# Arterial Progression—New Design Approach

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**This paper proposes a new approach for the design of traffic signal timings to coordinate the progression of traffic on arterial highways. The two most popular signal optimization policies in use today are the maximal bandwidth approach and the minimum delay and stops approach. The new approach is proposed as a measure of the quality of progression perceived by the driver. It deals with progression opportunities (PROS), and the policy is to maximize the number of PROS available on an arterial signal system. It differs from the maximal bandwidth approach by considering progression opportunities that occur outside the traditional through progression band. Arterial progression design based on this approach will usually show decreased stops and delay compared with the maximal bandwidth design without suffering the loss of perceived progression associated with direct minimization of stops and delay. The number of progression opportunities presented to the driver at any point in time is, by definition, the number of successive green signals that will be encountered at the design speed without stopping.**

The coordination of traffic signals on arterial highways is an extremely effective way of reducing excessive fuel consumption and annoying stops that cause delay as well as wear and tear on vehicles. As the sophistication of signal controllers has improved over the years, coordinated signal systems have been able to use a variety of phase sequences and other control parameters to improve traffic flow on these facilities, which remain the backbone of the urban transportation system. Likewise, the methods of optimizing signal settings have been enhanced by the increasing power and decreasing cost of off-line computational capabilities of digital computers.

At one time signal settings were determined from the time-space relation of signal timing and traffic flow by using manual methods. As researchers began to use computers to reduce the computational effort and to increase analysis flexibility, the objective of the design program was still based on the time-space relation and on maximizing the through bands to accomodate platoons of traffic. One of the first popular computer programs of this type was signalized arterial (SIGART), which produced offsets that maximized bandwidths based on cycle length, free speeds, and intersection spacing (1). SIGART could also favor one direction over the other to account for directional imbalances in demand by time of day. Other similar models have been proposed as well.

More recent models, progression analysis and signal system evaluation routine (PASSER) II (2) and maximal bandwidth (MAXBAND) (3), are based on the same underlying objective (maximizing through bandwidth) but, unlike earlier models, these models also take into account traffic demands to determine cycle length and splits. They are also more powerful in the functional aspect because, in addition to offsets, a range of cycle lengths, alternative phase sequences, and phase lengths can be optimized.

Maximal bandwidth is an appropriate design approach for arterials but does not adapt well to two-dimensional networks. Thus, the development of signal optimization strategies for networks has generally been based on minimizing a disutility, which has generally been a function of delay, stops, and, in some models, queue length. The traffic signal optimization program (SIGOP) (4) and traffic network study tool (TRANSYT) (5,6) are the more prominent models in this area.

Although the disutility approach is well accepted for network signal optimization, it has not been readily accepted for applications on arterials because through progression bands based on minimizing disutility may not be as clean as those produced by the maximal bandwidth method. A school of thought, nonetheless, contends that the disutility approach is indeed applicable to arterial design since the overall objective [i.e., minimizing delay and stops (and, optionally, other disutility values)] is actually more valid than simply maximization through bandwidth, which does not explicitly recognize the presence of traffic demand as a function of time. Thus, two somewhat conflicting design strategies might yield substantially different signal timings.

## NEW APPROACH: PROGRESSION OPPORTUNITIES

The maximal bandwidth approach will clearly produce offsets and other signal timing parameters that result in good through green bands, albeit this approach does not recognize partial progression opportunities (i.e., over short sections of the arterial) or the actual presence of demand with respect to the timings produced. On this latter point, it is assumed that traffic will conform to the signal timing and that relatively intact platoons will propagate through the entire length of the arterial. Particularly on long arterials, the bandwidth approach may produce signal timings that produce large system stops and delay.

On the other hand, the more realistic disutility models necessarily consider the actual traffic demand, because it is requisite to this approach that the traffic flow be simulated accurately. Designs based on this method automatically consider all traffic demands, thus the short trip, partial progression, and demand-dependent considerations are taken into account. However, progression bands produced by disutility models are often neither continuous nor wide.

A logical question is, "Can these methods be combined?" Indeed they can. The progression opportunities (PROS) model was initially developed (7,8) to improve only the maximal bandwidth policy. (The original concept was referred to as forward link opportunities but the acronym FLOS led to obvious confusion.)

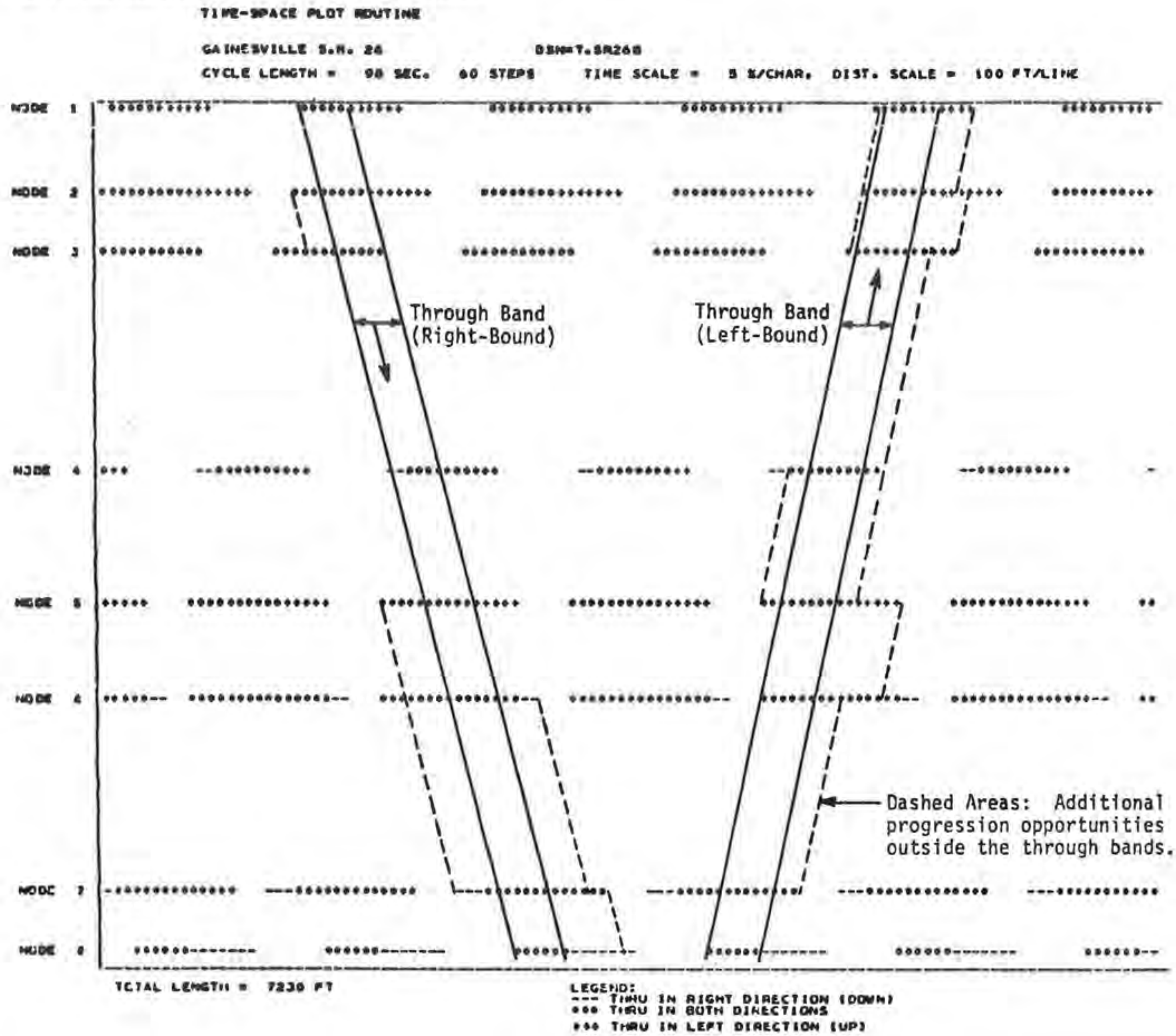
A progression opportunity is defined simply as the opportunity, presented at a given traffic signal and at a given point in time, to travel through a downstream signal without stopping. The number of progression opportunities presented to the driver at any time is determined by the number of successive green signals that will be encountered at the design speed without stopping. PROS can be determined for short increments of time, then accumulated to evaluate the total progression potential for any given set of signal timings.

PROS are based on a binary status function as follows (for one direction):

$$S_{jt} = \begin{cases} 1, \text{ if signal } j \text{ is green at time } t \text{ and signal } j+1 \text{ is green at} \\ \quad \text{time } t + T_{j,j+1} \\ 0, \text{ otherwise} \end{cases} \quad (1)$$

where $S_{jt}$ is the status of signal (j) at time (t), where t ranges from 1 to the cycle length; and T is

Figure 1. Time-space diagram of maximal bandwidth optimization.




the travel time at progression speed between the specified intersections.

A single forward progression opportunity exists at intersection j whenever $S_{jt}$ and $S_{(j+1)t}$ are 1 at any time increment (t).

PROS are then calculated for one direction by

$$\mathrm{PROS}_{it} = -S_{it} + \sum_{j=i}^{n} \prod_{k=i}^{j} S_{kt} \qquad (2)$$

where $\mathrm{PROS}_{it}$ is the forward progression opportunities from intersection (i) (of which there are n) at time interval (t).

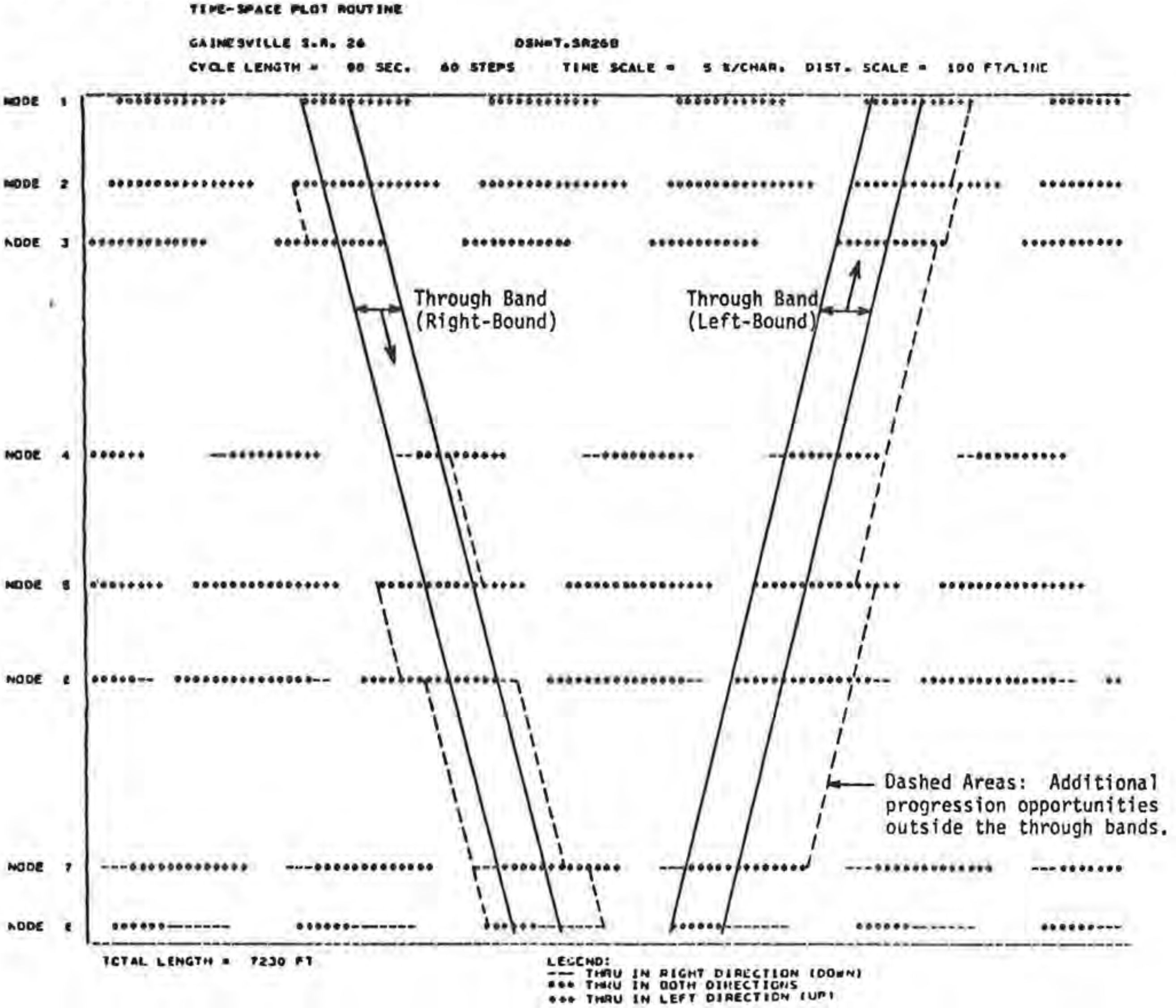
The product term in Equation 2 is necessary to count only those successive intersections for which all status variables are unity (for time increment t). It is necessary to decrement the sum by one (if $S_{it}$ is equal to unity) to indicate that the value of PROS represents the number of downstream forward progression opportunities from intersection i.

The PROS concept can best be visualized by use of a diagram. Consider a standard time-space diagram for the through links on an arterial (Figure 1). This time-space diagram represents a maximal bandwidth solution that uses PASSER II (2). The through bands are indicated by the solid lines and other partial progression opportunities are indicated by the dashed lines. Notice that the placement of the green at intersection 5 is arbitrary because this signal is not critical to the through bands.

If the offsets are adjusted to maximize PROS, thus considering the partial progression opportunities, the time-space diagram in Figure 2 results.

Perhaps a more useful illustration can result from an alteration to the traditional time-space diagram. If the signal offsets are adjusted for travel time, the time-space diagram can be adjusted such that the progression speed has zero slope. When this is done, the distance between intersections is no longer relevant (at progression speed) and the distance scale can be collapsed into a dimensionless scale where only relative location (or order) of intersections is pertinent. The PROS can then be shown for each intersection for each time increment (t) as illustrated in Figure 3. The circled two indicates that there are two forward

Figure 2. Time-space diagram of maximal PROS optimization.




progression opportunities from intersection five at time increment 20. The rows that have PROS indicated for all signals at each time increment (thus PROS at the first signal rightbound equals seven) represent the through progression bands.

Figure 3 is the PROS analysis of the maximal bandwidth optimization shown in Figure 1. When Figure 2 is adjusted to a time-location diagram, Figure 4 results, which clearly indicates superior overall progression. Note also that the value for the circled example has increased to three.

The general model for total aggregate PROS is as follows:

$$\mathrm{PROS} = C/T \sum_{k=1}^{2} \sum_{i=1}^{N} \sum_{t=1}^{T} \mathrm{PROS}_{jt}, \; j = \begin{cases} 1 & k=1, \text{ rightbound or} \\ N+1-i & k=2, \text{ leftbound} \end{cases} \qquad (3)$$

where C is the cycle length in seconds and all other variables have been previously defined.

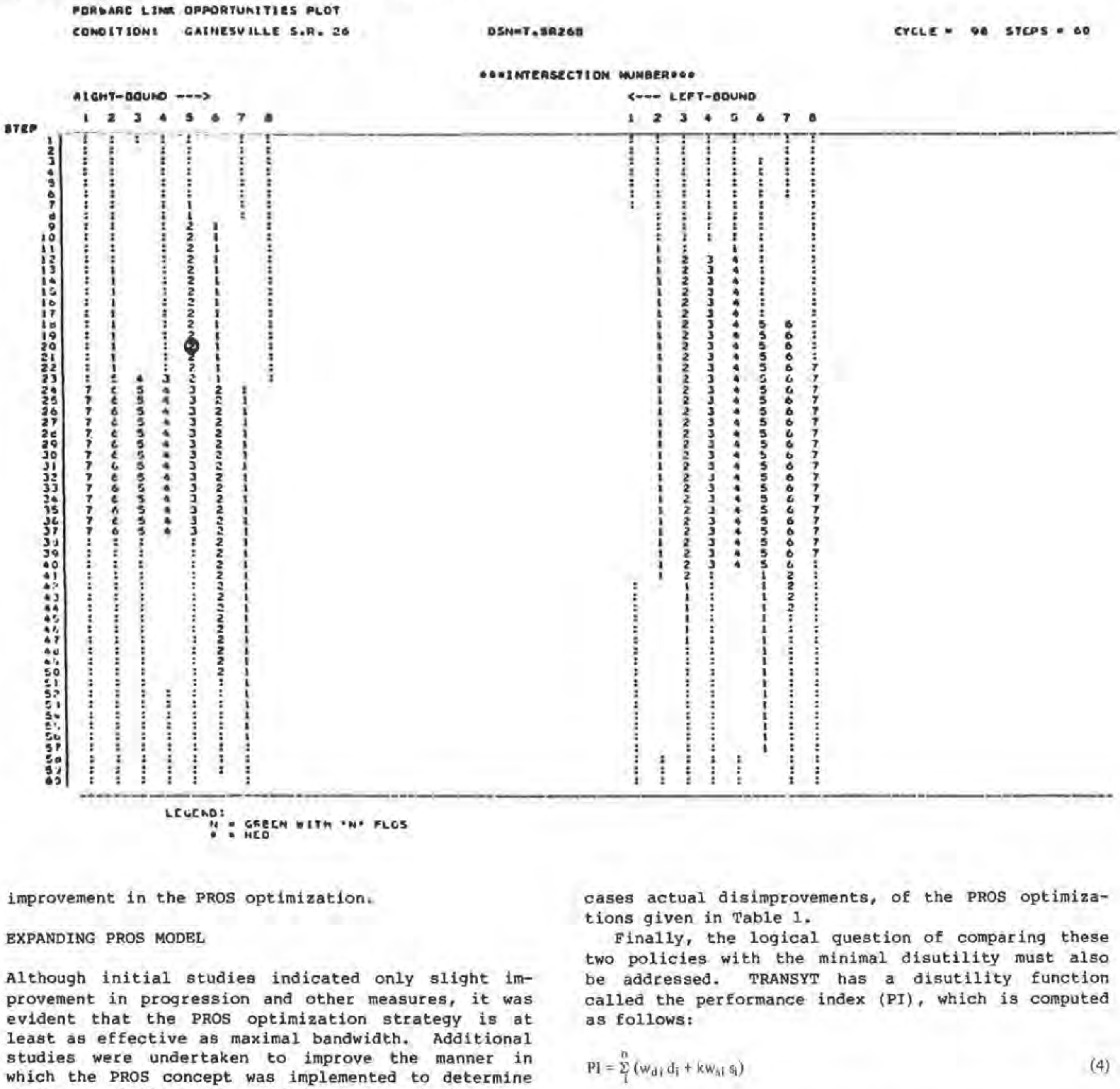
In the examples of Figures 3 and 4, the total PROS increased from 1978 in the maximal bandwidth solution to 2131 (or 7.7 percent) when offsets were changed to maximize PROS (i.e., max PROS in Equation 3).

To evaluate the PROS concept, the TRANSYT-6C model (9) was modified to perform the PROS calculations and to optimize offsets (and optionally splits) based on Equation 3. The use of TRANSYT permitted simulation of the alternative design strategies to evaluate their effectiveness.

A summary of comparative results of five arterials of differing configurations for the maximal bandwidth and PROS optimization policies is given in Table 1. As noted, most measures of effectiveness (MOE) were improved, albeit by very small magnitudes, by using the PROS optimization concept. In all these analyses, splits were based on balanced demand per capacity as determined by PASSER II, and these were held constant. Thus, only offsets were allowed to change.

The simple PROS optimization suffers the same disadvantage as the maximal bandwidth approach in that the actual traffic demand is not considered explicity. Variations of the objective functions were tested in which PROS were weighted by a number of other characteristics--namely, total demand, link length, link travel time, and stopline arrival pattern (i.e., a time-dependent demand weighting). None of these strategies demonstrated a significant

Figure 3. Time-location diagram of maximal bandwidth optimization.




improvement in the PROS optimization.

## EXPANDING PROS MODEL

Although initial studies indicated only slight improvement in progression and other measures, it was evident that the PROS optimization strategy is at least as effective as maximal bandwidth. Additional studies were undertaken to improve the manner in which the PROS concept was implemented to determine whether a single model could improve the basic time-space approach.

For example, splits can be considered in the optimization. When splits were optimized by using a simple PROS maximization, side street times were seriously affected. Since side streets are not considered in the PROS optimization, TRANSYT forces them to their minimums. The execution of multiple runs with different minimums was one way of overcoming this problem, but a more direct approach was desired.

Another problem with the PROS offsets was that, despite increased total progression opportunities, platoons were often propagated into the backs of queues, thus causing delay to through traffic. This is evident in Figure 4 for the leftbound direction since the leading edge of the band is essentially flat at time increment 22. This effect was responsible for the only limited improvements, and in some cases actual disimprovements, of the PROS optimizations given in Table 1.

Finally, the logical question of comparing these two policies with the minimal disutility must also be addressed. TRANSYT has a disutility function called the performance index (PI), which is computed as follows:

$$PI = \sum_{i}^{n} (w_{di} d_i + k w_{si} s_i) \quad (4)$$

where

- $d_i$ = delay on link i, of which there are n links (vehicle·h/h);
- $s_i$ = stops on link i (vehicles/s);
- k = stop penalty, which equates stops to delay; and
- $w_{di}$, $w_{si}$ = individual weights for link i.

For the purposes of this research, the stop penalty (k) was set to eight and the individual link weights were all set to unity. Note that the PI considers all links, including minor movements.

The objective of a normal TRANSYT optimization is to minimize PI, which is the equivalent of maximizing its inverse. A logical extension of the PROS concept was to redefine the TRANSYT objective function as follows:

$$\max (PROS/PI) \quad (5)$$

subject to minimum phase length constraints, as usual.

By using this formulation, splits can be optimized in addition to offsets because the minor movements will be accounted for in the PI. This optimization function attempts to maximize main street progression, subject to maintaining sufficient green time on the minor approaches. Equation 5 will also

Figure 4. Time-location diagram of maximal PROS optimization.

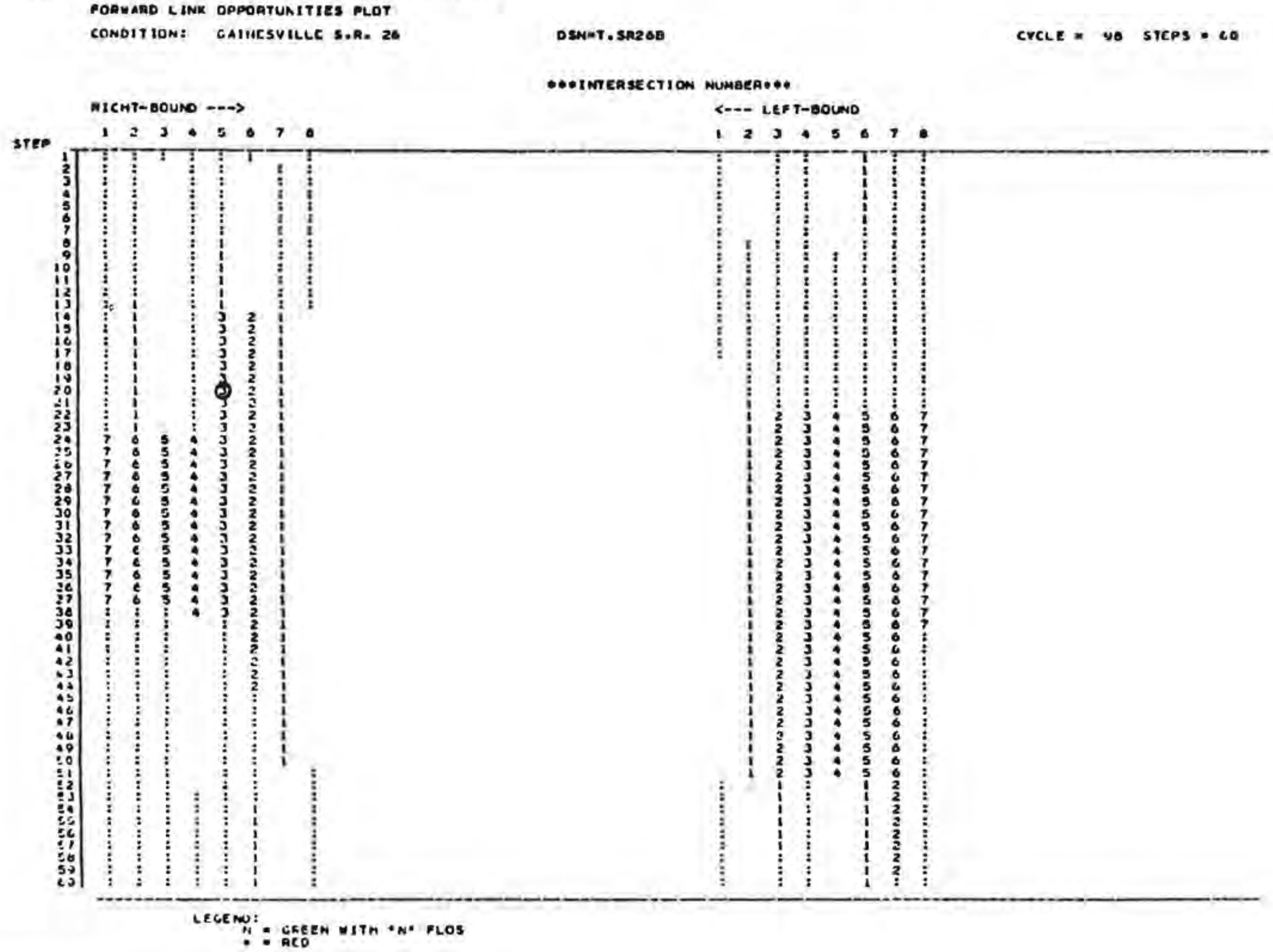



Table 1. Comparison of maximal bandwidth and PROS optimizations.

| | | Buffalo, Tampa | | FL-26, Gainesville | | FL-7A, Fort Lauderdale | | Beech Daly, Detroit | | FL-7B, Fort Lauderdale | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Characteristic | Optimization | No. | Change (%) | No. | Change (%) | No. | Change (%) | No. | Change (%) | No. | Change (%) |
| No. of signals | | 5 | | 8 | | 12 | | 16 | | 20 | |
| Length (ft) | | 3450 | | 7230 | | 29 900 | | 32 250 | | 34 450 | |
| Avg spacing (ft) | | 690 | | 1033 | | 2718 | | 2140 | | 1813 | |
| Cycle length[a] | | 60 | | 98 | | 102 | | 87 | | 106 | |
| Total bandwidth | BW | 42.0 | | 52.3 | | 34.0 | | 36.2 | | 51.2 | |
| | PROS | 43.0 | 2.4 | 52.3 | 0 | 35.7 | 5.0 | 36.2 | 0 | 51.2 | 0 |
| PROS | BW | 675.0 | | 1 977.9 | | 2 686.0 | | 5 573.7 | | 11 150.4 | |
| | PROS | 684.0 | 1.3 | 2 131.5 | 6.7 | 2 779.5 | 3.5 | 5 663.6 | 1.6 | 11 719.2 | 5.1 |
| Total delay (vehicle-h/h) | BW | 46.17 | | 67.77 | | 208.49 | | 209.03 | | 384.73 | |
| | PROS | 46.16 | ~0 | 66.81 | -1.4 | 205.88 | -1.3 | 208.32 | -0.3 | 374.87 | -2.6 |
| Delay on artery (vehicle-h/h) | BW | 21.07 | | 33.46 | | 90.42 | | 94.74 | | 179.54 | |
| | PROS | 21.06 | ~0 | 33.75 | 0.9 | 88.98 | -1.6 | 93.54 | -1.3 | 168.91 | -5.9 |
| Total stops (%) | BW | 62.1 | | 45.9 | | 70.7 | | 61.6 | | 58.6 | |
| | PROS | 61.4 | -6.7 | 44.9 | -1.0 | 69.8 | -0.9 | 60.7 | -0.9 | 57.2 | -1.4 |
| Stops on artery (%) | BW | 52.5 | | 35.8 | | 62.3 | | 51.1 | | 47.8 | |
| | PROS | 51.5 | -1.0 | 34.5 | -1.3 | 61.4 | -0.9 | 49.9 | -1.2 | 46.0 | -1.8 |
| Fuel consumption (gal/h) | BW | 88.58 | | 199.62 | | 537.66 | | 721.50 | | 1 138.59 | |
| | PROS | 88.36 | -0.2 | 197.22 | -1.2 | 534.91 | -0.5 | 719.48 | -0.3 | 1 131.37 | -0.6 |

Notes: All MOE as estimated by TRANSYT-6C, plus PROS MOE.
BW = Bandwidth by using PASSER II; PROS = forward progression opportunities, offsets only.
[a]Based on PASSER II solution; phase sequences are based on PASSER II.

**Table 2. Comparison of maximal bandwidth, TRANSYT, and PROS optimizations.**

| Characteristic | Optimization | Buffalo, Tampa | | FL-26, Gainesville | | FL-7A, Fort Lauderdale | | Beech Daly, Detroit | | FL-7B, Fort Lauderdale | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | No. | Change (%) | No. | Change (%) | No. | Change (%) | No. | Change (%) | No. | Change (%) |
| Total bandwidth | BW | 42.0 | | 52.3 | | 34.0 | | 36.2 | | 51.2 | |
| | PI | 37.0 | -11.9 | 47.4 | -9.4 | 40.8 | 20 | 21.7 | -40 | 26.5 | -48.2 |
| | PROS/PI | 45.0 | 7.1 | 58.8 | 12.4 | 45.9 | 35 | 46.4 | 28.2 | 53.0 | 3.5 |
| PROS | BW | 675.0 | | 1 977.9 | | 2 686.0 | | 5 573.7 | | 11 150.4 | |
| | PI | 649.0 | -3.8 | 1 977.5 | ~0 | 3 207.9 | 19.4 | 5 871.0 | 5.3 | 10 475.6 | -6.0 |
| | PROS/PI | 740.0 | 9.6 | 2 232.7 | 12.9 | 3 501.9 | 30.4 | 6 901.9 | 23.8 | 12 727.8 | 14.2 |
| Total delay (vehicle-h/h) | BW | 46.17 | | 67.77 | | 208.49 | | 209.03 | | 384.73 | |
| | PI | 45.20 | -2.1 | 62.70 | -7.5 | 199.10 | -4.5 | 196.49 | -6.0 | 360.84 | -6.2 |
| | PROS/PI | 46.29 | 0.3 | 64.38 | -5.0 | 202.44 | -2.9 | 201.79 | -3.5 | 366.75 | -4.7 |
| Delay on artery (vehicle-h/h) | BW | 21.07 | | 33.46 | | 90.42 | | 94.74 | | 179.54 | |
| | PI | 20.06 | -4.8 | 28.50 | -14.8 | 76.44 | -15.5 | 79.30 | -16.3 | 152.56 | -15.0 |
| | PROS/PI | 18.28 | -13.2 | 26.30 | -21.4 | 73.48 | -18.7 | 75.03 | -20.8 | 146.87 | -18.2 |
| Total stops (%) | BW | 62.1 | | 45.9 | | 70.7 | | 61.6 | | 58.6 | |
| | PI | 50.3 | -2.6 | 39.9 | -6.0 | 67.4 | -3.3 | 56.4 | -5.2 | 55.2 | -3.4 |
| | PROS/PI | 59.5 | -2.6 | 40.3 | -5.6 | 68.1 | -2.6 | 57.1 | -4.5 | 55.1 | -3.5 |
| Stops on artery (%) | BW | 52.5 | | 35.8 | | 62.3 | | 51.1 | | 47.8 | |
| | PI | 50.3 | -2.2 | 28.6 | -7.2 | 55.8 | -6.5 | 43.7 | -7.4 | 43.0 | -4.8 |
| | PROS/PI | 46.1 | -6.4 | 28.3 | -7.5 | 56.1 | -6.2 | 43.7 | -7.4 | 42.7 | -5.1 |
| Fuel consumption (gal/h) | BW | 88.58 | | 199.62 | | 537.66 | | 721.50 | | 1 138.59 | |
| | PI | 87.61 | -1.1 | 193.79 | -2.9 | 526.04 | -2.2 | 707.94 | -1.9 | 1 118.86 | -1.7 |
| | PROS/PI | 87.42 | -1.3 | 194.35 | -2.6 | 526.94 | -2.0 | 709.77 | -1.6 | 1 119.62 | -1.7 |

Notes: All characteristics, cycle lengths, and phase sequences as per Table 1.
BW = PASSER II bandwidth, PI = TRANSYT splits and offsets, PROS/PI = PROS/PI with offsets and splits.

result in offsets that tend to clear the existing queues before the progressed platoons arrive.

Table 2 contains the comparative results of the same five arterial highways by using Equation 5 as the objective function. Again, all values are based on TRANSYT-6C estimates of MOE. The standard TRANSYT PI optimization is also included for comparison.

Several significant observations can be drawn from the results in Table 2, which are summarized below (with all comparisons referenced to the maximal bandwidth optimization as the base condition):

1. Optimization based on PROS/PI always increased both bandwidth and total PROS; PI optimization alone had mixed effects, but was consistently less effective than PROS/PI.
2. As expected, total system delay was consistently lowest by using the TRANSYT minimization of the PI, and the PROS/PI optimization generally reduced total delay as well.
3. Significant reductions in main street delay occurred with both PI and PROS/PI optimizations, with the latter consistently superior.
4. The percentages of total and main street stops were also consistently lower with the PI and PROS/PI methods, again with the latter being generally better.
5. Reductions in fuel consumption were mixed between these two techniques, but both were better than the results by using the maximal bandwidth technique.

One might reasonably ask why the PROS/PI strategy would increase bandwidth more than would a maximal bandwidth optimization technique. The answer lies in that not only are offsets better aligned for the progression of actual platoons, but also the split optimization based on system disutility yields better splits than the balanced demand per capacity techniques common to maximal bandwidth algorithms.

On the basis of these analyses, the PROS approach in general, and the PROS/PI optimization strategy in particular, offer significant potential as design approaches that recognize both design objectives of maximizing bandwidth and reducing system disutility.

The PROS would appear to be a reasonable indicator of perceived progression.

## FUTURE RESEARCH

Although the PROS model appears to have merit, and the model has been automated by incorporation into TRANSYT-6C, several areas of additional research and development are needed.

First, the concept needs to be field tested. TRANSYT is sufficiently realistic that its estimates of several pertinent MOE suggest that traffic will operate more efficiently and with good progression by using the PROS (particularly the PROS/PI) optimization function, but the true test is field validation.

Second, additional sensitivity studies are needed to refine the model parameters further. Several weighting factors have been tested in a preliminary fashion. Among these, weighting of PROS by both a platoon dispersion factor (an inverse function of travel time) and by the stopline arrival pattern have shown promise in further improving the PROS optimization.

Third, the PROS model needs to be incorporated into a more recent version of TRANSYT (or some other model such as SIGOP) to improve the computational efficiency.

Finally, if this concept proves worthwhile, it should be incorporated into standard packages such as the Arterial Analysis Package, currently in preparation for the Federal Highway Administration.

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# Macroscopic Traffic Delay Model of Bus Signal Preemption

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**Productivity enhancement of public transportation is an essential goal, and bus signal preemption at intersections is one of the transportation system management strategies that strives for this goal. Improvements in bus speed and reductions in delay are the anticipated benefits accrued from such strategy. A macroscopic traffic delay model, which applies stochastic procedure, is presented to evaluate different bus preemption signal strategies at an isolated intersection. The model permits the user to evaluate a certain operational strategy provided for bus traffic on both main and cross streets. The signal controller modeled in this paper has a green extension and red truncation capabilities. A comparison between preemption on both main and cross street and preemption on main street only is provided to validate the model's logic. Sensitivity analyses were implemented and it was found that the delay savings due to signal preemption are sensitive to saturation flow rate and to bus passenger load. Potential applications and further enhancement are suggested.**

Transportation and traffic engineers realize the importance of system productivity and its major role in minimizing passenger delays and maximizing passengers throughput. Several transportation systems management (TSM) strategies have been identified to achieve such a goal, and one of those is the provision of bus priority treatment at urban intersections by means of signal preemption strategies. The federal government currently can fund the capital costs of TSM projects and it is necessary to investigate the worthiness of bus preemption.

Bus preemption demonstration experiments were conducted in Los Angeles, Miami, and Melbourne, Australia (1-3). All studies concluded that bus signal preemption could reduce total passenger delay. Two bus signal preemption studies (4,5), one in Sacramento, California, and the other in Concord, California, reported similar results and showed that, with low bus frequencies, the added delays to automobile occupants are negligible.

Two computer simulation models were developed and tested for bus signal preemption (6,7). These models are of a microscopic nature in which the status of the vehicle with regard to its location, speed, and delay is updated every small time interval. The Urban Traffic Control System-Bus Priority System (known as UTCS-BPS) and the network simulation-bus priority system (NETSIM-BPS) computer programs are, perhaps, the only packages available that provide bus preemption at urban intersections (8,9).

The complexity and high cost involved in developing and validating such software packages lead to the consideration of other macroscopic approaches. An analytical model of bus preemption, by using a deterministic vehicle arrival process, was developed for the purpose of evaluating pretimed signal priority treatments at isolated intersections (10). Delay values derived from this model are believed to be underestimated due to the deterministic nature. Another analytical model, which uses a stochastic approach, was developed to evaluate and assess priority treatment of buses at signalized intersections (11). The model provides green extension and red truncation signal strategies, however, it is limited to one direction signal capability (preemption on main street only).

Evaluation of signal strategy effects on traffic flow requires, in general, a detailed analysis of a vehicle's speed, location, acceleration and deceleration capabilities, and the status of the signal. Use of microscopic computer simulation packages for system evaluation and justification can be an accurate way. However, the time and cost involved in running the program constrains and sometimes prohibits the completion of an extensive analysis. A solution for this problem is to use macroscopic analytical models that can reasonably do the job with possibly 10 percent the price of the microscopic model. The analytical models cited in the literature lack the ability to evaluate the bus signal preemption option on both main and cross street approaches.

## DELAY MODEL AT AN INTERSECTION

Several models have been developed for estimating queues and delays at signalized intersections. Winsten and coworkers were the first to use the binomial distribution in an analysis of delays at pretimed signals (12). The Poisson distribution that describes the arrival of vehicles at intersections has been used by Adams, Webster, and Wardrop (13-15). Newell used a model in which the arrival headways were assumed to have a shifted exponential distribution (16). Most models assume departures at equal time intervals, providing a queue exists and the first departure is at the start of the effective green time.

One of the better known models for delay is the one developed by Webster (14) by using data result-