OPTIMUM STAGING OF PROJECTS IN A HIGHWAY PLAN

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Many transportation studies recommend improvements for some future design year (normally 20 years hence) and stage construction of these improvements by 5-year increments. Numerous methods have been used to stage recommended improvements, but only limited work has been done on developing procedures that optimize a special objective function for priority selection. One previous approach to staging was to examine current capacity-deficient corridors and the target year volumes on the proposed facilities. Priorities were then set so that the facilities needed to relieve existing congestion were first, the facilities most heavily used in the future were next, and the less used future facilities were last. Another approach was to develop intermediate year travel forecasts from land use or traffic assignment models for intermediate years. The staging determination was similar to the full system evaluation process except that the intermediate year alternatives considered were combinations of projects composing the design year plan.

•THE UNDERLYING problem in optimal staging of highway projects can be stated as follows: Given a base year highway network, an ultimate (20th) year highway network, a budget available in 5-year increments, and a trip table for travel demands in 5-year increments, find the optimal assignment of construction projects to 5-year intervals so as to maximize system effectiveness while completing the 20-year highway plan within budget restrictions.

For the conduct of the research, system effectiveness was defined in terms of systemwide travel time saved. Several approaches to approximating systemwide travel time saved were developed and tested. The two prominent methods described in this paper are (a) computing and weighting vehicle hours of travel on a link and across the system and (b) assuming proportionality between time saved and vehicle miles (vehicle kilometers) reduced.

After the contribution of each link to systemwide time saved is approximated by one of the methods, this contribution is compared to the cost of the link by a priority ranking method so that the appropriate order for constructing link improvements can be selected.

In the remainder of the paper, the details of each method along with the results of a test of each method on the highway network for the small community of Hopkinsville, Kentucky, are described.

EFFECTIVE SPEED APPROACH

The research conducted to date based on heuristic methods will provide an operational methodology for staging the construction of improvements on large-scale networks. The improvements are elements of a long-range highway plan. Development of this

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methodology has progressed to a point justifying confidence in its ability to select (within a given budget constraint) transportation system improvements that will minimize the vehicle hours of travel at the budget-year demand level. In addition, the procedures developed summarize other data elements that can be used to evaluate the reliability of the methodology. The steps undertaken to develop this procedure and the results obtained are described below.

Methodological Construct

Assumptions

The assumptions of the procedure are as follows:

1. The improvement elements, their cost, and resulting capacity are known and define recommended system additions for some future year;
2. A travel demand trip table for the future year is used to select the ultimate recommended system; and
3. A network description and travel demand trip table for the current year are available.

Data Generation

With the above-defined data available, intermediate year budgets and travel demand trip tables must be estimated. The steps of the procedure are as follows:

1. The minimum distance paths between all zones are computed by using the recommended network;
2. The minimum time paths between all zones are computed by using the recommended network;
3. The distance from the minimum distance path is divided by the time from the minimum time path for each zone pair to determine the effective speed between zone i and zone j; and
4. The distance and effective speed between zone i and zone j are then used to enter a table of effective speed standards established for the urban area under investigation.

Table 1 gives the standards used to analyze the Hopkinsville, Kentucky, test system. When the table is entered with a distance and effective speed between two zones, travel between those zones can be classified according to the area of the table in which it falls: below minimum standard, standard, and above standard.

The procedure described in item 4 above is used to disaggregate an intermediate year demand trip table into demand trip tables for three intermediate years. Then the budget from the current year to the intermediate year is estimated; each of the demand trip tables for the three intermediate years is assigned to the recommended system network, and the volume on each improvement link produced from each assignment is stored for analysis.

Basic Data Analysis

The analysis procedures used in this research compare the total volume for the three assignments with the capacity for each improvement. If the volume of the assigned improvement exceeds the original capacity, the difference is computed and multiplied by the length of the facility to determine the vehicle miles of excess demand on the facility. This value is divided into the cost of the improvement to determine a measure of cost effectiveness that can be compared to the cost effectiveness of all other improvements. If, however, the assigned improvement volume is less than the original capacity, the cost-effectiveness ratio of the improvement facility is assumed to be infinity.

The cost effectiveness of each improvement is computed, and the improvements are ordered from the most cost effective to the least. Then, the least cost-effective improvements are eliminated until the cost of the improvement retained in the network is less than the available budget.

This is one cycle of the process. For the second cycle, the first grouping of intermediate year improvements selected is assumed to define a new recommended system, and then the process is repeated with a new intermediate year budget and demand trip table.

The analysis presented below assumes that the recommended system is to be completed in 20 years at a given cost. Staging of facilities is then accomplished for the fifteenth, tenth, and fifth intermediate years.

Analysis Variations

The procedure described was modified for this program in a number of ways. First, provisions were added so that the excess demand on a facility from each of the three assignments could be factored differently for each effective speed category. Then, the service provided to one class of trip could be more significant than that provided to another. In the studies that follow, below minimum standard trips were given a smaller factor than above standard trips.

Second, provisions were made to vary the factors incrementally between limits. This permitted the cost effectiveness of all improvements to be computed with multiple sets of weighting factors. The results are then aggregated to show the percentage of all possible sets of factors that produce a given priority for a given facility.

Third, the procedures can set capacity restraint on the networks so that there is a consistency between network speeds and volume-capacity ratios on system elements. This is done by loading the intermediate year demand trip table to the recommended year network with capacity restraint. The restrained network is then used for the individual assignment and summary of the three classes of trips.

Research Results

The effective speed procedures produce a near-optimal solution in terms of total vehicle hours of travel when the intermediate year demand trip table is stratified by the three classes of trips and when selected factors are applied to each of the three effective speed classes in a logical way. These findings may be verified from the description of the research results that follows.

One method used for determining optimal system staging was to establish the following weighting factors for the three classes of trips:

1. Below minimum, range between 0.1 and 1.0 in increments of 0.1;
2. Standard, range between 1.0 and 2.0 in increments of 0.1; and
3. Above standard, range between 2.0 and 4.0 in increments of 0.2.

These ranges and increments yield 1,210 combinations of factors for investigation. By applying each set of factors to the intermediate year assignment of each class of trip, improvements are ordered according to effective cost. By aggregating the results from the 1,210 applications of this procedure, the number of times that a particular facility is ranked in a specific position is obtained. The results of this consensus analysis are given in Table 2 for the 15-year demand assignment to the 20-year recommended network. The improvements to be made by the fifteenth year with this process are assumed to be those that are most cost effective and that are within the 15-year budget constraint. Based on this evaluation, improvements 3, 5, 11, and 16 (stage 2) were removed from the 20-year network to create the 15-year network.

The process was rerun by using the 10-year intermediate demand trip tables and

Table 1. Effective speed standards for Hopkinsville.

Trip Length (miles)	Below Minimum Standard Trips (mph)	Standard Trips (mph)	Above Standard Trips (mph)
0.5	<14.5	14.5 to 17.0	>17.0
1.0	<14.5	14.5 to 17.0	>17.0
1.5	<18.9	18.9 to 22.0	>22.0
2.0	<19.2	19.2 to 23.7	>23.7
2.5	<21.4	21.4 to 24.8	>24.8
3.0	<22.4	22.4 to 25.5	>25.5
3.5	<24.2	24.2 to 28.1	>28.1
4.0	<25.3	25.3 to 29.6	>29.6
4.5	<25.4	25.4 to 29.8	>29.8
5.0	<26.1	26.1 to 30.0	>30.0
5.5	<28.1	28.1 to 31.5	>31.5
6.0	<29.0	29.0 to 32.3	>32.3
6.5	<31.5	31.5 to 33.5	>33.5
7.0	<31.7	31.7 to 34.0	>34.0
7.5	<36.0	36.0 to 37.5	>37.5
8.0	<36.5	36.5 to 37.5	>37.5

Note: 1 mile = 1.6 km; 1 mph = 1.6 km/h.

Table 2. Composite ranking of improvements to be deleted from 20-year network.

Improvement	Stage	Rank																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.03	0.09	0.19	0.24	0.45	0.0	0.0	0.0	0.0	0.0	0.0
2	1	0.0	0.0	0.0	0.0	0.80	0.20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	1	0.0	0.0	0.35	0.65	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.74	0.26	0.0	0.0	0.0	0.0
4	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.97	0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	1	0.02	0.35	0.28	0.35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.27	0.20	0.05	0.48	0.0	0.0	0.0	0.0	0.0	0.0
6	2	0.0	0.0	0.0	0.0	0.16	0.32	0.16	0.07	0.29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0
8	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
8	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.97	0.03	0.0
9	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.61	0.36	0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.77	0.23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	1	0.0	0.63	0.37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.03	0.96	0.0
13	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.25	0.68	0.07	0.0	0.0	0.0	0.0	0.0	0.0
14	1	0.0	0.0	0.0	0.0	0.04	0.13	0.24	0.12	0.47	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	1	0.0	0.0	0.0	0.0	0.01	0.35	0.59	0.04	0.01	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.26	0.74	0.0	0.0	0.0	0.0
16	2	0.98	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3. Composite ranking of improvements to be deleted from 15-year network.

Improvement	Stage	Rank															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	0.0	0.0	0.0	0.0	0.0	0.0	0.20	0.43	0.12	0.25	0.0	0.0	0.0	0.0	0.0	0.0
2	1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
4	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.13	0.59	0.27	0.01	0.0	0.0	0.0	0.0	0.0
6	1	0.0	0.0	0.0	0.0	0.0	0.0	0.24	0.07	0.16	0.30	0.22	0.0	0.0	0.0	0.0	0.0
6	2	0.0	0.48	0.28	0.04	0.14	0.06	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.01	0.99
8	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.81	0.19	0.0
8	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0
9	1	0.0	0.0	0.0	0.0	0.28	0.72	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	1	0.0	0.0	0.02	0.89	0.09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.19	0.80	0.01
13	1	0.0	0.0	0.0	0.0	0.0	0.0	0.56	0.37	0.07	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	1	0.0	0.02	0.21	0.07	0.49	0.21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	1	0.0	0.50	0.50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.05	0.18	0.77	0.0	0.0	0.0	0.0	0.0

Table 4. Composite ranking of improvements to be deleted from 10-year network.

Improvement	Stage	Rank													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	0.0	0.0	0.0	0.0	0.08	0.20	0.66	0.04	0.02	0.0	0.0	0.0	0.0	0.0
4	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.33	0.67	0.0	0.0	0.0
4	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.31	0.69	0.0	0.0	0.0	0.0	0.0
6	1	0.0	0.0	0.0	0.0	0.0	0.02	0.04	0.65	0.29	0.0	0.0	0.0	0.0	0.0
6	2	0.0	0.0	0.03	0.09	0.62	0.11	0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.12	0.03	0.85
8	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.94	0.06
8	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.67	0.33	0.0	0.0	0.0
9	1	0.0	0.0	0.0	0.0	0.18	0.67	0.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	1	0.0	0.92	0.08	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.88	0.03	0.09
13	1	0.0	0.0	0.27	0.61	0.12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	1	0.0	0.08	0.62	0.30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

the new 15-year recommended network. The results, given in Table 3, provided the basis for selecting improvements to be removed from the 15-year network to develop the 10-year network. Based on this evaluation, improvements 2 and 15 were removed from the 15-year network. Table 4 gives similar results when the 10-year network was analyzed to determine the first and second 5-year improvement programs.

The 15-, 10-, and 5-year networks were also developed by using a weighting factor of 1.0 for all three classes of trips. This procedure resulted in a different ordering of the improvements based on cost-effectiveness values. Table 5 gives the 20-year improvements to be included in the 15-year network, the 15-year improvements included in the 10-year network, and the 10-year improvements to be included in the 5-year network for both procedures.

The order of staging is different for the two methods. Furthermore, there was no assurance that either method gives the best staging solution. (Most probably they did not.) Therefore, the results of the analysis were used to establish a series of 15-year networks (by removing logical candidates from the 20-year network). The 15-year networks with the 15-year demand trip tables were then used to assign trips and summarize results to determine whether the consensus 15-year networks did, in fact, produce the minimum vehicle hours of travel. This analysis was reasonably reliable inasmuch as most of the candidate systems that satisfied the budget constraints could be defined and the number of improvements was small enough to keep track of manually. The assignments and results are given in Table 5. The assignment descriptions indicate the improvements that are assumed to be removed from the 20-year network to create the 15-year network. Assignment 3-5-11-16(2) is the consensus network. The total assignment is the assignment of the 15-year demand trip table to the 20-year recommended system.

From Table 6 it is evident that improvements 3, 11, and 16 produce the minimum vehicle hours of travel of all 15-year networks analyzed. In addition, a rough cost-benefit analysis for each system was developed from the output data. Vehicle miles of travel were multiplied by $0.135. Vehicle hours of travel were multiplied by $2.50, and the system capital costs were multiplied by 0.0667 to develop an estimate of annualized cost. Based on this rough measure of the benefit-cost ratio, wherein the unit costs were assumed, improvements 15 and 11 were better than the consensus system results (improvements 3-5-11-16). However, when the two were compared directly by using the secondary benefit procedure discussed below, improvements 3, 5, 11, and 16 proved to be the superior system.

These results led to further evaluation to determine why improvement 5 was eliminated from the 15-year network in the consensus analysis. The location of the improvement in the fringe of the CBD was causing it to attract trips which, without the improvement, would travel through the CBD. Consequently, adding improvement 5 to the 15-year network produced significantly increased trip speeds and substantial benefits. However, the speeds were not increased enough to put the trips in the standard or above standard categories, which caused them to be insensitive to the factoring techniques. A procedure, possibly a preprocessor, must be developed to handle improvements of this type. If improvement 5 could be handled properly, then improvements 3, 11, and 16 would be the consensus network.

After the consensus procedure was modified, it identified the best 15-year network. This led to an approximation procedure useful in determining the specific weighting factors that should be applied to define the best system.

Test Network

Figure 1 shows the Hopkinsville test network.

Table 5. Summary of intermediate networks by consensus of factors and number of factors methods.

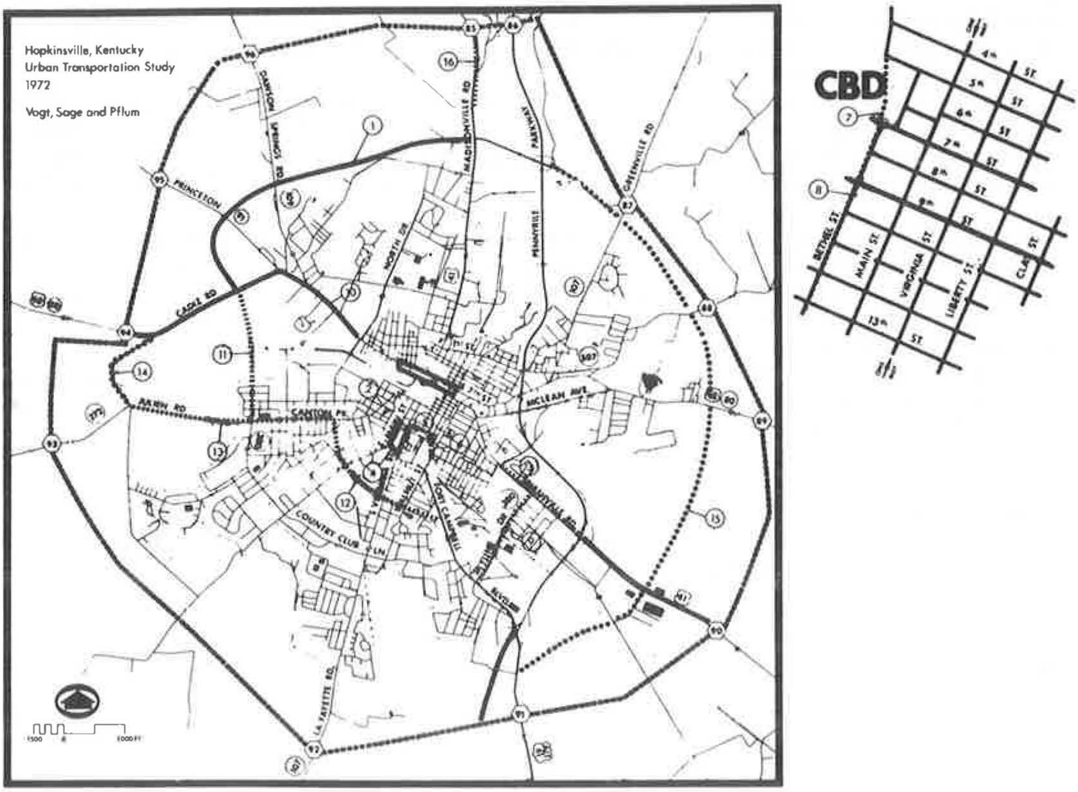
Item	15-Year Network: Consensus of Factors	15-Year Network: Number of Factors	10-Year Network: Consensus of Factors	10-Year Network: Number of Factors	5-Year Network: Consensus of Factors	5-Year Network: Number of Factors
Improvements needed	1 2 4(1) 4(2) 6(1) 6(2) 7 8(1) 8(2) 9 10 12 13 14 15 16(1)	1 2 4(1) 4(2) 6(1) 6(2) 7 8(1) 8(2) 9 10 12 13 14 15 16(1)	1 4(1) 4(2) 6(1) 6(2) 7 8(1) 8(2) 9 10 12 13 14 16(1)	1 4(1) 4(2) 6(1) 6(2) 7 8(1) 8(2) 9 10 12 13 16(1)	1 4(1) 4(2) 6(1) 7 8(1) 8(2) 9 12	4(1) 4(2) 6(1) 6(2) 7 8(1) 8(2) 9 12 13 16(1)
Improvements not needed	3 5 11 16(2)	3 5 11 16(2)	2 3 5 11 15 16(2)	2 3 5 11 14 15 16(2)	2 3 5 6(2) 10 11 13 14 15 16	1 2 5 10 11 14 15 16(2)

Table 6. Summary of results based on effective speed methodology.

Improvements	Vehicle Miles	Vehicle Hours	Below Minimum Standard: Vehicle Miles	Below Minimum Standard: Vehicle Hours	Below Minimum Standard: Trips	Annual Operating Cost (dollars)	Total Capital Cost (dollars)	Benefit-Cost Ratio
15, 2	530,262	17,190	178,798	6,729	64,604	41,814,400	9,423,000	5.043
15, 11	531,396	17,122	176,091	6,547	62,796	41,808,195	9,126,000	5.217
15, 14	530,867	17,114	174,718	6,504	62,546	41,774,980	9,806,000	4.906
15, 16	530,932	17,096	174,626	6,501	62,494	41,761,840	9,520,000	5.074
2, 3, 11	527,705	17,147	178,027	6,707	64,918	41,649,420	9,773,000	5.116
3, 11, 16	528,383	17,056	173,417	6,468	62,735	41,599,780	9,870,000	5.141
3, 5, 11, 16	528,972	17,069	173,172	6,461	62,625	41,640,660	9,834,000	5.097
3, 6, 11, 16	528,417	17,061	173,574	6,477	62,797	41,613,285	9,835,000	5.138
3, 11, 14	528,216	17,072	173,837	6,482	62,849	41,605,985	10,156,000	4.987
2, 10, 11, 14, 16	528,170	17,246	182,859	6,900	65,844	41,762,570	9,619,000	5.021
2, 10, 11, 16	528,621	17,217	180,657	6,832	65,512	41,758,555	9,829,000	4.920
3, 10, 14	529,423	17,173	181,852	6,769	64,548	41,757,825	9,789,000	4.941
3, 11, 12	527,543	17,264	184,857	6,971	66,404	41,747,970	9,698,000	5.003
All	528,593	16,934	166,434	6,207	60,943	41,498,675	13,065,000	4.000

Note: 1 vehicle mile = 1.6 vehicle kilometer.

Figure 1. Hopkinsville test network.



TIME-SAVED APPROACH

Objective

The methods described thus far have been oriented to identify the contribution of an individual improvement to this objective. After the contribution of an improvement is obtained, a cost-effectiveness cost-contribution ratio is calculated to rank the improvements.

Vehicle Hours as an Estimate of Contribution

One estimate of the contribution of an improvement to the systemwide objective is that of vehicle hours saved. The process of assigning vehicle loads to individual links is based on the construction (using the Federal Highway Administration's urban transportation planning software package) of minimum time paths in the 20-year network for origin-destination combinations in the 15-year trip table. Thus, vehicles are attracted to improvements if these improvements reduce travel time. Past experience has indicated that, generally, time saved is related to the length of an improvement. The longer vehicles travel at a higher speed, the more time they will save.

If a proportional relationship between time saved and vehicle miles on an improvement is assumed, the method of ranking improvements according to their contribution to system time saved is cost/(k × vehicle miles). When k is the same over all links in the system, it may be dropped from the ratio and the quantity cost/vehicle mile is the ranking criterion.

Relaxing the Assumption That the Proportionality Factor Is Constant Over the Entire System

Because not all vehicles traveling over a given improvement require the same travel time, individual origin-destination information was considered to determine the contribution of the improvement to systemwide time saved. Specifically, individual vehicle miles on an improvement from a given origin to a destination were weighted according to their relative importance to total time saved and were summed to obtain a weighted estimate of vehicle miles on an improvement. It was felt that such a weighting reflected the contribution of an improvement more accurately than assigning equal importance to all trips. The process of assigning weights to trips was based on quality of service considerations. For each trip loaded by the FHWA package, trip length and average speed were computed. As before, based on the speed and trip lengths, the trip was classified into three categories with respect to quality of service: below minimum standard, standard, and above standard. Those with below minimum standard quality of service were given low weight; those with standard quality of service were assigned higher weight; and those with above standard quality of service ratings were given highest weight.

The assumption is that system time saved is accurately defined for all improvements by the quantity cost/weighted vehicle mile where

$$\text{Weighted vehicle miles} = \Sigma_{O_iD_j} (k)_{\text{length, speed}} (\text{vehicle miles})_{O_iD_j}$$

Allocating Total System Time Saved Directly to Individual Links

Experience with the first two methods of computing the contribution of an improvement tended to suggest that some direct allocation of total systemwide time saved to improvements might be even more desirable in the ranking process. Several methods for performing this allocation were hypothesized, and one method was tested. Test results are presented subsequently.

A reasonable measure of total systemwide time saved can be computed in the following manner: Use the FHWA package to build shortest time trees in the base year and 20-year networks. For each origin-destination pair, the difference between the base year travel time and the 20-year travel time is the amount of time saved for each trip between that origin and destination. Multiply these time savings/trip by the 15-year trip table to get an estimate of total travel time saved by all vehicles in the system.

The Allocation Problem

After the systemwide time saved has been estimated, it must be allocated among the individual improvements. Using the network shown in Figure 2 will illustrate the point. The dotted lines indicate possible improvement links that could be added to the existing network, which is indicated by the solid lines. Suppose the origin-destination demands are A to D, 100 trips, and B to D, 300 trips.

Without the improvements, A to D traffic can only be routed A to C to E to D and B to D traffic must go B to E to D. If, however, improvement links BC and CD were available, then B to D traffic would go B to C to D. If the solid lines in the figure represent the base year network and the dotted lines the improvements added to form the 20-year network, total travel time saved may be as given in Table 7. Thus, total travel time saved equals 14,000 min. This total time saved must be allocated to the improvement links BC and CD. Clearly, the 2,000 min saved for AD traffic is independent of whether link BC is added to the network and hence should be allocated completely to link CD. The problem is in allocating the 12,000 min for the BD traffic. One method is to allocate the time saved as a function of the total link lengths. If both BC and CD are the same length, 6,000 min would be allocated to each. Thus, BC would be responsible for saving 6,000 min and CD for saving 8,000. Suppose, however, that the cost-effectiveness ratios turned out such that BC was preferred over CD, and, because of budget restrictions, only BC would be constructed. In such a case, no time would be saved because, without link CD, link BC is of no value in reducing travel time for BD traffic. In effect, links BC and CD are interdependent. If only CD is built, the total time saved would be 2,000 min. If only BC is built, no time would be saved, but, if both are built, the total time saved would be 14,000 min.

In this simple case, we have what might be called a second order interaction. This problem can be modeled as a quadratic 0,1 integer programming problem. Although it is conceptually and theoretically a correct formulation, in no way does it aid in solving optimum staging problems, since quadratic 0,1 integer programming problems are much more difficult to solve than linear 0,1 integer programming problems. It is possible that an interactive type of procedure could be developed wherein the allocation of time saved is changed at each interaction and the process stops when the predicted time saved, according to the allocation, is within reasonable limits of the actual time saved. The problem becomes even more complex when higher order interactions, which occur in most actual problems, are included.

Heuristic Approach: Maximize and Allocate Time Saved

As the research team defined, tested, and either rejected or modified various solution approaches, the need for an approach that could obtain satisfactory answers rapidly was clearly recognized. Therefore, a concept was designed to determine which improvement links should be added to a system so that the total budget is not exceeded and so that the total time saved by all system users is the maximum when compared to all other combinations of improvements that satisfied the budget constraint. Development and application of this concept required that a method be defined for allocating total time saved to individual improvements such that the summation of the time saved by the addition of each individual improvement equalled the total time saved when all improvement links were added to the network. With this capability, the procedure can rank

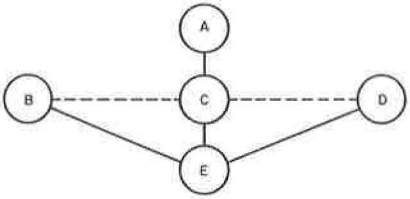


Figure 2. Sample network for allocating time saved.

Table 7. Time savings for network shown in Figure 2.

Origin-Destination	Demand Trips	Base Year Time (min)	20-Year Network Times (min)	Time Saved (min)
AD	100	60	40	2,000
BD	300	90	50	12,000

each improvement in order by a time saved-cost ratio.

IMPLEMENTATION OF THE HEURISTIC APPROACH FOR MAXIMIZING TIME SAVED

A series of 360 FHWA battery and FORTRAN programs was developed to implement the theory of maximizing time saved. The programs were written to obtain answers as rapidly as possible. Computer efficiency and operational ease were not prime considerations. The programs determine the impedance saved over any time span for each improvement in any highway plan. Based on the cost for each improvement, a final program ranks each improvement in order of a time saved-cost ratio.

Methodological Construct

The programs initially subtract the future year impedance matrix from the base year impedance matrix. The resulting matrix is then multiplied by a trip table, and a matrix of total impedance saved is created. Various programs are used to segregate portions of the total impedance saved into five categories. All impedance saved within a category is identified by an improvement number. The categories are as follows:

1. All impedance saved that goes through only one improvement—The impedance saved for this category is self-explanatory.
2. All impedance saved that goes through an improved link in the future year and goes through the same link (unimproved) in the base year—The impedance saved is defined by the difference between the base year and future year impedance for the link.
3. All impedance saved that goes through only one improvement in addition to those defined in 2—The impedance saved for the one improvement is the total impedance saved for an interchange minus the impedance saved for those links defined in 2.
4. All impedance saved that goes through two improvements or two improvements in addition to those defined in 1—The impedance saved for the two improvements is the total impedance saved for an interchange minus the impedance saved, if any, for those links defined in 2. A two-dimensional matrix of impedance saved by improvement number is created. The impedance saved in each cell is allocated to individual improvements in proportion to time saved per trip by improvement, determined from 1 and 3.
5. All other impedance saved that does not fall in the above categories—This is not evaluated, for it is insignificant by comparison (this assumption introduces little systemwide error).

Research Results

The series of programs developed was applied to the Hopkinsville test network. Travel time was used as the impedance. The 20-year skim trees were subtracted from the base year skim trees. The result was multiplied by the 15-year trip table to create a

Table 8. Time saved per unit cost.

Improvement	Time Saved Categories 1 and 3	Category 2	Category 4	Total Time Saved	Cost (dollars)	Time Saved/ Cost
16	0	459.4	1.1	460.5	626,000	0.74
11	213.2	–	1,707.5	1,920.7	890,000	2.16
3	71.3	4,996.4	115.2	5,182.9	1,809,000	2.87
15	9,585.5	–	1,484.7	11,070.2	3,049,000	3.63
1	2,802.6	–	5,513.3	8,315.9	1,772,000	4.69
14	0	1,295.9	0	1,295.9	210,000	6.17
10	357.3	7,819.5	477.4	8,654.2	1,257,000	6.88
13	5.1	8,315.8	164.5	8,485.4	1,225,000	6.93
2	41.2	4,600.7	240.4	4,882.3	593,000	8.23
9	21.8	4.834.4	219.6	5.075.8	568.000	8.94
8	0	1,546.7	0	1,546.7	157,000	9.85
4	1,206.6	–	91.4	1,298.0	85,000	15.27
6	1,463.1	–	77.2	1,540.3	80,000	19.25
12	9,716.8	–	5,034.0	14,750.8	668,000	22.08
5	765.3	–	93.8	895.1	36,000	23.86
7	6,483.8	–	3,195.1	9,678.9	40,000	241.97
Total	32,733.6	33,868.8	18,415.2	85,017.6	13,065,000	6.51
Percentage of grand total[a]	34.6	35.8	19.5	89.9		

[a] Grand total is the total time for all categories.

Table 9. Analysis of predicted time saved.

Network ID	Actual Time Savings Lost (hours/day)	Predicted Time Savings Lost (hours/day)	Percentage Difference
2, 15	256	266	3.9
11, 15	188	217	15.4
14, 15	180	206	14.4
15, 16	162	192	18.5
2, 3, 11	213	200	6.1
3, 11, 16	122	126	3.3
3, 5, 11, 16	135	140	3.7
3, 6, 11, 16	127	151	11.0
3, 11, 14	138	140	1.4
2, 10, 11, 16	283	265	6.4
2, 10, 11, 14, 16	312	286	8.3
3, 10, 14	239	252	5.4
3, 11, 12	330	364	10.3
Average			8.3

matrix of total 15-year time saved. This matrix was processed through the various programs, which allocated the time saved to the various categories and improvements described. Improvement costs were entered, and data given in Table 8, ranked by time saved-cost, were produced. All time saved is in min/day. The 15-year network with the minimum amount of travel time, as defined previously, is one that does not include improvements 3, 11, and 16. The time saved procedure ranks these as the lowest. This procedure does determine the best 15-year network for Hopkinsville based on the selected criteria.

Although the primary interest was whether this procedure could determine the best network, another concern was the accuracy of the predicted time saved. To evaluate this accuracy, 13 reasonable 15-year networks were selected. The 15-year trip table was loaded onto each of these networks, and resulting total travel time was determined. These travel times were then compared to the total travel time of the 15-year trip table loaded on the 20-year network. This comparison yielded the actual time saved that was lost by eliminating improvements for each network. This value was then compared to the value predicted by the time saved procedure (Table 9).

CONCLUSION

The research reported here demonstrates the validity of both the effective speed approach and the time-saved approach to staging elements in a highway plan. Although neither approach is proposed as optimal, both were able to select the best staged plan for the Hopkinsville, Kentucky, network within the constraints imposed. Further understanding of the critical issues involved in the development of procedures for staging a recommended highway plan can be obtained by analyzing and testing a large-scale urban system with the two procedures developed in this research.