Urban Form Optimization System: A Computer-Aided Design and Evaluation Tool for Assisting the Investigation of Interrelationships Between Land Use and Transportation

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Solving traffic congestion problems has long been a major objective of urban transportation studies. Neither construction nor operations management can totally solve congestion problems economically, efficiently, and equitably. Urban congestion problems can be reduced only if a better understanding of the long-term interrelationships between land use and transportation is achieved. The Urban Form Optimization System (UFOS) represents an initial attempt to develop a computer-aided design and evaluation tool to aid investigations of interrelationships between land use and transportation. UFOS contains a land use–network editor, an integrated land use–transportation simulation model, an interactive graphic mapping module, and a multicriteria evaluation module. These modules are linked together so they can support an interactive graphic design and evaluation process. To date UFOS has been proven effective in designing and evaluating land use–transportation alternatives in the classroom. UFOS's major functions are described in this paper, and some examples that illustrate its capabilities are provided.

Solving traffic congestion problems has long been a major objective of urban transportation studies. Neither construction nor operations management can totally solve congestion problems economically, efficiently, and equitably. Urban congestion problems can be reduced only if a better understanding of the long-term interrelationships between land use and transportation is achieved. Traditionally, such long-term interrelationships have been investigated using an integrated land use and transportation simulation model *(1–5)*. There are four major weaknesses in these studies. First, they usually do not use equilibrium solutions. Second, they are limited in the number of alternatives generated and evaluated. Third, they produce large quantities of data that are hard to comprehend and interpret. The last and most important weakness is that they usually lack an explicit multicriteria evaluation component. For these reasons, an improved computer-aided design and evaluation simulation model is needed to help in better understanding the complexities of an urban system.

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URBAN FORM OPTIMIZATION SYSTEM

The Urban Form Optimization System (UFOS) is an interactive graphic computer program that is designed to allow a user to formulate and test a wide variety of ideas about the design of a city. It allows a user to change an existing land use pattern or to change the capacity of various links in an existing transportation network (or to change both simultaneously) and then immediately calculate values for a set of criteria that is used to evaluate how well the resulting land use–transportation alternative performs in relation to other alternatives. It supports a man-machine intuitively guided design process that consists of the generation and evaluation of a series of alternative designs. The overall objective is to maximize performance in relation to multiple criteria. It is operational on a CDC Cyber 180/855 computer and uses the TEMPLATE graphics program. UFOS has four main features: it (a) is user friendly, (b) is interactive and graphic, (c) includes equilibrium conditions, and (d) uses a multicriteria evaluation technique. These features are present in four individual modules:

1. The UFOS1 module supports input data editing, such as task title, land use pattern, network attributes, and other parameters. UFOS1 has a built-in data consistency checking function to help the user avoid input errors.
2. The UFOS2 module performs land use–transportation simulations, given a distribution of basic employment and a transportation network. It allocates population and service employment to zones and loads the transportation network with journey-from-work trips. It is basically an integration of a Lowry-type land use allocation model and an equilibrium traffic assignment model. It uses an iterative technique that adjusts both land use and network loads so that an equilibrium condition results from the computations of the assignment model. Congestion is the main link between land use and transportation in the model. As congestion rises, link speeds are reduced and the land use allocation process changes accordingly.
3. The UFOS3 module generates graphic displays using the input data to and output data from the simulation model, such as basic employment distribution, population distribution, network loading, and congestion patterns. It also allows changes between the previous design and the current design to be

displayed. UFOS3 employs TEMPLATE graphics subroutines to draw maps on a Tektronix graphics terminal and hardcopy machine. Figure 1 shows examples of graphic displays that can be generated by UFOS3.

4. The UFOS4 module performs the multicriteria evaluations and displays the results to help the user identify superior designs. UFOS4 automatically records up to 13 areawide performance criteria calculated from UFOS2. For most applications these 13 criteria are related to broad objectives in a hierarchical manner:

		+ V/C (less is better)
		+ WTT (less is better)
	+ Efficiency --	+ WTS (more is better)
	+	+ NWTT (less is better)
	+	+ NWTS (more is better)
	+	+ AENG (less is better)
	+	
	+	+ COST (less is better)
Total Worth -	+ Economy --	+ SMP (less is better)
of Design	+	+ SME (less is better)
	+	+ TRAN (more is better)
	+	
	+	+ ACCP (more is better)
	+ Equity ----	+ ACCS (more is better)
		+ ACCN (more is better)

where

V/C = the average of the link-specific volume-to-capacity ratios for the entire network.

WTT = the areawide average work-trip travel time in minutes.

WTS = the average work-trip travel speed in miles per hour.

NWTT = the average non-work-trip travel time in minutes.

NWTS = the average non-work-trip travel speed in miles per hour.

AENG = the average gasoline cost in dollars.

COST = the combined arterial and freeway network construction cost derived from the equivalent lane-miles of each facility type.

SMP = the second moment of the total population distribution. Larger values indicate more dispersed distribution patterns. For UFOS design problems, it is assumed that less is better for the SMP in order to capture the cost-reduction benefits of compact urban forms. More important, lower values avoid unreasonably dispersed population distributions that have few agglomeration economies.

SME = the second moment of the total employment distribution. As is the case for SMP, smaller values are preferred.

TRAN = transit ridership share as a percentage of total person trips.

ACCP = the sum of all zone-specific accessibility indices to total population.

ACCN = the sum of all zone-specific accessibility indices to non-location-oriented service employment.

ACCS = the sum of all zone-specific accessibility indices to location-oriented service employment.

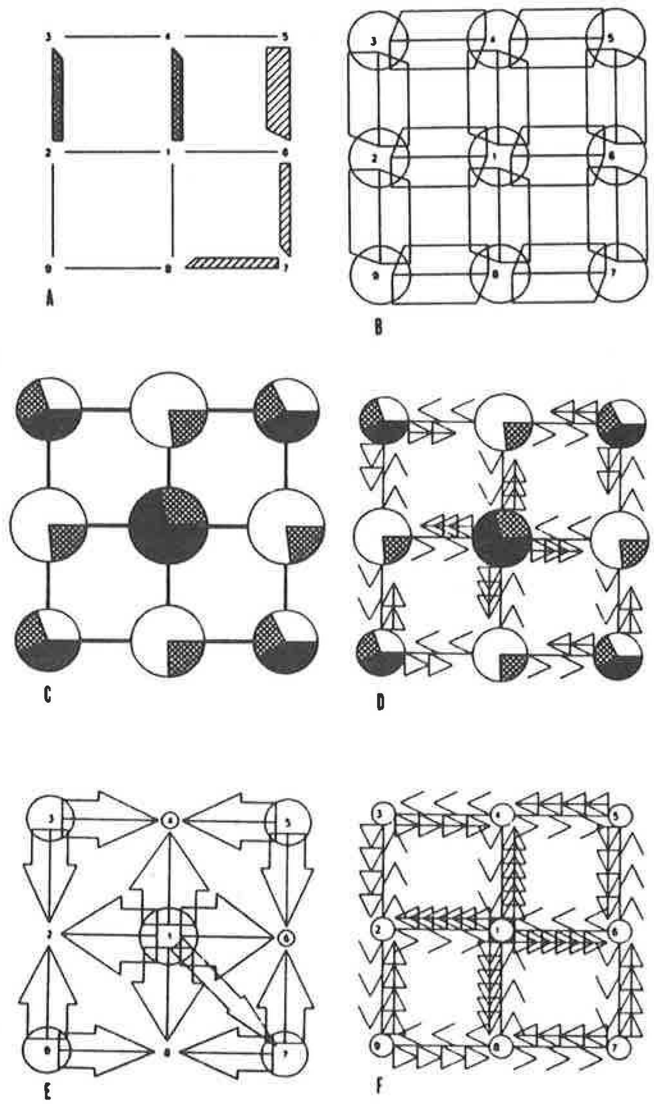

FIGURE 1 Examples of UFOS3 graphics: A, link attribute changes; B, link attributes; C, land use (employment and population); D, land use and congestion; E, origin-destination flows; and F, link congestion.

The design problem is to find a way to raise the values of the six more-is-better criteria while reducing the values of the seven less-is-better criteria. In addition to these 13 criteria, there are 2 other criteria that are not included in the concordance analysis but are nevertheless important indicators of network efficiency:

OLL: the number of overloaded links and
ULL: the number of underloaded links.

The multicriteria evaluation is performed by using concordance analysis *(6, 7)*. This technique makes it possible to deal effectively with multiple, conflicting criteria that are always present in land use–transportation problems. Basically, concordance analysis involves normalizing a project effects matrix, devising sets of relative importance weights for the criteria, and comparing each alternative with all other alternatives. It produces a ranking of the alternatives and indicates those that are nondominated. These are usually referred to as "best-compromise" alternatives because they have been found to be generally superior with respect to all of the multiple viewpoints or value sets represented by the sets of relative importance weights used in the analysis. The essence of the concordance analysis results is shown graphically in Figure 2.

ILLUSTRATIVE EXAMPLE

In this section is provided an illustrative example drawn from a network design exercise in which five alternative network designs were generated and evaluated. Given several designs and weighting schemes, the purpose of a design and evaluation process is to identify a best-compromise design with respect to several different and conflicting criteria. The city shape used is defined by a grid and radial network shown in Figure 3. A total of 30,000 basic jobs are allocated first. One-third of these jobs are located at the center (Node 1) of the network. The other 20,000 basic jobs are equally distributed among four nearby nodes (3, 5, 7, and 9). The initial link capacity is set at 800 vehicles per hour (vph) for each grid and 1,300 vph for each radial link. For all internal links, a capacity of 2,000 vph is used. In addition, a transit network is evenly spread over the city.

The land use attractiveness factors are asymmetric as given in Table 1. Given these initial land use and network input data, UFOS2 generated the land use and network congestion pattern shown in Figure 4. In the model, the 30,000 basic jobs internally generate a total population of 120,000 and a service employment of 30,000. A total of 60,000 work trips are loaded on the network and produce considerable congestion.

The resulting land use attractiveness factors are not uniformly distributed. Figure 5 shows the congestion pattern as represented by link-specific V/C ratios. From this map it can seen that the links that are connected to Node 2 are heavily congested. This is because Node 2 has been allocated the

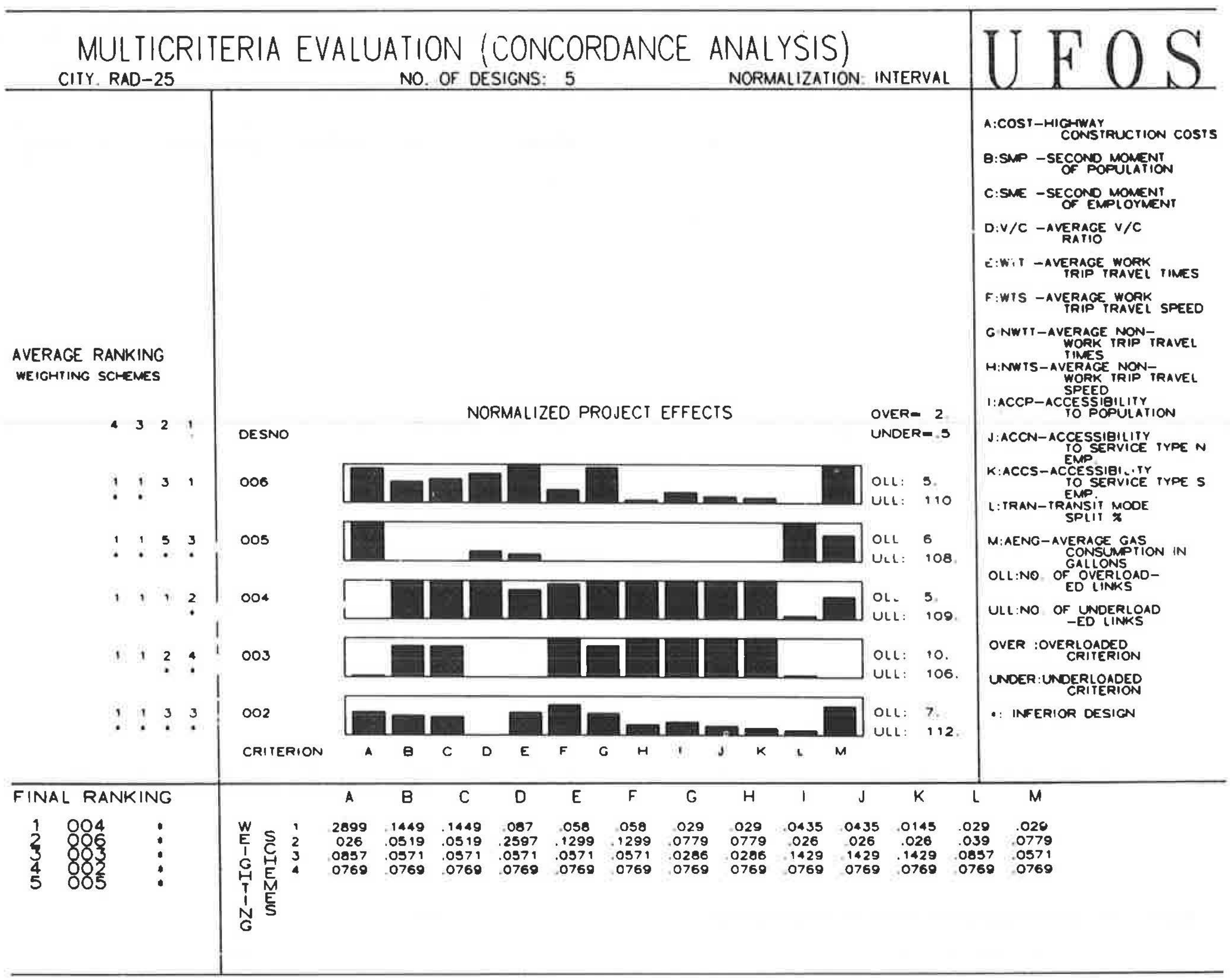

FIGURE 2 Multicriteria evaluation display using concordance analysis results.

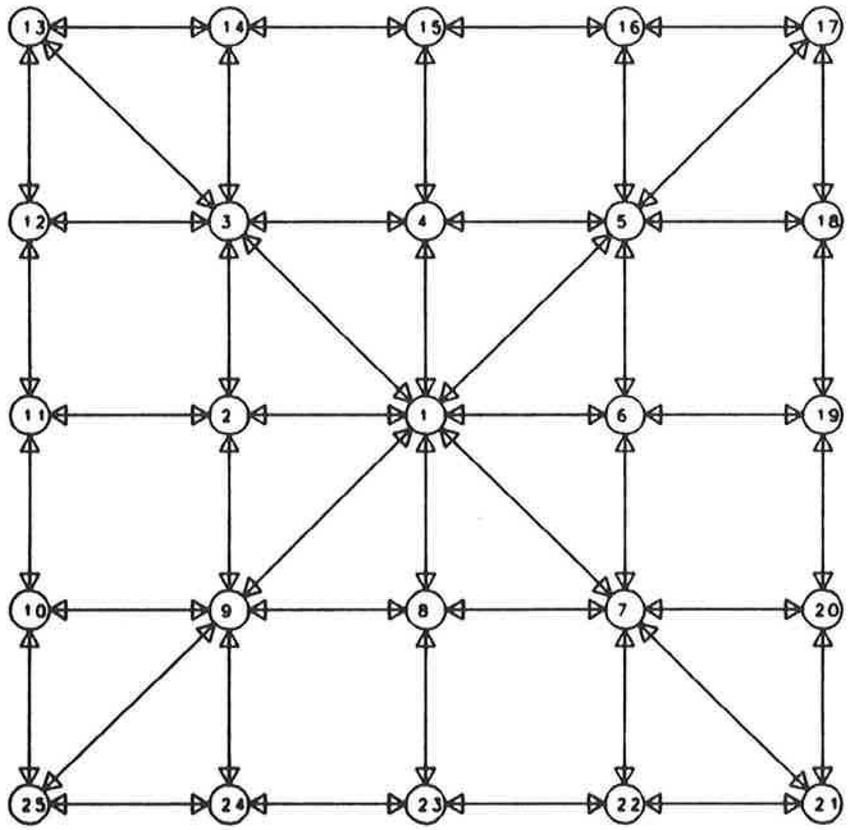

FIGURE 3 Network configuration (Design 1).

TABLE 1 LAND USE ATTRIBUTES FOR ILLUSTRATIVE EXAMPLE

Zone[a]	No. of Basic Jobs[b]	Residential Attractiveness Index[b]	Service-N Attractiveness Index[b]	Service-S Attractiveness Index[b]
1	10,000	100	100	100
2		200	50	50
3	5,000	300	50	50
4		200	50	50
5	5,000	200	50	50
6		200	50	50
7	5,000	200	50	30
8		200	50	50
9	5,000	200	50	50
10		300	50	30
11		400	50	60
12		500	30	50
13		100	70	50
14		100	50	50
15		200	50	50
16		100	50	50
17		400	50	50
18		300	20	50
19		300	50	50
20		100	10	80
21		200	50	90
22		100	50	30
23		100	50	50
24		200	50	50
25		400	50	50

[a]Each node in the network represents a zone in the city.
[b]More is better.

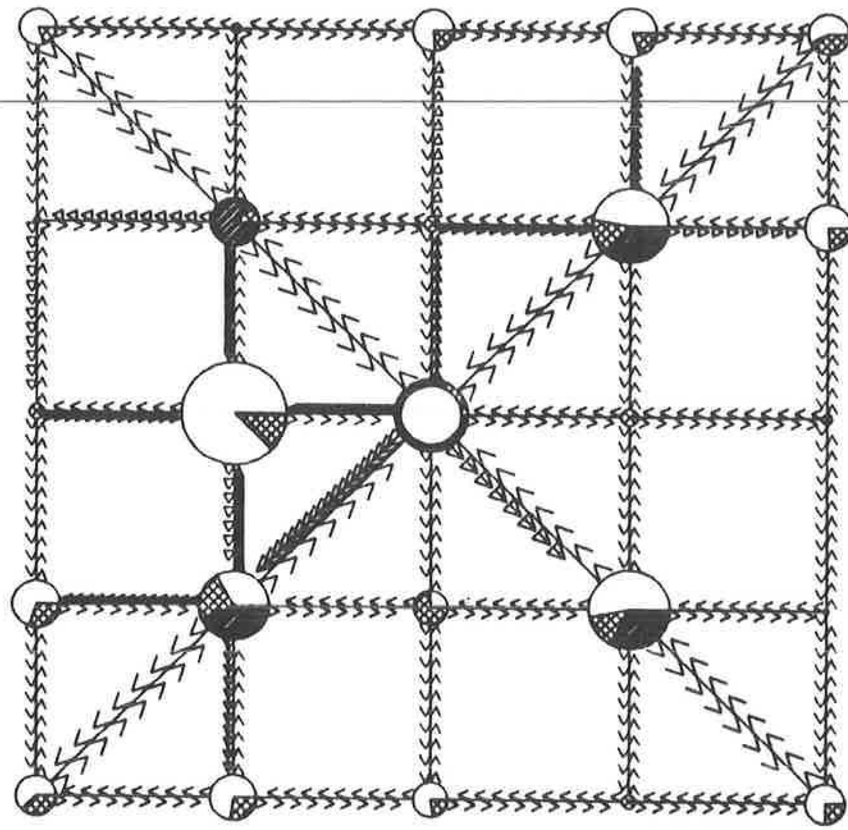

FIGURE 4 Land use and link congestion of base design with loaded network, population, and employment (Design 1).

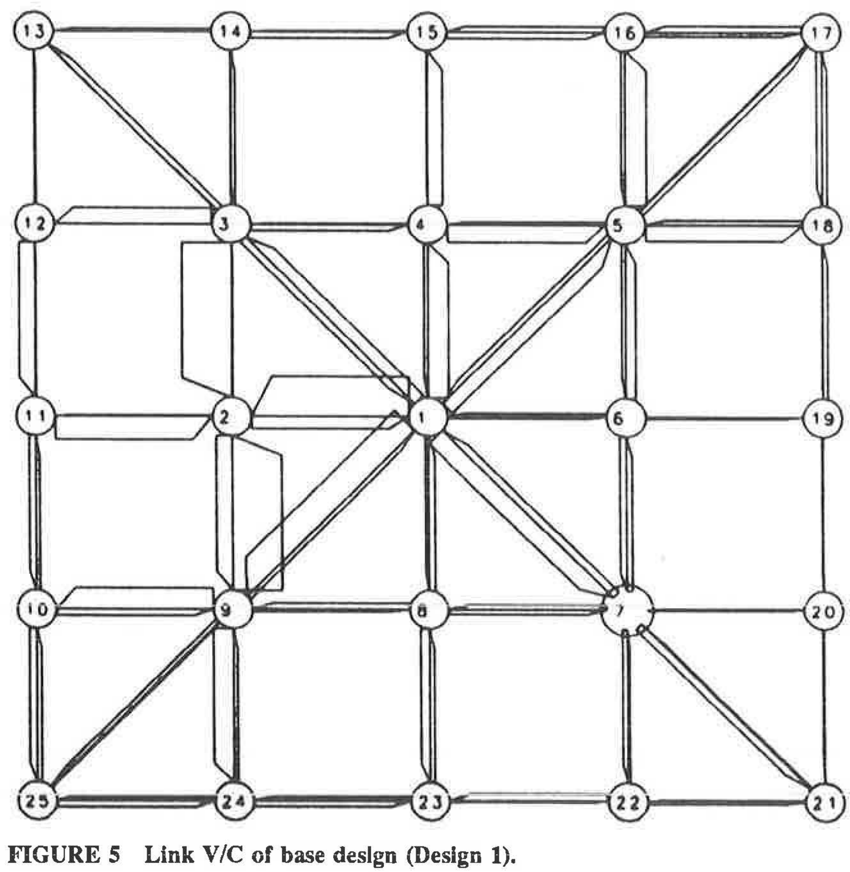

FIGURE 5 Link V/C of base design (Design 1).

largest population and so attracts heavy volumes of work-to-home trips during the evening peak hour. The high V/C ratios (e.g., 3.4, 3.4, and 2.8) on these links indicate that the link capacities are not well matched to the land use pattern in this area.

If the location of basic jobs is kept fixed, one way to relieve the heavy congestion is to change certain link capacities. This can be done by (a) adding capacity, (b) reducing capacity, (c) building new roadway links, and (d) improving the transit network. Increasing link capacities will usually reduce the average network congestion level. But, because construction budgets are normally limited, capacity cannot simply be added to every congested link. Usually, the optimal network design problem involves finding the smallest construction budget that produces the greatest set of benefits.

Solving this problem involves determining how much capacity to add or to delete or from each link and where to do so. Conceptually, there are billions of alternative designs possible even for this small network. In reality, only a few of these designs will be economical, efficient, and equitable. However, the more alternatives that can be generated and evaluated, the more likely it is that a truly superior solution will be found.

For the example, five designs (2–6) were generated. All of these alternative designs represent a conventional reaction to congestion in that additional capacity was added to congested links. Each of the designs represents a different way of dealing with the same problem. The land use pattern was always considered in resetting the link capacities. Some selected results of these designs are shown in Figures 6–9. The values calculated for the 13 criteria used to evaluate the five designs are given in Table 2. The overall evaluation display from UFOS4 is shown in Figure 2.

Figure 6 (Design 2) shows the land use and congestion pattern that was produced by adding capacity to congested links as shown in Figure 7. By comparing Figure 4 (Design 1) and Figure 6 (Design 2), it can be quickly seen that most of the heavy congestion in Design 1 is no longer present in Design 2. Still, there are several congested links in Design 2 that need further attention. The large increase in population and employment at Node 8 that resulted from the link capacity additions made to the network of Design 1 can also be seen.

Figure 8 (Design 4) shows the land use and congestion results of adding capacity to the first roadway ring (shown in Figure 9). Comparing Figures 4, 6, and 8 reveals several congestion levels and land use differences. Design 4 still has some congestion problems but they are relatively minor compared with those of Design 1. Designs 5 and 6 used different capacity change patterns, but neither produced results that were better than Design 4 (Figure 8).

Four different weighting schemes were generated to reflect the different viewpoints that decision makers might bring to this problem. The first weighting scheme is economy oriented, the second is efficiency oriented, and the third is equity oriented. The last weighting scheme assumes that all criteria are equally important. These weighting schemes are included in the multicriteria evaluation display (Figure 2). Given the criteria values (Table 2) for each of the six designs and the four weight sets, concordance analysis first sequentially evaluates

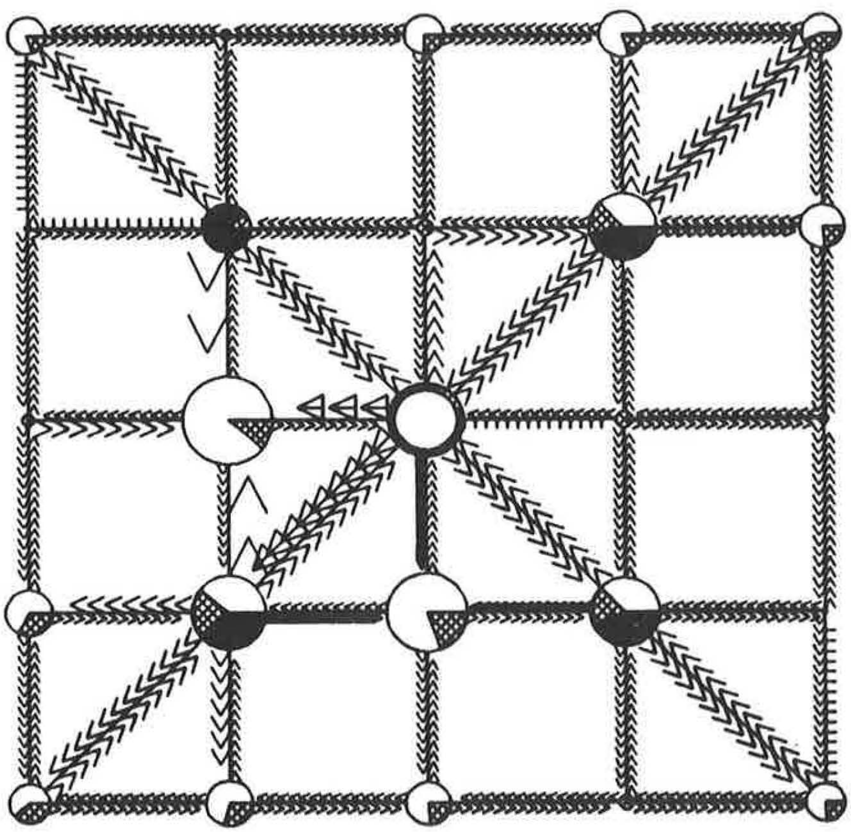

FIGURE 6 Land use and congestion with loaded network, population, and employment (Design 2).

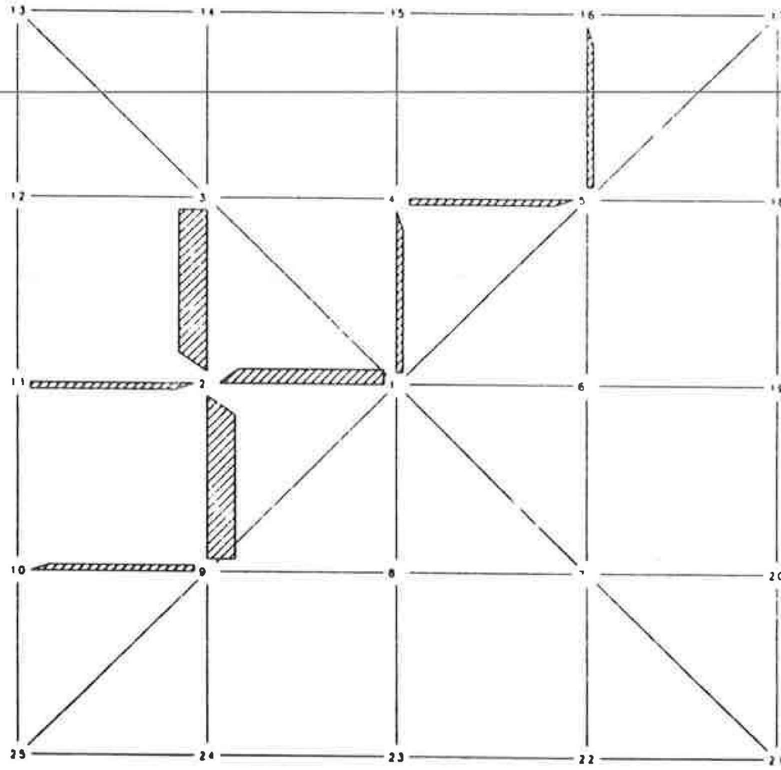

FIGURE 7 Link capacity changes between Designs 1 and 2.

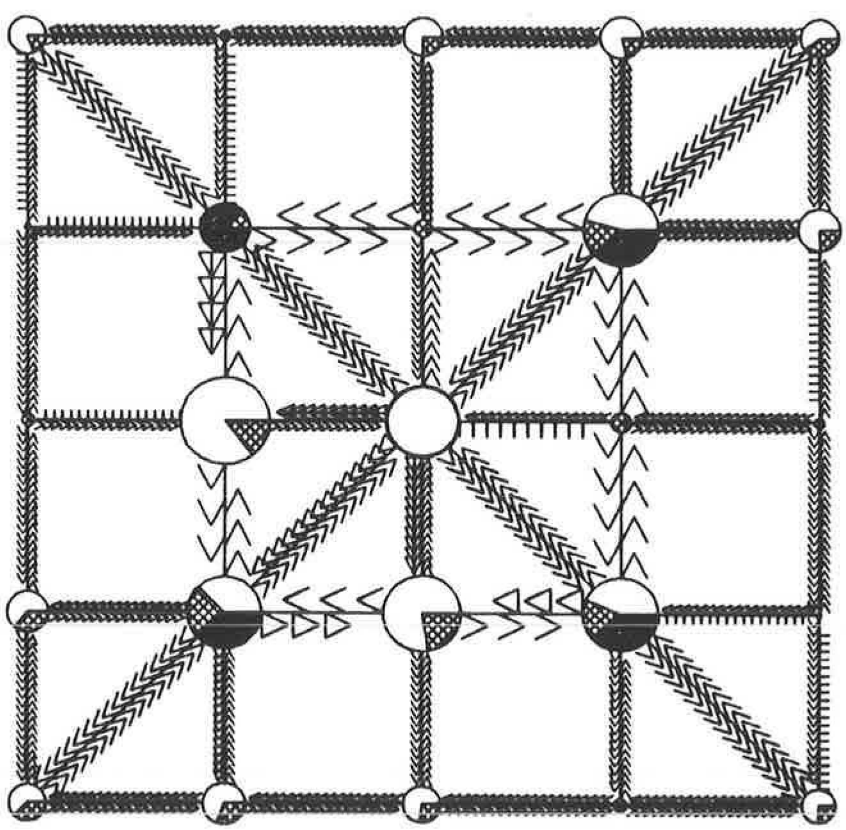

FIGURE 8 Land use and link congestion with loaded network, population, and employment (Design 4).

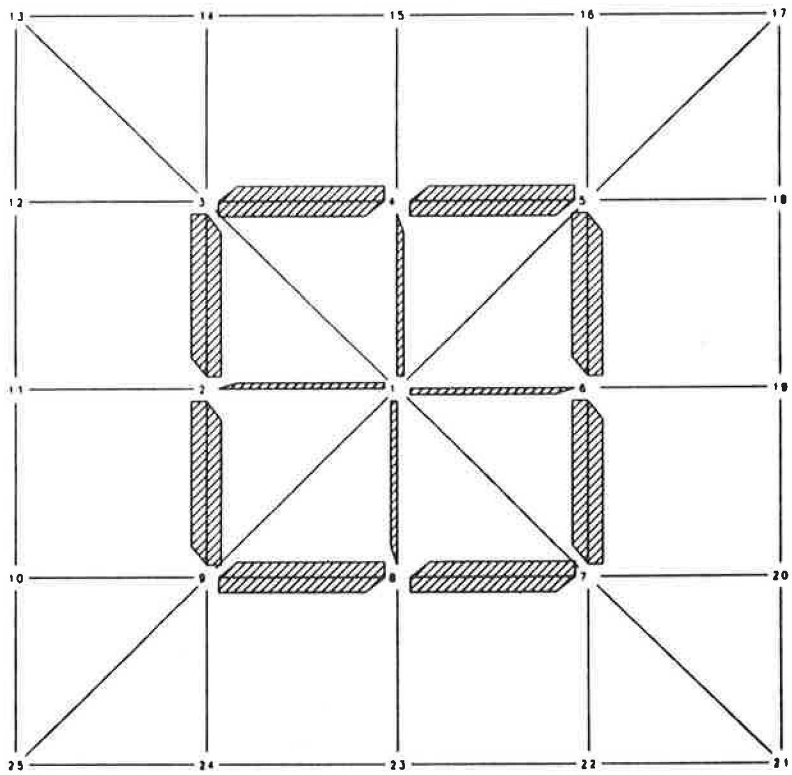

FIGURE 9 Link capacity changes between Designs 1 and 4.

TABLE 2 AREAWIDE PERFORMANCE CRITERIA VALUES FOR ONE BASE AND FIVE ALTERNATIVE DESIGNS

Performance Criterion	Base (starting) Design 1	Alternative Design 2	3	4	5	6
COSTS	1280	1731	2216	2206	1413	1496
SMP	51853	48744	47219	46193	51277	48503
SME	20115	19578	19237	18995	20088	19421
V/C	0.47	0.38	0.38	0.34	0.37	0.35
WTT	22.06	17.55	18.99	17.13	18.57	16.53
WTS	5.65	6.69	6.85	6.78	6.12	6.37
NWTT	10.21	10.21	10.15	10.10	10.35	10.12
NWTS	18.41	19.76	22.69	22.53	18.70	19.00
ACCP	388.97	423.42	468.38	468.29	400.37	418.72
ACCN	113.06	121.88	150.98	151.86	112.85	119.21
ACCS	116.09	122.81	152.98	153.57	116.17	120.90
TRAN	16.34	15.38	15.22	15.29	18.57	15.14
AENG	0.73	0.62	0.71	0.64	0.63	0.59

the alternative designs relative to each weight set. Finally, all designs are evaluated and ranked in relation to all weight sets. The details of this calculation are available in other published papers [e.g., Giuliano *(7)*].

Using UFOS4, the user can obtain a display of the evaluation as shown in Figure 2. In the center of this display, bar charts of normalized criteria values are displayed and the associated number of overloaded and underloaded links is shown for each design. The average rank of each design of the four weighting schemes is shown on the left side of the display. These average ranks are aggregated and averaged to produce the final ranking that shows the best-compromise design (Design 4). Ideally, the design that is ranked highest and is nondominated for every weighting scheme is the best one. However, in many cases, this result is not easily achieved and a more detailed examination of the sensitivities of the weighting schemes is necessary.

In this example, the interval normalization method is used and Design 4 is ranked highest. None of the designs is totally nondominated for all weighting schemes. However, Design 4 is nondominated for Weighting Schemes 1–3 and is clearly the best-compromise design of this set. Although Design 4 is the second most costly alternative, it produces better marginal benefits for the other criteria than do the other designs. Design 4 is dominant using only the cost-oriented weighting scheme. This indicates that when the weight on cost is moved down to as little as 0.3, Design 4 will be dominated by Design 6, which costs considerably less. This is an example of the type of trade-off information that can be obtained from the multicriteria evaluation display. Selection of the proper weighting schemes

that will allow the development of a consensus among decision makers is, as always, the major task in selecting a preferred design.

It is not suggested that the results from concordance analysis be accepted and used alone for decision making. They simply represent an objective evaluation for use in a decision-making process. Before a final decision is reached, such results need to be carefully examined. UFOS has been designed to facilitate an effective design evaluation process and to help the user more clearly identify the often mysterious trade-offs that exist in any multicriteria evaluation process.

DISCUSSION OF RESULTS

In this paper has been described the initial version of a new computer-aided design and evaluation tool that is currently being used to investigate the interrelationships between land use and transportation at the University of Washington. UFOS can be used to generate and evaluate a wide range of designs effectively and efficiently. A small-scale network design problem has been used to illustrate its capabilities with reference to five alternative designs. Several maps were developed to display data on the spatial relationships of the land use pattern and the network performance attributes of each design. The congestion pattern is easily seen on these maps. Concordance analysis is used to identify the best-compromise design of the five considered. Four different weighting schemes were used in the evaluation.

It is suggested that use of this computer-aided design and evaluation tool will help practicing professionals find a more efficient and effective approach to dealing with complicated multicriteria land use–transportation problems. UFOS is currently being used to conduct a variety of experiments that are designed to investigate and identify land use–transportation interrelationships more clearly than has been possible previously. For example, the results from 120 designs for a small test problem are being examined to see if there are any strong relationships among the 13 criteria used for evaluation. If strong relationships can be found, they may be powerful aids in the design process for networks that are too large for the practical application of mathematical programming techniques.

As it stands, UFOS is a tool that can be used to investigate a wide variety of questions in a laboratory setting. Various parts of the problem can be held constant or allowed to vary. Interpretation of results is greatly eased by the readily available graphics. Finally, evaluation of alternatives, an often underdeveloped part of the planning process, is given a major role in the design process.

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