Single-Arterial Versus Networkwide Optimization in Signal Network Optimization Programs

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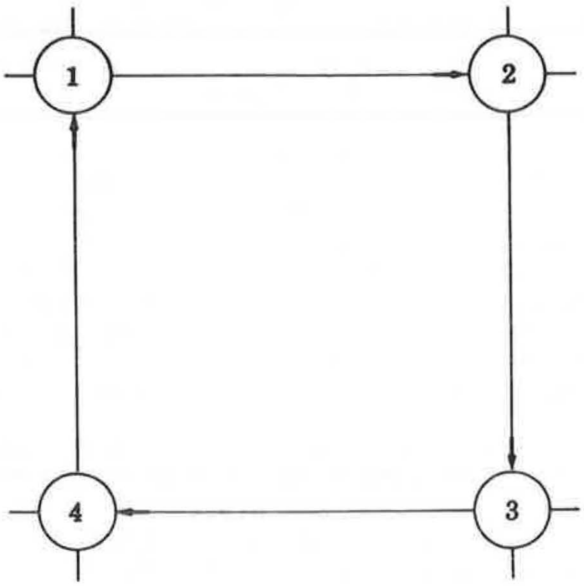
The optimization of signal timing in a traffic network involves finding the timing plan that optimizes the overall performance in the network. In theory, the network closure constraints limit the performance on individual arteries of the network. Thus networkwide optimization has the potential of imposing some cost or penalty, or both, to individual arterials in the network. The objective of this study was to determine how or if the network closure constraint affects or limits arterial performance in the program for maximum-bandwidth, MAXBAND, and in the program for minimum stops, delay, and fuel consumption, TRANSYT-7F. The results of this study show that for small and medium-sized closed networks, optimization of an entire network using MAXBAND or TRANSYT-7F costs very little in terms of stops, delay, and green bandwidth on the arteries within the network. The added cost associated with the additional stops and delays resulting from networkwide optimization can be expected to impose approximately a 5 percent penalty on individual arteries within the network.

The optimization of signal timing in a traffic network requires finding the timing plan that optimizes the overall performance in the network. In a closed network, the timing plan must satisfy a network closure constraint not required for arterials. Thus, it may be the case that individual arteries in the network are sacrificed for the good of the whole. The purpose of this study is to determine the cost or penalty (if any) that networkwide optimization would impose on the individual arteries of the network.



A Network with 1 Loop: 1→2→3— 4→1

Links of loop: (1,2),(2,3),(3,4),(4,1)

Loop constraint: $O_{12} + O_{23} + O_{34} + O_{41} = nC$
for some natural number n.

FIGURE 1 The network loop constraint.

NETWORK CLOSURE CONSTRAINT

For fixed cycle length and splits at each intersection of a network, the network closure constraint simply requires the sum of the offsets around any loop of the network to be a multiple of the cycle time. This can be stated as follows:

Let C be the cycle length, Oij be the offset between signals i and j, and l be a set of links that form a closed loop.

Define $L = \{l{:}l \text{ is a loop}\}$.

Then the network closure constraint is $Oij = nC$, where n is an integer and the sum is taken over all links (i, j) in the loop l.

For the network shown in Figure 1, the constraint requires that $O12 + O23 + O34 + O41 = nC$ for some integer n.

Closure constraints have the effect, at least in theory, of degrading traffic performance on individual arteries within the network in order to optimize overall performance. For instance, in the case of bandwidth optimization, these constraints would prevent individual arteries from obtaining the maximum bandwidths that they could obtain if optimized separately.

PROBLEM DISCUSSION

Some computerized signal network optimization programs such as TRANSYT-7F and MAXBAND can be used both on single arteries and on networks *(1, 2)*.

MAXBAND simultaneously optimizes cycle length, phase sequences, and offsets to maximize a weighted sum of all bandwidths on all arteries of the network. Thus for single-artery optimization this reduces to the maximization of the bandwidths in each direction of the artery. Also, for the single-artery case there are no loops, so there are fewer restrictions on the choice of offsets at each intersection. Hence, one objective of the study is to determine how the additional restrictions of

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the network closure constraint on the offsets limit arterial performance in the maximal bandwidth program MAXBAND.

TRANSYT-7F adjusts offsets and green time separately to minimize a weighted sum of stops and delay. Again the offset selection is limited by the network closure constraint in the networkwide optimization. In this study the objective is to determine how this constraint affects the individual arteries of the network.

STUDY OBJECTIVE

Network closure constraints impose additional restrictions on the arterial settings within a network, which might result in less than absolute optimal settings for individual arteries of a network. The objective of this study is to determine how or whether the additional network constraint affects or limits arterial performance, or both, in the signal optimization programs TRANSYT-7F and MAXBAND, that is, to determine (a) the loss (if any) of bandwidth to individual arteries of a network that results from networkwide optimization rather than individual-artery optimization and (b) the increase in cost (if any) associated with delay and stops to the individual arteries of a network that results from networkwide optimization.

DESCRIPTION OF PROGRAMS

MAXBAND

The MAXBAND programs find traffic signal settings on arteries and general grid networks by using optimization of green bandwidths as the criterion. The optimization problem can be stated as follows: Compute offsets, cycle length, and left-turn phase sequence so as to maximize a weighted sum of all bandwidths on all arteries of the network. This problem is formulated as a mixed-integer linear programming problem. User inputs to the program include the usual volume, capacity, minimum green time, and link length as well as left-turn patterns to be considered and inter- and intraartery weighting.

MAXBAND 86 is the name of the new network version of MAXBAND. For the new program, algorithms were developed that convert network loop characteristics into equivalent mixed-integer linear programming formulations. It was found that large or complex network problems, or both, pushed the optimization technique beyond its capability to produce optimal solutions within reasonable computation time. Networks optimized by using MAXBAND 86 must be completely connected, and no more than two arterials may compose an intersection.

TRANSYT-7F

The TRANSYT program finds the traffic signal settings on networks that minimize a weighted sum of stops and delay. A hill-climbing optimization procedure adjusts offsets and green time separately to minimize a weighted sum of stops and delay called the performance index. User inputs to the program include volume, capacity, minimum green time, link lengths, flow patterns, cycle length, and initial offsets and splits. A TRANSYT optimization run may be of five types: (a) optimization of offsets, cycle length, and splits; (b) optimization of offsets only, (c) simulation only, (d) cycle-length selection only, or (e) optimization of offsets and splits.

EXPERIMENTAL DESIGN

A three-phase experimental plan was used to accomplish the objectives of the study. For the first phase of the study MAXBAND was used to optimize four small closed networks. Each entire network and each artery was optimized individually. A total of 37 MAXBAND optimization runs were made during this phase. A comparison was made between the bandwidths obtained on each artery within the network and those obtained when a single artery was optimized.

The second phase of the study consisted of TRANSYT-7F optimizations of the same four networks used in Phase 1. Each artery of each network was optimized individually and within its network by using TRANSYT-7F. The costs associated with delay and stops were compared for each artery under individual optimization and networkwide optimization.

Phase 3 of the study was essentially a repeat of Phase 2 except that three larger networks were optimized.

TEST DATA SETS

This research concentrated on small closed networks. Pretimed, common-cycle, coordinated traffic signals with primarily two-phase operation were emphasized.

Seven data sets were used. Five of the data sets—Daytona Beach; Washington, D.C., Section 3; Lexington; Chicago; and Washington, D.C., west central business district (CBD)—were obtained from FHWA files. The remaining two—Ann Arbor and Battle Creek—were provided by the University of Florida's Transportation Research Center.

Smaller Networks

Washington, D.C., Section 3

Eight arteries from the Washington, D.C., UTCS-1 network system were used. The network includes three east-west arteries, two of which are one-way streets, and five north-south arteries, two of which are also one-way streets. This network, which is located in the downtown area of the District, is shown in Figure 2.

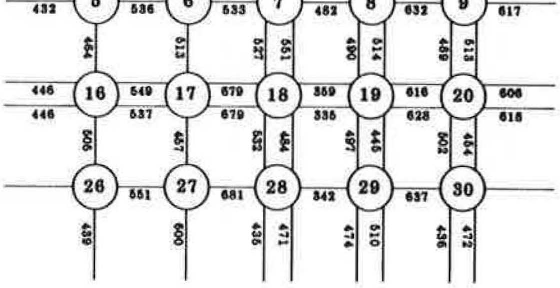

FIGURE 2 Washington, D.C., Section 3 network.

Lexington

The test network is part of the Lexington, Kentucky, downtown signal system. There are five east-west arteries and four north-south arteries. All the east-west arteries and two north-south arteries are one-way streets. The Lexington network is shown in Figure 3.

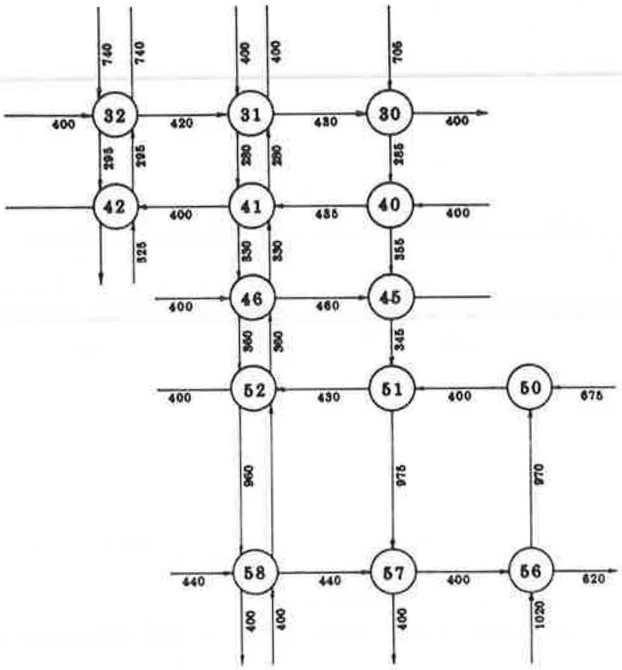

FIGURE 3 Lexington, Kentucky, network.

Daytona Beach

The test network is located in downtown Daytona Beach, Florida. There are three east-west arteries and four north-south arteries, all of which are two-way streets. Included in this network are two major arterials, Ridgewood Avenue and Volusia Avenue. This is the network system example included in the TRANSYT-7F User's Manual. Figure 4 shows this network.

Chicago

The test network is a nine-artery system centered around two major arterials (Michigan Avenue and NS2) in Chicago, Illinois. The two major arterials are two-way, north-south streets and the remaining seven arteries are east-west streets, two of which are two-way streets. Figure 5 shows this network.

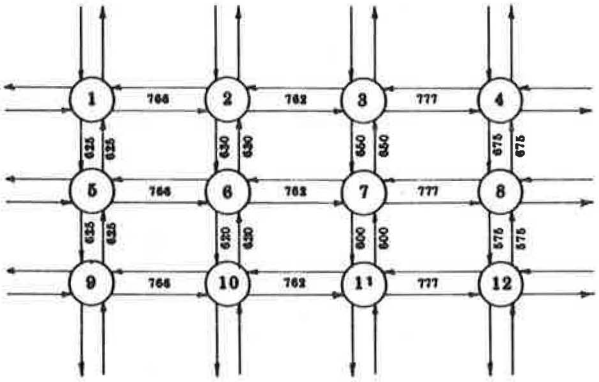

FIGURE 4 Daytona Beach, Florida, network.

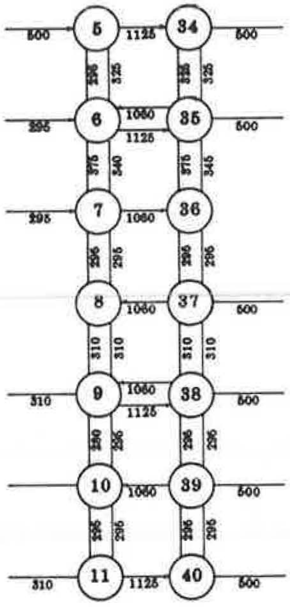

FIGURE 5 Chicago, Illinois, network.

Larger Networks

Ann Arbor

The 15-artery test network is located in the Ann Arbor, Michigan, CBD. Two of the seven east-west streets and one of the nine north-south streets are one way. The Ann Arbor network is shown in Figure 6.

Battle Creek

The test network is part of the Battle Creek, Michigan, CBD. Included are four major north-south arteries and several shorter east-west arteries. This network is shown in Figure 7.

Washington, D.C., West CBD

The largest of the test networks is located in the Washington, D.C., CBD. All six east-west arteries are one-way streets as are all but three of the north-south arteries.

EXPERIMENTAL PLAN

A series of experiments was performed to accomplish the goals of the study.

Experiment 1:

1. Individual arteries of the small networks (Daytona Beach, Florida; Lexington, Kentucky; Chicago, Illinois; and Washington, D.C., Section 3) optimized with MAXBAND; cycle

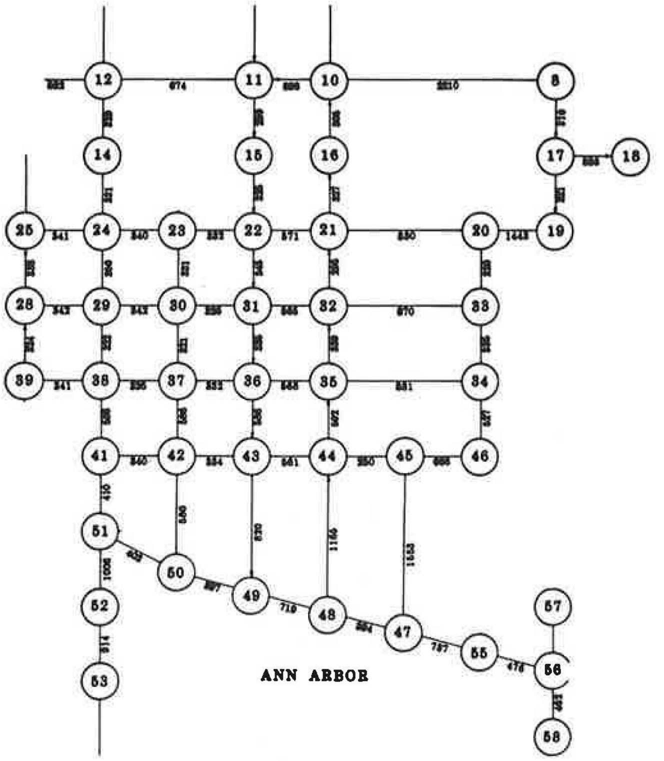

FIGURE 6 Ann Arbor, Michigan, network.

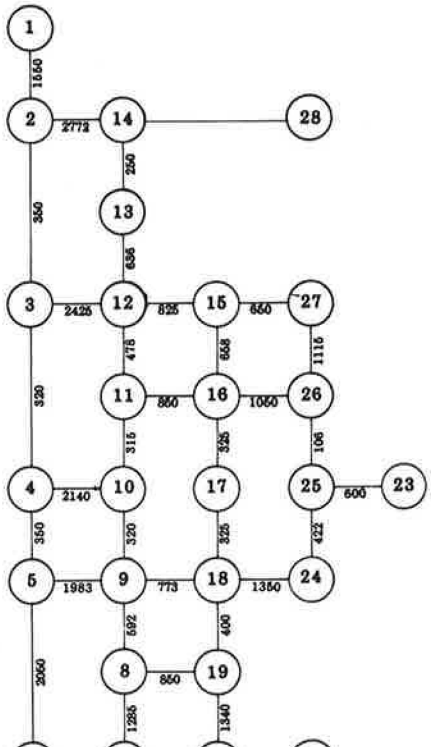

FIGURE 7 Battle Creek, Michigan, network.

lengths and phase sequences fixed for each artery; none of the arteries provided directional weighting.

2. Each of the four small networks network-optimized with MAXBAND; cycle lengths and phase sequences fixed; no directional or between-artery weighting coded.

Experiment 2:

1. Small networks offset-only optimized with TRANSYT-7F; MAXBAND solution of each network used as the starting solution for the TRANSYT-7F runs.
2. Each artery of each small network offset-only optimized with TRANSYT-7F; MAXBAND solution of each artery used as the starting solution for the TRANSYT-7F optimizations.

Experiment 3:

1. Each of the three larger networks (Ann Arbor, Battle Creek, and Washington, D.C., west CBD) optimized normally with TRANSYT-7F; existing conditions of each network used as the starting TRANSYT-7F solution.
2. Larger networks offset-only optimized with TRANSYT-7F; existing timing used as the starting solution; all east-west links of the networks delinked, that is, no nodes connected by east-west links (equivalent to optimizing the north-south arteries separately).
3. Three larger networks offset-only optimized with TRANSYT-7F; existing timing used as the starting solution with all north-south links delinked (equivalent to optimizing the east-west arteries separately).

Comparisons were made between the bandwidths obtained in Parts 1 and 2 of Experiment 1, the cost of uniform stops and of delay obtained in Parts 1 and 2 of Experiment 2, and the cost of stops and delay obtained in Parts 1 and 2 or 1 and 3 (as appropriate) of Experiment 3.

To study the cost of networkwide optimization to the individual arteries of a network, the cost of stops was computed as $0.04 per stop and the cost of delay as $0.50 per vehicle hour of delay. These values were taken from the National Signal Timing Optimization Project final report *(3)*.

The detailed comparison of the results was made with a spreadsheet program.

RESULTS

The results of Phase 1 of the study are shown in Tables 1 through 4. The results indicate that, most of the time, under network optimization individual arteries achieve bandwidths that approach or equal the bandwidths that could be achieved if the arteries were optimized separately. Only Connecticut Avenue in the Washington, D.C., Section 3 network and the EW1 artery in the Chicago network showed any substantial degradation in performance. Thus the primary effect of using the network optimization is to provide a means for taking individual arteries, optimized separately, and adjusting the offset of the first intersections of each artery so that the offsets for the network are consistent.

TABLE 1 BANDWIDTH COMPARISONS OF DAYTONA BEACH ARTERIES

ARTERY	SINGLE BANDWIDTH	NETWORKWIDE BANDWIDTH	DIFFERENCE
RIDGEWOOD	28.2	27	1.2
PALMETTO	6.6	6.6	0
BEACH	31	31	0
ORANGE	25.7	25.7	0
MAGNOLIA	10.1	10.1	0
VOLUSIA	26.9	26.9	0
BAY	2.5	2.5	0
TOTAL	131	129.8	1.2

TABLE 2 BANDWIDTH COMPARISONS OF CHICAGO ARTERIES

ARTERY	SINGLE BANDWIDTH	NETWORKWIDE BANDWIDTH	DIFFERENCE
MICHIGAN	26.1	24.4	1.7
NS2	18.6	17.8	0.8
EW1	30.1	20	10.1
EW2	9.6	9.6	0
EW3	28.9	28.9	0
EW4	27.2	27.2	0
EW5	19.7	16	3.7
EW6	17.5	17.5	0
EW7	44.4	44.4	0
TOTAL	222.1	205.8	16.3

TABLE 3 BANDWIDTH COMPARISONS OF LEXINGTON ARTERIES

ARTERY	SINGLE BANDWIDTH	NETWORKWIDE BANDWIDTH	DIFFERENCE
EW1	26.1	23.4	2.7
EW2	23.9	23.9	0
EW3	27	27	0
EW4	30.2	30.2	0
EW5	22.3	22.3	0
NS1	38.5	38.5	0
NS2	3.9	2.8	1.1
NS3	17.5	17.5	0
NS4	28.5	28.5	0
TOTAL	217.9	214.1	3.8

TABLE 4 BANDWIDTH COMPARISONS OF WASHINGTON, D.C., SECTION 3, ARTERIES

ARTERY	SINGLE BANDWIDTH	NETWORKWIDE BANDWIDTH	DIFFERENCE
L STREET	25.3	24.1	1.2
K STREET	12.5	11.5	1
I STREET	2	2	0
19TH ST	35.1	35.1	0
18TH ST	30.2	30.2	0
CONN AV	50.2	31.4	18.8
17TH ST	8.3	7	1.3
16TH ST	24.3	24.3	0
TOTAL	187.9	165.6	22.3

TABLE 5 COST COMPARISONS FOR DAYTONA BEACH

	SINGLE			NETWORKWIDE				
ARTERY	DELAY	STOPS	COST	DELAY	STOPS	COST	COST DIFF	% DIFF
RIDGEWOOD	25.63	2651.9	118.891	25.01	2637	117.985	-0.906	-0.00762
PALMETTO	8.97	800.49	36.5046	10	1105.3	49.212	12.7074	0.348104
BEACH	24	2212.6	100.504	23.46	2126.1	96.774	-3.73	-0.037113
ORANGE	14.4	1365.7	61.828	14.32	1339.5	60.74	-1.088	-0.017597
MAGNOLIA	12.88	908.7	42.788	13.44	903.9	42.876	0.088	0.002057
VOLUSIA	31.17	2729.1	124.749	30.94	2724.3	124.442	-0.307	-0.002461
BAY	10.3	835	38.55	9.95	824.2	37.943	-0.607	-0.015746
TOTAL COST			523.8146			529.972		

DIFFERENCE 6.1574

% DIFF 0.0117549

TABLE 6 COST COMPARISONS FOR CHICAGO

	SINGLE			NETWORKWIDE				
ARTERY	DELAY	STOPS	COST	DELAY	STOPS	COST	COST DIFF	% DIFF
MICHIGAN	127.32	4912.6	260.164	128.94	5488.9	284.026	23.862	0.091719
NS2	6.69	1109.6	47.729	9.12	1343.9	58.316	10.587	0.221814
EW1	5.22	502.8	22.722	5.27	596.7	26.503	3.781	0.166403
EW2	6.38	712	31.67	5.84	668.6	29.664	-2.006	-0.063341
EW3	4.28	161.1	8.584	4.88	394.3	18.212	9.628	1.121622
EW5	3.06	338.1	15.054	3.71	392.9	17.571	2.517	0.167198
EW6	3.93	475	20.965	3.32	392.9	17.376	-3.589	-0.17119
EW7	104.21	1209.5	100.485	105.12	392.9	68.276	-32.209	-0.320535
TOTAL COST			533.971			551.395		
				DIFFERENCE	17.424			
				% DIFF	0.032631			

TABLE 7 COST COMPARISONS FOR LEXINGTON

	SINGLE			NETWORKWIDE				
ARTERY	DELAY	STOPS	COST	DELAY	STOPS	COST	COST DIFF	% DIFF
EW1	3.33	488.5	21.205	4.39	577.9	25.311	4.106	0.1936336
EW2	135.23	1787.8	139.127	162.64	2075.1	164.324	25.197	0.1811079
EW3	3.4	631.2	26.948	3.01	608.4	25.841	-1.107	-0.041079
EW4	2.87	484	20.795	2.79	517.9	22.111	1.316	0.0632844
EW5	3.38	535.4	23.106	4.69	668	29.065	5.959	0.2578984
NS1	122.04	2088.1	144.544	127.1	2390.5	159.17	14.626	0.1011872
NS2	7.69	887.9	39.361	8.52	1065.5	46.88	7.519	0.1910267
NS3	5.33	704.4	30.841	6.13	742.7	32.773	1.932	0.0626439
NS4	4.03	600.1	26.019	5	660.2	28.908	2.889	0.1110342
TOTAL COST			471.946			534.383		
				DIFFERENCE	62.437			
				% DIFF	0.1322969			

Comparisons of the cost of stops and delay for individual arteries of each network under arterial and networkwide optimization were made in Phase 2. Each network contained some arteries for which the cost associated with stops and delay when the artery was optimized separately was greater and some for which it was lower. The Lexington network showed the greatest increase in overall cost under networkwide optimization. The Daytona Beach; Washington, D.C., Section 3; and Chicago networks showed very small increases in cost of 0.4, 1.2, and 3.3 percent, respectively. The results of this phase of the study are shown in Tables 5 through 8.

Phase 3 of the study focused on the larger networks—Ann Arbor, Battle Creek, and Washington, D.C., west CBD. The results were similar to those found in Phase 2, with overall increases in the cost associated with stops and delay of 3.9, 4, and 4.8 percent, respectively. Each network had some arteries for which the cost was lower under individual-artery optimization and some for which it was lower under networkwide optimization. In most cases, as in Phase 2, the arteries that showed increased cost under networkwide optimization were offset by others that showed lower cost. The number of stops, the delay, and the cost associated with stops and delay found in this phase of the study are shown in Tables 9 through 11.

In Phases 2 and 3 it was found that the network that was the least rectangular (Lexington) and the ones that had predominantly one-way streets (Lexington and Washington, D.C., west CBD) showed greater degradation with networkwide optimization than did the other networks of the study.

TABLE 8 COST COMPARISONS FOR WASHINGTON, D.C., SECTION 3

ARTERY	SINGLE DELAY	STOPS	COST	NETWORKWIDE DELAY	STOPS	COST	COST DIF	% DIFF
L STREET	613.58	3723.9	455.746	606.58	2539.3	404.862	-50.884	-0.11165
K STREET	35.63	4107.6	182.119	40.49	5279.3	231.417	49.298	0.2706911
I STREET	4.67	358.7	16.683	9.36	379.6	19.864	3.181	0.1906731
19TH ST	18.3	1389.8	64.742	18.32	1394.2	64.928	0.186	0.0028729
18TH ST	8.29	1029.9	45.341	9.13	1062.5	47.065	1.724	0.038023
CONN AV	170.87	2413.1	181.959	170.81	2480.6	184.629	2.67	0.0146736
17TH ST	64.54	1681.3	99.522	64.62	1655.3	98.522	-1	-0.010048
16TH ST	13.14	1550.7	68.598	13.02	1549.7	68.498	-0.1	-0.001458
TOTAL COST			1114.71			1119.785		

DIFFERENCE 5.075

% DIFF 0.0045528

TABLE 9 COST COMPARISONS FOR ANN ARBOR

ARTERY	SINGLE DELAY	STOPS	COST	NETWORKWIDE DELAY	STOPS	COST	COST DIFF	% DIFF
CATHERINE	10.2	1472.8	64.012	10.07	1458.9	63.391	-0.621	-0.009701
ANN	7.42	918.7	40.458	7.15	960.3	41.987	1.529	0.0377923
HURON	14.32	1280.1	58.364	13.83	1307	59.195	0.831	0.0142382
WASHINGTON	6.83	880.3	38.627	6.97	905.6	39.709	1.082	0.0280115
LIBERTY	3.86	494.4	21.706	5.12	667.6	29.264	7.558	0.3481987
WILLIAM	10.1	1328.7	58.198	11.02	1493.1	65.234	7.036	0.1208976
PACKARD	17.75	2361.1	103.319	17.84	2478.8	108.072	4.753	0.0460032
ASHLEY	4.45	810	34.625	4.41	831.8	35.477	0.852	0.0246065
MAIN	15.46	1736.8	77.202	15.9	1811.8	80.422	3.22	0.0417088
FOURTH	4.83	704.5	30.595	4.08	645.2	27.848	-2.747	-0.089786
FIFTH	4.43	642.8	27.927	5.27	757.3	32.927	5	0.1790382
DIVISION	8.68	1637.9	69.856	8.3	1434.6	61.534	-8.322	-0.119131
NN1	6.46	825.1	36.234	6.53	887.5	38.765	2.531	0.0698515
NN2	6.93	829.7	36.653	7.03	917.2	40.203	3.55	0.0968543
THOMPSON	2.53	621.7	26.133	3.11	667.1	28.239	2.106	0.0805878
TOTAL COST			723.909			752.267		

DIFFERENCE 28.358

% DIFF 0.0391734

TABLE 10 COST COMPARISONS FOR BATTLE CREEK

	SINGLE			NETWORKWIDE				
ARTERY	DELAY	STOPS	COST	DELAY	STOPS	COST	COST DIFF	% DIFF
WASHINGTON	12.65	2279.9	97.521	12.4	2359.8	100.592	3.071	0.0314907
McCAMLY	10.58	1993.5	85.03	10.78	2027	86.47	1.44	0.0169352
CAPITAL	12.7	2291	97.99	12.44	2303	98.34	0.35	0.0035718
CAPITAL2	11.42	1573	68.63	42.31	1343.4	74.891	6.261	0.0912283
CALHOUN	3.92	608.1	26.284	3.95	623.6	26.919	0.635	0.0241592
VAN BUREN	9.84	1452.4	63.016	10.14	1625.8	70.102	7.086	0.1124476
MICHIGAN	3.46	506.7	21.998	3.71	510.8	22.287	0.289	0.0131376
STATE	3.46	591.1	25.374	3.98	640.4	27.606	2.232	0.0879641
JACKSON	6.08	885.2	38.448	6.59	1018.4	44.031	5.583	0.1452091
HAMBLIN	2.28	502.5	21.24	2.53	498.4	21.201	-0.039	-0.001836
DICKMAN	10.46	2009.4	85.606	10.47	1998.6	85.179	-0.427	-0.004988
SPECIAL	3.99	499.7	21.983	3.85	502.7	22.033	0.05	0.0022745
TOTAL COST			653.12			679.651		
				DIFFERENCE	26.531			
				% DIFF	0.0406219			

TABLE 11 COST COMPARISONS FOR WASHINGTON, D.C., WEST CBD

		SINGLE			NETWORKWIDE			
ARTERY	DELAY	STOPS	COST	DELAY	STOPS	COST	COST DIFF	% DIFF
K STREET	8.27	1079.9	47.331	7.03	1340.4	57.131	9.8	0.2070525
L STREET	8.47	1057.5	46.535	7.08	1233	52.86	6.325	0.1359192
M STREET	11.62	2170.4	92.626	11.66	2229	94.99	2.364	0.025522
N STREET	9.57	1946	82.625	11.07	1804.7	77.723	-4.902	-0.059328
O STREET	14.51	1559.5	69.635	11.01	2014.9	86.101	16.466	0.2364615
P STREET	10.53	1751.8	75.337	11.09	1669.4	72.321	-3.016	-0.040033
Q STREET	9.44	1549.5	66.7	9.12	1579.9	67.756	1.056	0.0158321
9TH ST	11.28	1418.9	62.396	8.83	1883.5	79.755	17.359	0.2782069
10TH ST	11.51	1546	67.595	9.53	1582.9	68.081	0.486	0.0071899
11TH ST	10.06	1763.7	75.578	8.09	1910.4	80.461	4.883	0.0646087
12TH ST	12.72	2108	90.68	10.19	2330.1	98.299	7.619	0.0840207
13TH ST	12.66	2043.7	88.078	11.24	2065.4	88.236	0.158	0.0017939
14TH ST	13.67	2806.5	119.095	15.51	2600.4	111.771	-7.324	-0.061497
15TH ST	4.48	1109.2	46.608	4.81	1068.9	45.161	-1.447	-0.031046
TOTAL COST			1030.819			1080.646		
				DIFFERENCE	49.827			
				% DIFF	0.0483373			

CONCLUSIONS

The first phase of the study shows that optimization of arteries within networks using MAXBAND involves no cost other than that of computer time. About the only effect of imposing the network closure constraint is to take the individual timing plans for each artery in the network and put them together in a consistent network timing plan. That is, in small closed networks the bandwidths obtained with networkwide optimization are not significantly different from those obtained with single-artery optimization.

Phases 2 and 3 show that for small and medium-sized closed networks, optimization of the arteries by using TRANSYT-7F results in some cost increases to the networks but not necessarily to individual arteries. In fact, some arteries operate more efficiently when optimized as a part of a network.

RECOMMENDATIONS

Because network MAXBAND is relatively expensive to run, the traffic engineer might be wise to simply optimize each artery of small closed networks individually and adjust offsets manually to achieve near-optimal networkwide performance.

For small and medium-sized closed networks, optimizing an entire network by using TRANSYT-7F results in very little increased cost of stops and delay to the network as a whole. Lower cost associated with stops and delay can be expected for some arteries when optimized as a part of a network. Therefore it is recommended that networkwide optimization rather than individual-artery optimization be done on networks of this sort.

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DISCUSSION

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Several computerized signal timing optimization programs, such as TRANSYT-7F and MAXBAND 86, are currently available to optimize signal timing plans for linear arterials and grid signal networks. The maximal bandwidth program, MAXBAND, was enhanced by the Texas Transportation Institute in 1986 to maximize simultaneously the weighted sum of all progression bandwidths on all arteries of the signalized network. In addition to individual arterial progression constraints, an independent loop identification algorithm and a network closure constraint were added to describe the interconnected network topology in a closed signal network. This added condition requires that the sum of the relative signal offsets around any independent loop of the signal network be equal to a multiple of the common background cycle length. Therefore, it provides a progression-based network approach to optimize the overall traffic system performance of all the arterials within the signal network.

This study was to determine whether the network closure constraint in MAXBAND 86 would limit individual arterial performance in network runs. It essentially evaluated how the network closure constraint put additional restrictions on the coordinated progression offsets. A parallel effort was made to investigate the performance evaluation of minimal stops, delay, and fuel consumption as evaluated by the TRANSYT-7F program. Experimental designs were conducted by running MAXBAND 86 on both small and large closed signal networks. The bandwidths obtained from both the single arterials and signalized networks were compared. Then TRANSYT-7F optimization runs were executed for the same signalized networks. Individual runs of MAXBAND 86, TRANSYT-7F, and combined MAXBAND 86–TRANSYT-7F programs were later made to study the effects of different offset optimization schemes. Finally, the equivalent costs were used to compare the delay and stop measurements as recommended in the National Signal Timing Optimization Project.

When individual arteries were optimized separately, the results indicated that they could achieve approximately the same bandwidths as they would under network optimization. This implies that the signal timing optimization for a small network can be best improved by first optimizing individual arteries separately using MAXBAND 86. Then the offsets can be adjusted for each artery to obtain the needed signal timing plan. The comparisons of stops and delay measurements in small networks demonstrate that network progression can be better optimized when the network contains arteries with greater cost penalties for stops and delay. Large networks with arteries having lower penalty costs would provide better solutions when they are optimized as a network. Overall, the study demonstrated that the progression solution obtained from network optimization in small networks is not significantly different from those obtained with single-artery optimization. In effect, network closure constraints prevent individual arteries from obtaining the maximum bandwidths possible if these arterials were optimized separately. On the other hand, the potential gains in progression optimization are significant for large signal networks.

The major criticism of this study is that the full capacity of MAXBAND 86 network optimization may not have been properly evaluated. Two of the most important network optimization features of MAXBAND 86, phase sequence optimization and bandwidth weighting, were not considered. This was because of the computer resource available in the evaluation. One unique advantage of using MAXBAND 86 for optimizing network signal timing plans is that it provides network phase sequence optimization among all other signal timing programs. Because this particular study used only two-phase settings in all cases, it in fact did not examine the full phase sequence optimization capacity of MAXBAND 86. Furthermore, the study specifically stated that the network MAXBAND 86 runs did not provide more arterial progression bandwidths than the separated MAXBAND 86 arterial runs. Examination of the data sets and the signal timing plans may reveal that most signalized intersections have already reached their available maximum green times for progression optimization under current phase sequences. Therefore, MAXBAND 86 would not provide further improvement in network optimization over the use of single-arterial runs.

The other valuable feature of MAXBAND 86 is its capability of providing both intra- and interartery bandwidth weighting options. The intraartery bandwidth weighting, also called "within-artery" or "directional" bandwidth weighting, provides a method to split progression bandwidths within one artery for inbound and outbound travel. In contrast, the interartery or "cross-artery" bandwidth weighting option provides another technique to supply more weights or emphasis on certain arteries than the others. This new feature in MAXBAND 86 can intentionally constrain or enlarge the progression bandwidths in part of the network. Therefore, priority treatments can be made for a particular part of the overall signal network. In this way, the congested part of the signalized network can be emphasized dynamically in the signal timing optimization process. This new capability in MAXBAND 86 can supply a more flexible progression-based network signal timing optimization scheme for urban traffic management.

In summary, it is relatively easy to modify MAXBAND 86 for handling different network sizes and examining various levels of bandwidths weighting. The optimized timing plan in MAXBAND 86 can later be used as the initial starting solution for TRANSYT-7F after all the possible signal phase sequences for optimized network operations have been investigated. The current deficiency of MAXBAND 86 is neither the capability of problem formulation nor the flexibility of the program to model different traffic signal network configurations. Instead, the deficiency lies mainly in its relatively inefficient execution as a result of using the 1973 version of the Mixed-Integer Linear Programming (MILP) code for solving complicated network optimization problems. Significant improvements have been developed in MILP optimization in the past decade. Therefore, it is highly recommended that

1. Heuristic algorithms be implemented in MAXBAND 86 for developing interartery bandwidth weighting in addition to the available intraartery bandwidth weighting approach in the model, and
2. Significant investigations and revisions replace the existing MILP code with another updated MILP code for more efficient optimization execution in MAXBAND 86 in order to benefit from the unique feature of this progression-based network signal timing model.

AUTHORS' CLOSURE

The discussant points out that the scope of the study reported in this paper was limited by the computational resources, which are consumed by the current MAXBAND 86 optimization algorithms. The authors concur in the recommendation to improve the efficiency of these algorithms. We appreciate the discussant's interest in this paper.

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