical at the present time. Therefore, it has been decided to implement the following alternative approach in PASSER IV:

Step 1. Obtain optimal signal timing solutions using PASSER IV as before.

Step 2. Fix all integer variables from Step 1 in the enhanced formulation. Optimize progression bandwidth. Since this results in a simple linear program, it can be easily optimized in a few seconds.

This approach was used on a subset of five network test problems. Step 1 problems were optimized using the three-step heuristic method. In these optimization runs, all the minor cross streets had volume-to-capacity ratios less than 0.95. Table 5 shows a summary of computational results and provides a comparison of these results with those given in Table 2. The results show significant improvement in total bandwidth for each problem. These improvements range from 18.00 percent to 125.29 percent with an average improvement of 73.79 percent. It should be noted that these improvements were achieved with an insignificant number of additional calculations requiring only a few seconds.

Concurrent Bandwidth and Delay Optimization

A considerable amount of research by Cohen and Liu (*4,5,17*) has demonstrated that concurrent use of bandwidth and delay programs can produce better signal timings than either program alone. However, unlike the AAP for arterial problems, no computer package exists that provides for the automated use of this methodology for networks. This gap is being filled by adding a NAP (Network Analysis Package) option in PASSER IV. This option allows utilization of PASSER IV input data and optimal PASSER IV signal timing solution to generate a TRANSYT 7F input data file for bandwidth-constrained optimization. The implementation of this option in PASSER IV is complete and is being tested.

Delay Estimation Routine

The existing PASSER IV package has no capability to estimate delay at intersections. Such a capability is needed to

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*** PASSER IV-94 TIME-SPACE DIAGRAM ***

NAME OF ARTERY: CARSON                        TIME  SCALE =   3 SEC/CHAR
CYCLE LENGTH  :  90.00 SECONDS                DIST. SCALE =   70  M/LINE
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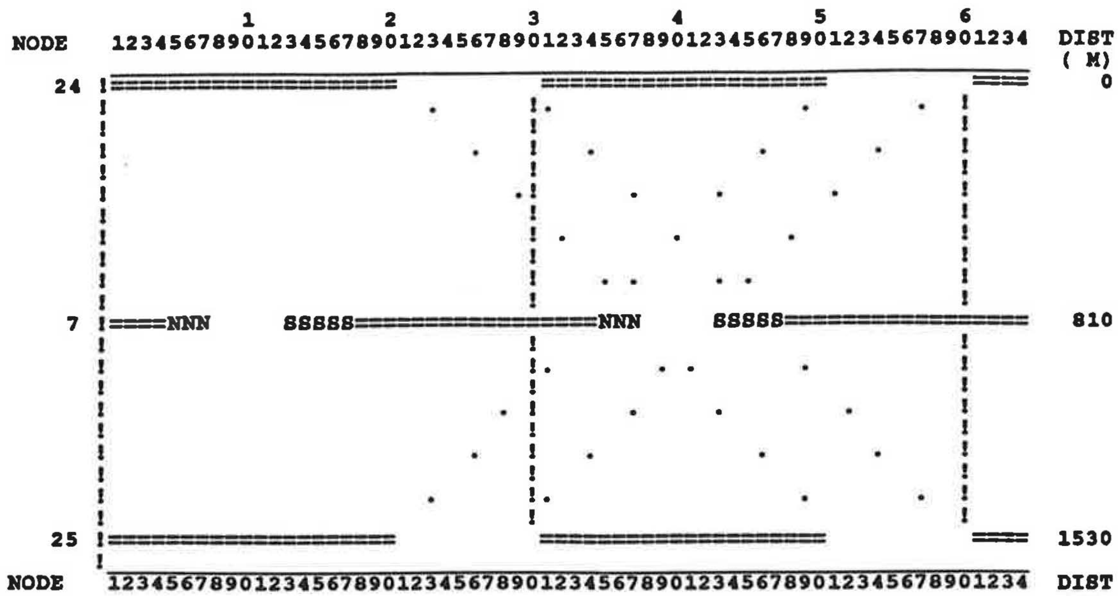


```
NODE    24 ---> NODE    25: SOUTHBOUND: DIRECTION-DOWNWARDS  : GREEN -  SSSSSS
NODE    25 ---> NODE    24: NORTHBOUND: DIRECTION-UPWARDS    : GREEN -  NNNNNN
SOUTHBOUND BAND =   25.0 SECS AT 58.2 KPH             GREEN IN BOTH DIRECTIONS
NORTHBOUND BAND =   25.0 SECS AT 58.2 KPH    ======   RED    IN BOTH DIRECTIONS
```

**** SUMMARY OF PASSER IV-94 BEST SIGNAL TIMING SOLUTION ****

NODE NO. 7

	HAWTHORNE (W-E) ARTERY 2 -- SIGNAL 2			CARSON (N-S) ARTERY 4 -- SIGNAL 2		
PHASE NUMBER	1		2	3	4	5
NEMA MOVEMENTS	1+5	-	2+6	3+8	4+8	4+7
PHASE (SEC)	10.0	-	42.1	10.0	15.0	12.9
PHASE (%)	11.1	-	46.8	11.1	16.7	14.3
PIN SET (%) 100 /	0.0	-	11.1	57.9	69.0	85.7

OFFSET POINT = 50.4 SEC (56.0%)
SYSTEM REFERENCE: START OF PHASE NO. 1 OF THE MASTER SIGNAL.

FIGURE 6 PASSER IV time-space diagram and signal timing table.

select the alternative optimal solution for implementation or further analysis. A delay estimation routine is currently being added in the program. The delay estimation approach described by Malakapalli and Messer in another paper in this Record is being used.

FUTURE PASSER IV ENHANCEMENTS

The following enhancements are scheduled to be implemented before the release of PASSER IV. Major research related to each of the following enhancements has been conducted; however, the implementation phase for these options is not as advanced as that for the options described in the previous sections.

Combined NEMA and Circular Phasing Optimization

Chaudhary et al. developed a scheme to simultaneously optimize NEMA and circular phasing sequences and produced an arterial optimization program called MAXBAND 89T that provided for an automated use of this capability (*18*). Circular phasing is a subset of main-cross split phasing with four phases

TABLE 5 Results from Green Split Optimization

NO.	NETWORK NAME	PASSER IV Bandwidth	Enhanced Bandwidth	% increase in Bandwidth	Additional LP iteration
1.	University/ Canyon/ 12th/ Street	1.281	2.886	125.29	207
4.	Hawthorne Blvd. mini network, California	3.996	4.728	18	281
6.	Daytona Beach Network, Florida	2.910	4.360	49.83	541
11.	Owosso, Michigan	4.196	6.609	57.51	459
13.	Downtown Memphis Network, Tennessee	3.408	7.441	118.34	689

(main lead, cross lead, main lag, and cross lag) at an intersection. This phasing is applicable in some special cases. Combined NEMA and circular phasing has been shown to provide larger progression bands. Once extensive testing is completed and successful, the circular phasing sequence optimization capability will be incorporated into PASSER IV.

Multiband Maximization

Traditional bandwidth optimization programs maximize uniform progression bands along the arterials. Gartner et al. (*19*) recently developed an arterial signal timing program, MULTIBAND, that maximizes volume-weighted bands for each link. In MULTIBAND, the center of the progression band on each link coincides with a line that goes through all intersections on the arterial. Gartner's research showed that MULTIBAND produces solutions with less delay then did its parent, MAXBAND. The authors have applied combined multiband and green-split optimization to a subset of multiarterial test networks. Although this feature results in a significant increase in the optimization problem size, the initial results look promising. All problems were formulated manually and solved using the two-step and three-step heuristic methods. The resulting sum of bands (objective function) was much larger than that for the uniform bandwidth cases. A direct comparison of the two cases for each network problem is not possible without further analysis of traffic performance measures. This research, however, remains to be done and will be facilitated by the NAP option in PASSER IV.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

PASSER IV is now a practical program for optimizing progression bandwidth-based signal timings for arterial as well as multiarterial closed-loop networks. To the authors' knowledge, it is the only network program of its type that is available to traffic engineers for use on a PC. It is envisioned that the program will be extremely useful for solving many problems that are experienced by cities in the United States and in many other parts of the world. Nevertheless, PASSER IV has room for further enhancements, some of which are listed in the next section.

Recommendations

The following are possible enhancements that can increase PASSER IV utility:

1. Bus route optimization as a secondary objective.
2. Explicit optimization of NEMA phasing sequences without overlap.
3. Explicit protected/permitted phasing optimization.
4. Special phasing sequence optimization, such as starting a phase twice within a cycle (sometimes called conditional service).
5. Double cycling some intersections.
6. Capability to assess advantages of removing a traffic signal.
7. Capability to run multiple jobs using the BATCH mode, given only new demand data (this would make the program more suitable for use as a submodule in traffic management systems for urban networks).
8. Fine-tuning existing signal timings for changed traffic conditions without resolving a new MILP from scratch.
9. Capability to integrate signal optimization programs such that one can fix offsets and signal timings for a subnetwork and optimize the remaining network [i.e., diamond interchanges within a network could be optimized using PASSER III (*20*)].
10. Currently, PASSER IV is only applicable to undersaturated networks; however, situations where some subnetworks are oversaturated are not uncommon. Extension of PASSER IV mathematical formulation to address such networks would greatly enhance the program's utility. One such approach could be the combination of internal metering principles (*21*) and bandwidth optimization.

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The authors would also like to acknowledge contributions made to PASSER IV by the following graduate students: Anulark Pinnoi implemented and tested the two-step and three-step heuristic methods and main-cross split phasing optimization option. Tai-Hsi Wu examined the nonuniform bandwidth models and green time optimization models and implemented the NAP option in PASSER IV. Rajivendra Nath developed the data structures and the first version of the PASSER IV GUI. Bogju Lee is performing ongoing enhancements to the GUI.

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DISCUSSION

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PASSER IV is a new name given by Chaudhary and Messer to a bandwidth optimization model that has existed for a long time under the name MAXBAND. This raises a number of important questions beyond the technical details of their paper.

The name MAXBAND was coined by Little et al. (*1*) in 1981 for a mixed-integer linear programming (MILP) formulation and computer program for the bandwidth maximization problem in arteries and triangular networks. The development of this program was supported by FHWA and was based on earlier work by Little (*2*) and subsequent refinements. Chang et al. (*3*) then extended the MAXBAND model, also under FHWA sponsorship, to grid network optimization. The new version was dubbed MAXBAND-86. In a 1991 paper, Chaudhary et al. (*4*) showed that the application of various heuristic techniques to the MILP optimization process in MAXBAND can lead to substantial reductions in execution time and can make it feasible to run this model on personal computers. Other researchers have also proposed a variety of enhancements to the MAXBAND optimization process, and this continues to be an area of intensive research (*5,6*). We are pleased to see the development of improved solution strategies, which are likely to lead to significant reductions in running times for the larger network bandwidth optimization problems and to make the program more accessible and usable for practicing traffic engineers.

In their 1991 paper (*4*), Chaudhary et al. state:

> MAXBAND-86 is the only operational traffic signal program that allows progression bandwidth optimization in multiarterial closed-loop networks. The program formulates the problem as a mixed integer linear program and is capable of optimizing network-wide cycle length, signal offsets, and signal phasing sequences.

Now PASSER IV claims identical capabilities. We believe that renaming the enhanced version of MAXBAND-86 as

PASSER IV is inappropriate on several grounds. First, it implies that this program is a continuation of the well-known PASSER family, which it is not—other programs in this family do not use the MILP model and optimization. Second, the introduction of a well-known model (MAXBAND) under a different guise is likely to lead to misunderstanding and general confusion in the traffic profession. Third, the introduction of a new name for a model that is well known by a different name obfuscates the origins and the intellectual ownership of said model.

We believe that it would be desirable for the authors to find another name for their program that more adequately reflects the source of the model and the share of their contribution to its development.

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AUTHORS' CLOSURE

In the discussion of our paper describing PASSER IV, Gartner and Little question the use of the name PASSER IV for our computer software. In support of their logic, they have cited only selected references. We present here more representative citations that negate their claim.

Little developed mixed-integer linear programming (MILP) formulation for arterial bandwidth optimization in 1966 (*1*). In 1980, under an FHWA contract, Little and Kelson extended the basic formulation and developed MAXBAND, a program for optimizing arterial and triangular network problems (*2*). The discussants state that the name MAXBAND was coined for both the mathematical program and the computer software; however, the MAXBAND Summary Report (*2*) clearly indicates that this name was given only to the computer program, which is the property of FHWA. In addition, MAXBAND was hard-wired to handle restricted networks composed of only three arterials in a triangular configuration. The MILP optimization module used in MAXBAND is composed of a set of routines developed by others and available to the general public (*3*).

In a subsequent FHWA contract, Messer et al. at Texas Transportation Institute (TTI) developed MAXBAND-86 by enhancing MAXBAND to handle general grid networks with up to 20 arterials and 50 signals (*4*). Chang et al. (of TTI) later described MAXBAND-86 (*5*). Some of the specific enhancements included a revision of the data structures, modifications to the input data stream, incorporation of a general loop generation algorithm, additional output to provide phase interval setting for each signal, and more. Although the program retained the basic arterial mathematical formulation developed by Little (*1*), the computer program was substantially upgraded by TTI to formulate the MILP for general multiarterial closed-loop network problems. However, to our knowledge, the MAXBAND-86 program never became widely accepted among the traffic engineering community because of its computational inefficiency and dependence on mainframe computers. It has, however, been used by selected groups of researchers.

A number of researchers have developed other modifications to the basic arterial mathematical formulation as well as to the MAXBAND program (*6–11*). However, by referring only to the work of Mireault and Solanki (*6,7*), the discussants give the impression that none of the other researchers but us have given new names to the programs they produced as a result of their enhancements to the basic arterial formulation. Some of the known cases that indicate otherwise are as follows:

- Gartner et al. (*8*) developed an enhancement to MAXBAND and called the resulting program MULTIBAND,
- Tsay and Lin (*9*) modified MAXBAND and gave it the name BANDTOP, and
- Khatib (*10*) called his modified version the ZMODEL.

Thus, using a new name for the resulting software product based on mathematical programming is not unusual. In fact, one of the discussants has himself coined a new name recently.

As for the use of the name PASSER IV, we would like to point out that PASSER IV is not a new name. In fact, a TTI research team, originally led by Messer, began in September 1979 to develop a software package by this name and with the same applications in mind. This research was funded by the Texas State Department of Highways and Public Transportation in cooperation with FHWA. The first version of PASSER IV was released in 1984 (*12*). The PASSER series of programs is extremely popular among the traffic engineering community because of its computational efficiency and ease of use. Our continued use of the name PASSER IV reflects our continued commitment to enhancing our progression optimization programs.

The PASSER IV-94 version, which is about to be released, draws on all the work that we have performed since 1979, including the original PASSER IV research program. It has several features not available in MAXBAND-86, which TTI developed for FHWA. These include

- A user-friendly interface for PCs,
- Enhanced green split calculation routine,
- Ability to explicitly model one-way arterials,
- Efficient heuristic optimization procedures,
- Ability to run on PCs with 640K of RAM,
- Ability to minimize cycle length,
- Ability to estimate traffic delay and other measures of effectiveness,

- Ability to generate multiple solutions, and
- Ability to generate TRANSYT-7F input data files and to run TRANSYT-7F from the main menu.

Last, we would like to point out that we have consistently acknowledged the fact that the basic arterial formulation for optimizing arterial problems used in PASSER IV-94 is due to Little. His work has been fully acknowledged in all of our related technical papers. It is, however, only a small portion of the overall program's operation. We certainly do not believe users will be confused between FHWA's program (using the title MAXBAND) and our software (using the trademark PASSER).

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