Grade-Separated Pedestrian Circulation Systems

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Grade-separated pedestrian networks, which are generally partial networks that serve as alternative systems to regular sidewalk networks, are analyzed. Indicators for selecting new grade-separated links for implementation, out of many available, are proposed. The proposals include measures of network connectivity (considering land use in, and separation of, origin-destination pairs) and network circuitry. A microcomputer program GSPCS has been developed to assist planners. Several examples are given based on the city of Calgary PLUS 15 elevated walkway system.

During the last 25 years, many cities have shown an interest in implementing grade-separated pedestrian circulation systems (bridge or tunnel networks) as alternative facilities for pedestrian circulation in downtown areas. The Calgary (Alberta) PLUS 15 walkway system, Minneapolis and St. Paul (Minnesota) Skyway system, Cincinnati (Ohio) and Des Moines (Iowa) Skywalk systems, and Houston Downtown Tunnel System are some examples.

The purpose of implementing these alternative pedestrian circulation systems changes from place to place. A few of the main objectives are to separate pedestrian traffic from vehicular traffic, to protect pedestrians from inclement weather, and to promote development such as an additional level of retail space (*1*). However, where the pedestrians are concerned, all of those objectives converge into a single goal: convenience.

There are concerns regarding the introduction of grade-separated pedestrian circulation systems (alternative networks) in downtown areas. Some argue that they may keep the pedestrian off the streets and eventually kill and sterilize the ground-level activities that reflect the liveliness of a city. Those who are in favor argue that pedestrian convenience outweighs the disadvantages (*2*) and that alternative networks can actually help to keep a downtown area alive, particularly in cities with severe climates. Other concerns are personal safety, particularly in tunnels, and the difficulty of way-finding indoors.

NEED FOR PLANNING TOOLS

The negative effects of alternative networks could be minimized if given careful consideration at the planning stage. The ideal is for an alternative network to have connectors between all the adjacent activity centers (blocks). However, topographical, land use, and financial constraints usually interfere with achieving that ideal condition. In such situations it is important to determine the most efficient network subject to constraints.

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At present very little information is available on planning and designing alternative circulation systems. Sound quantitative methods to estimate the origin-destination distribution (O-D matrix) and link flows of pedestrians are not readily available. Even with the availability of a methodology to estimate the O-D matrix and link flows, it is not easy to determine the best alternative network without the help of indicators to rank the different networks. Therefore, indicators that are used to evaluate the performance of an alternative network should be useful to planners.

OBJECTIVES

The aim of this study was to develop a methodology to evaluate a grade-separated pedestrian circulation network, so that different design alternatives can be compared at the planning stage, especially when links are added to an existing system. The main objectives are to develop indexes to evaluate the network in terms of connectivity and ease of pedestrian circulation. As an example, an idealized nine-block area is shown in Figure 1, with four existing links. Because of various constraints such as lack of a suitable connecting building, only four out of eight new links are feasible. Given that funds are available to build a fixed number of links (fewer than four), a question arises as to which one or ones should be built. A personal-computer-based tool that can undertake the above analysis should prove useful to planners in the decision-making process, which also takes into account a variety of other factors.

PLANNING PEDESTRIAN CIRCULATION SYSTEMS

Literature Review

Some studies have been done to estimate pedestrian trip generation, trip distribution, or trip assignment in downtown areas. However, specific studies on grade-separated pedestrian circulation systems are lacking in the literature. Bhalla and Pant (*3*) used regression analysis to estimate the link volumes in the Cincinnati Skywalk system. They showed that land use types have a significant impact on the link flows between blocks. Seneviratne and Morrall (*4*) identified the shortest route as the major criterion for pedestrian route choice in downtown Calgary. In general, the literature shows that land use type and distance between O-D pairs are the main parameters that govern pedestrian flow between different downtown blocks.

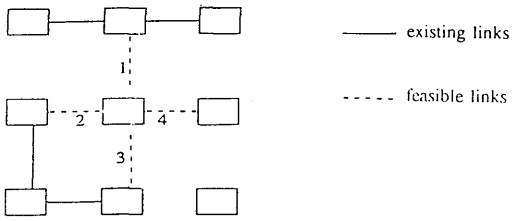

FIGURE 1 Idealized nine-block area.

Analytical Approach

In the absence of detailed information on pedestran behaviour and trip distribution, grade-separated pedestrian circulation networks can be evaluated in terms of the connectivity of the network and the ease of pedestrian circulation, as defined below. Connectivity of a network can be defined as the degree to which blocks are connected by a set of grade-separated links. Ease of pedestrian circulation depends on the directness of the alternative route network compared with the street-level shortest route, the availability of connections with the street level, and the ease of orientation (way-finding) in the network.

Measure of Connectivity

Connectivity Ratio (CR) The basic measure of connectivity of a network is the ratio between the number of links and the total possible links (CR). A link between blocks is possible in the PLUS 15 system if suitable buildings are available on both sides of the street separating the blocks. The connectivity ratio increases when links are added to the network. It can be calculated for individual subnetworks or for the entire system. When all the possible links are available, CR is equal to 1. However, the ratio does not take into account the location of a link. Thus, if a new link is added to the system, CR will be increased by the same amount irrespective of the location of the link. Further, CR does not reflect the attraction between O-D pairs and the spatial separation between them.

Weighted Connectivity Index (WCI) Total pedestrian flow between two blocks will essentially depend on the type and extent of land use in the two blocks and the separation between them. Given a measure to represent the intrinsic attractiveness between two land use types m and n (k_{mn}), one possible weighted connectivity index (WCI)—that is, a measure of how well the alternative network connects land uses between which there is likely to be travel—can be defined as follows:

$$WCI = \sum_{\substack{\text{for all} \\ i,j \\ i \neq j}} \left[\frac{\sum_{\substack{\text{for all} \\ m,n}} K_{mn} A_{mi} A_{nj}}{D_{ij}^2} \right]$$

where

K_{mn} = factor that represents the intrinsic attractiveness between land-use types m and n,
i,j = block pairs that are connected by the alternative network,
A_{mi} = floor area of land use type m at origin i,
A_{nj} = floor area of land use type n at destination j, and
D_{ij} = distance between origin i and destination j via the alternative network.

The WCI is a formulation of the gravity type. Connections that provide a route between land use types that are highly attracted to each other (e.g., shopping and parking) will increase WCI relatively more, as will higher amounts of land use. Routes between blocks that are far apart will increase WCI by relatively smaller amounts. The use of the function D_{ij}^2 is based on certain gravity-type models (*5*). The exponent 2 or the function itself can be changed (e.g., to an exponential form) if network-specific data are available.

The factor K_{mn} is defined here as the probability that a trip originating in land use type m will be destined for land use type n. Thus the product $K_{mn}A_{mi}A_{nj}$ is representative of the potential for trips of the m-n type from i to j. The summation over all m,n gives the potential for trips of all types from i to j. The division by D_{ij}^2 reflects the resistance caused by distance to trips between i and j on the alternative network. The ratio between the square brackets is a measure of the connectivity between an i,j pair weighted by the potential for trips and the resistance to trip making. The summation over all i,j provides a measure of weighted connectivity for the alternative network.

WCI can be calculated for the entire grade-separated circulation system or for a particular subnetwork. Higher values of the index indicate a higher connectivity. However, WCI can increase with the number of blocks in a particular subnetwork. Therefore, if different subnetworks are being compared, the number of blocks and the number of bridges (or tunnels) should also be taken into account along with the WCI value.

Ease of Circulation

The network efficiency will also depend on the relative ease of pedestrian circulation within the alternative network. Pedestrians usually like to take the shortest route between their origin and destination (*4*), and this is usually available at the ground level. If the grade-separated network requires additional walking and additional level changes, that will lead to lower network usage. The following two indexes can be used to evaluate the ease of pedestrian circulation.

Subnetwork Circuitry Coefficient (SNCC) The circuitry coefficient for a group of blocks that are connected by an alternative network (subnetwork) can be defined as the average of the ratio between the minimum street-level distance and the minimum distance via the alternative network for each pair of blocks:

$$SNCC = \frac{1}{n} \left[\sum_{\substack{\text{for all} \\ i,j \\ i \neq j}} \frac{SD_{ij}}{GD_{ij}} \right]$$

where

n = total number of O-D block pairs that belongs to a particular subnetwork:
i,j = origin block and destination block, respectively;

SD_{ij} = minimum distance between O-D pair i,j at street level; and

GD_{ij} = minimum distance between O-D pair i,j along grade-separated system.

For example, in the idealized six-block system in Figure 2, the use of the alternative network for travel from O to D will result in an additional two links of travel; the SNCC for that O-D pair is 3/5 or 0.6.

When all possible links between the blocks that belong to a subnetwork are available, the value of SNCC is 1. If additional walking is needed to use the grade-separated network, SNCC is less than 1.

System Circuitry Coefficient (SCC) In considering a group of blocks that may or may not be fully connected by an alternative network, the minimum distance traveled via the grade-separated network can be replaced by the minimum weighted distance traveled using the grade-separated network and the at-grade network. If different weights are introduced to represent walking at the street level and the grade-separated level, the minimum weighted distance between O-D pairs for the combined system can be calculated. Then SCC for individual subnetworks or for the entire system is defined as follows:

$$SCC = \frac{1}{n}\left[\sum_{\substack{\text{for all} \\ i,j \\ i \neq j}} \frac{SD_{ij}}{CD_{ij}}\right]$$

where n is the total number of O-D pairs that belongs to the subnetwork or the system, as the case may be, and CD_{ij} is the minimum weighted distance between the O-D pair i,j via a route combining ground level and grade-separated links, defined as

$$CD_{ij} = GD^c_{ij} + \delta_1 SD^c_{ij} + \delta_2 LC_{ij}$$

where SD^c_{ij} and GD^c_{ij} are the distances at the street and grade-separated levels for the combined route LC_{ij} is the additional number of level changes that are required because of the combined route. The coefficient δ_1 (≥ 1) is a penalty factor that represents the relative unattractiveness of the street travel (e.g., extra travel time because of pedestrian signals), and δ_2 is a penalty factor representing the grade-level distance equivalent to one level change.

Ignoring the $\delta_2 LC_{ij}$ term, it may be seen that the system SCC varies from $1/\delta_1$ to 1 for a 0 percent to a 100 percent linked system, respectively. Therefore, the closer the system SCC is to 1, the more likely the pedestrians will use the grade-separated network. If the $\delta_2 LC_{ij}$ term is taken into account, the system SCC values will be reduced and can never be 1.

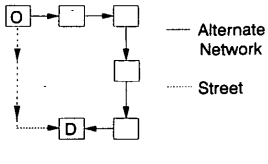

FIGURE 2 Idealized six-block area.

Further research is required to determine behaviorally validated values for δ_1 and δ_2.

COMPUTER PROGRAM GSPCS

The computer program GSPCS was developed to calculate CR, WCI, SNCC, and SCC for a given grade-separated pedestrian circulation system. The program is written in PASCAL and operates on IBM-compatible microcomputers. It is capable of handling any network (system) with maximum of 120 nodes and 30 subnetworks. The maximum number of links from a particular node is limited to four. At a particular node, up to five different land use types can be taken into account. However, most of these limitations can be changed with minor modifications to the GSPCS program.

Input for Program

The user can interactively enter the information that is required. The program first prompts for an input file name. If the input file entered already exists, the program will retrieve the input information. Otherwise it will prompt the user to advise whether to create a file under the given name. Then the user can update the input file or calculate the indexes if the input file already exists.

The input requirement for this program can be divided into two main categories: system related and user related. System-related information is entered on a block-by-block basis. The user should provide the floor areas belonging to different land use types, neighbors, and bridges for each block in the system. The user can add, edit, or delete individual blocks, neighbors, or bridges when updating the input file.

The user-related information is entered globally as factors K_{mn} to represent the attractiveness between different land use types and the disutility factor δ_1 to represent the disutility of street-level walking. The program as it is currently configured does not include the level change term $\delta_2 LC_{ij}$.

Calculations

When all the information has been entered, the user can request the program to calculate the different indexes that are used to evaluate the system performance. The program first calculates the minimum street level, grade-separated level, and combined (weighted) distances between each of the block pairs. A modified version of the well-known Dijkstra algorithm is used to determine the shortest path between all pairs of blocks (*6*) under the above three scenarios. Then the program identifies the nodes (blocks) belonging to different subnetworks. Finally, CR, WCI, SNCC, and SCC for each subnetwork and CR, WCI, and SCC for the entire system are calculated.

Output of Program

GSPCS gives an output on the screen after each calculation indicating the number of blocks, number of bridges, and CR, WCI, SNCC, and SCC for each subnetwork and for the entire system, as shown in Table 1.

TABLE 1 GSPCS Program Output

Subnetwork	No. of Blocks	No. of Bridges	CR	WCI	SNCC	SCC
1	14	14	0.875	55.090	0.876	0.899
2	20	19	0.731	378.382	0.766	0.856
3	7	6	0.750	87.567	0.870	0.909
4	8	8	1.000	228.189	0.975	0.975
Total	49	47	0.331	749.228		0.697

A user's manual for the program GSPCS (*7*) is available.

CASE STUDY 1

Calgary's PLUS 15 System

The Calgary PLUS 15 system is reputed to be the largest grade-separated pedestrian circulation system in the world. This system enables pedestrian circulation within the downtown area in walkways and on bridges that are approximately 15 ft above the street level. The PLUS 15 system currently consists of 50 bridges.

Application

System-Related Information

Study Area An area consisting of 79 blocks in downtown Calgary, as shown in Figure 3, is considered the study area. The PLUS 15 system had 47 bridges in 1989 distributed among four different subnetworks in the north, south, east, and west cores of downtown Calgary. The notations given in Figure 4 were used to identify individual blocks.

Floor Area Floor area measured in square meters was used to represent the various land uses on each block (*7*, Appendix B). There were five different land use types: office, residential, hotel and restaurant, parking, and other.

Neighbors and Bridges The blocks to the north, south, east, and west of a particular block are considered neighbors. It is assumed that no bridge will be built diagonally across an intersection. The distance between two adjacent blocks is considered to be uniform and equal to one distance unit, and it is assumed that the average walking distance of a pedestrian within a block at the origins or destinations is equal to one-half the block length. If the actual distances between the centroids of the blocks are available, they can be used at the input stage and the uniform block length assumption abandoned.

User-Related Information

Disutility Factor A value of 2 was arbitrarily selected to represent the disutility factor δ_1 associated with walking at the street level relative to walking at the PLUS 15 level when considering combined routes. One can alter this disutility factor globally by adjusting the GSPCS program. The factor δ_2 was set to zero because of lack of easily available information regarding facilities available for level changes.

Attractiveness Between Different Land Use Types The factor representing the intrinsic attractiveness between land use types m and n (K_{mn}) is defined as the probability that a randomly selected pedestrian will originate in an area of land use type m and will travel to an area of land use type n. Results of a PLUS 15 user survey (*8*) were used to determine the factors (K-values) for various land use pairs. This information was entered into a data file in matrix form so that it could be edited before use of the GSPCS program. The percentage values given in Table 2 were used for the subsequent calculations.

System Evaluation

First, the PLUS 15 system in 1989 consisting of 47 bridges, as shown in the Figure 4, was considered for the analysis. Table 3 shows the number of blocks and bridges belonging to each of the subnetworks and the entire system and the four performance indicators, namely, the connectivity ratio (CR), the weighted connectivity index (based on attractiveness between different land use types) (WCI), subnetwork circuity coefficient (SNCC), and system circuitry coefficient (SCC).

Then the best location for an additional link in the north core subnetwork was investigated. Seven alternatives were considered for the comparison. Because the total number of bridges does not change with the alternative, the new system CR value is uniform at 0.736 (an increase of 0.005 from the existing system). Table 4 shows how the subnetwork and the system performance indicators change with the different alternatives.

Discussion of 1989 System

From Table 3 it can be seen that the south core subnetwork has the best performance properties with respect to connectivity and circulation despite the lower WCI value. However, if WCI per bridge is taken into account, the south core subnetwork will rank 1 with respect to that indicator, too.

The low WCI value for the east core subnetwork is due to the low total floor area in that region and comparatively longer distances betweeen O-D pairs. The pedestrian counts carried out by the city of Calgary also show low system usage in this subnetwork (*8*).

Referring to Table 4, it can be seen that Link CR26-CR27 or Link CR15-CR16 would be the best alternative since they rank

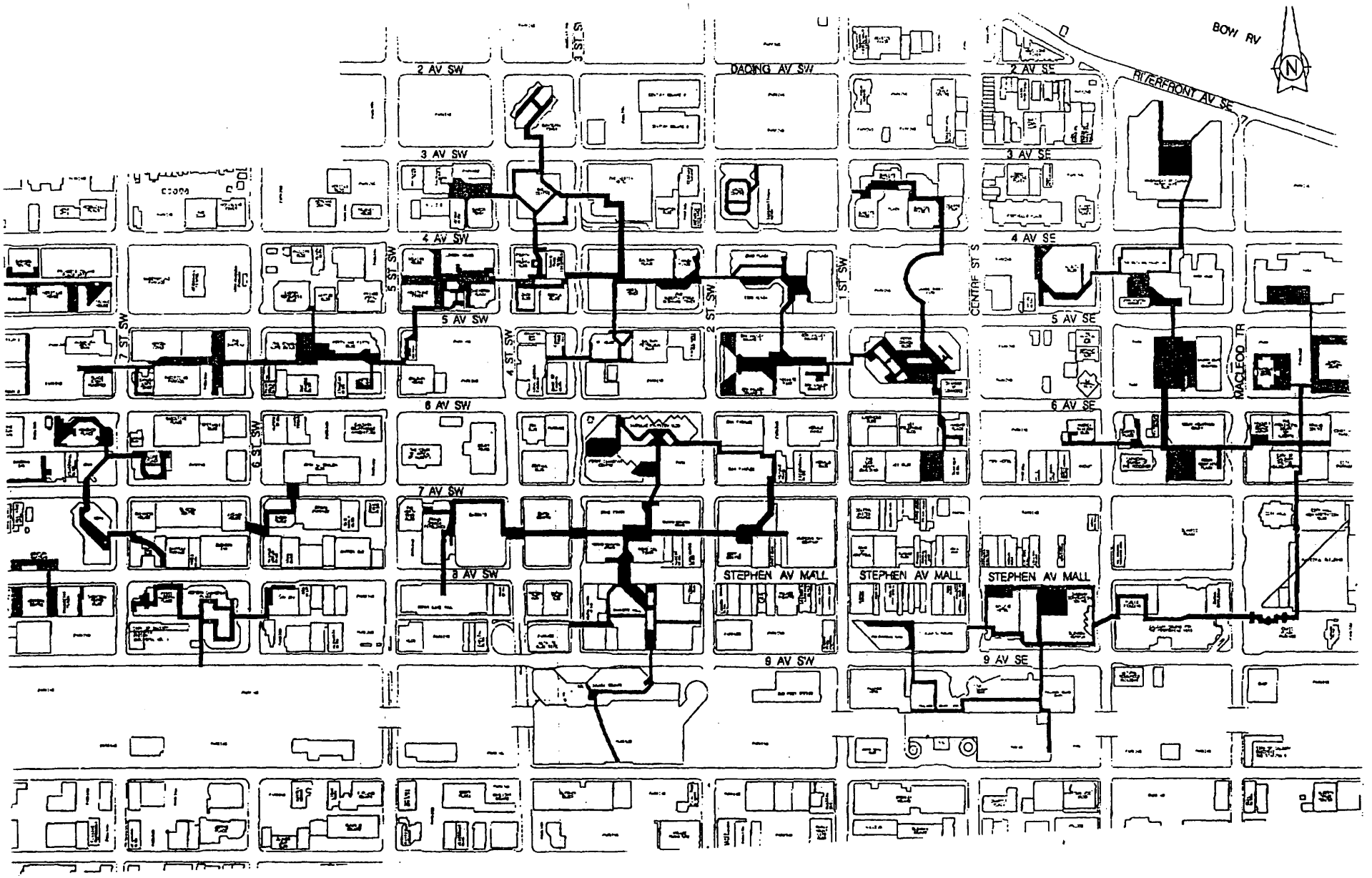

FIGURE 3 PLUS 15 pedestrian walkway system, Calgary, Alberta, Canada.

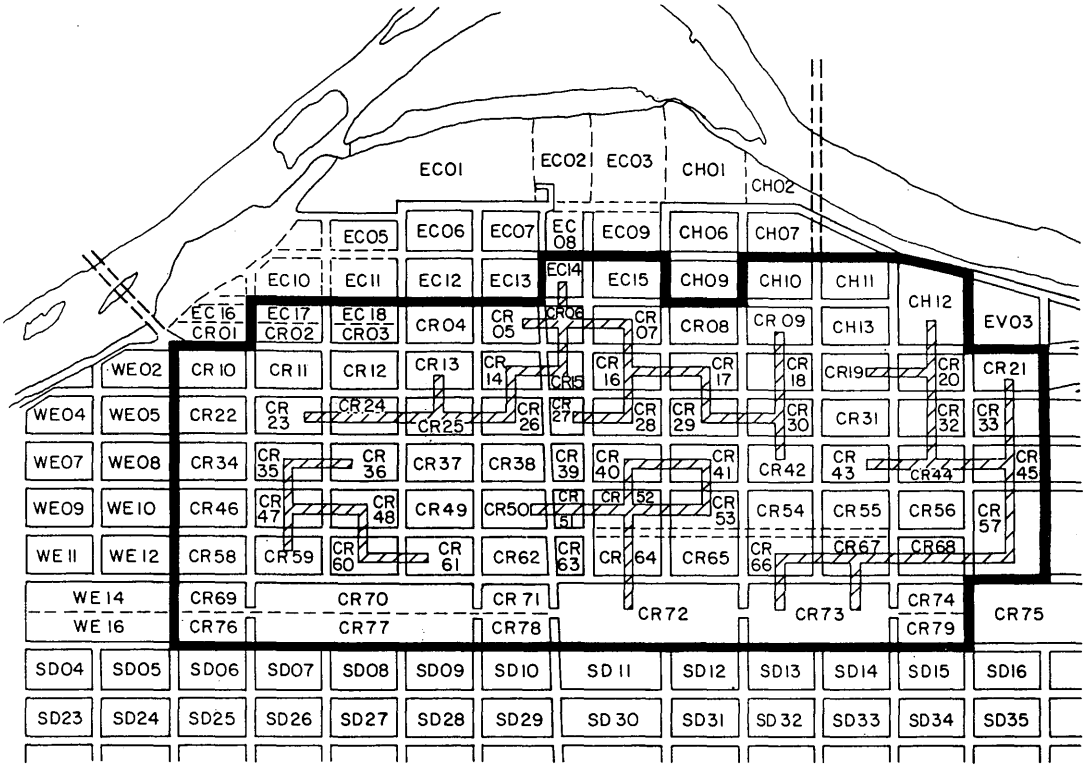

FIGURE 4 PLUS 15 network: 1989.

TABLE 2 K-Values

	Destination					
Origin	Office	Residential	Hotel	Parking	Other	Total
Office	10	1	14	4	16	45
Residential	1	0	0	1	1	3
Hotel	7	0	0	3	0	10
Parking	12	0	2	0	4	18
Other	10	1	2	3	8	24
Total	40	2	18	11	29	100

TABLE 3 Existing System

Subnetwork	No. of Blocks	No. of Bridges	CR	WCI	SNCC	SCC
East (1)	14	14	0.875	55	0.876	0.899
North (2)	20	19	0.731	378	0.766	0.856
West (3)	7	6	0.750	87	0.870	0.909
South (4)	8	8	1.000	228	0.975	0.975
Total	49	47	0.331	748		0.697

TABLE 4 North Core Subnetwork

Link	Subnetwork WCI	SNCC	SCC Subnetwork	SCC System
CR13-CR14	391	0.785	0.868	0.697
CR05-CR15	389	0.778	0.864	0.696
CR15-CR16	404	0.836	0.890	0.702
CR15-CR27	384	0.796	0.867	0.697
CR26-CR27	391	0.838	0.893	0.707
CR28-CR29	395	0.788	0.883	0.703
CR17-CR18	388	0.805	0.879	0.702

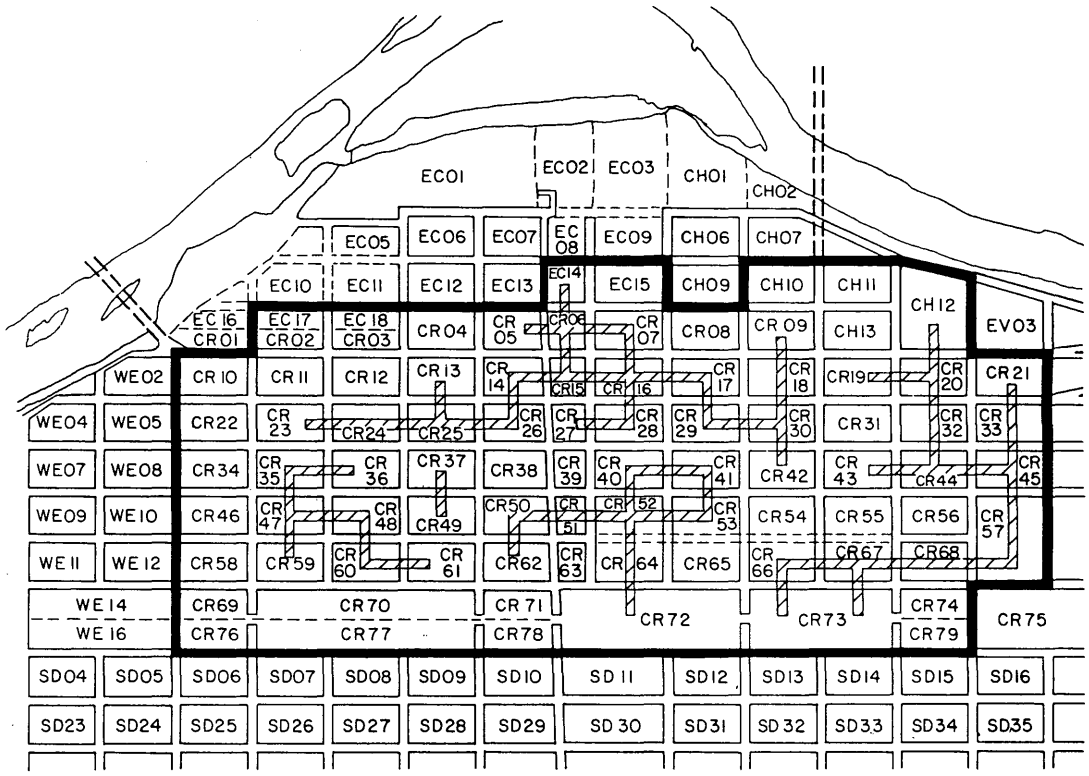

FIGURE 5 PLUS 15 network: 1993.

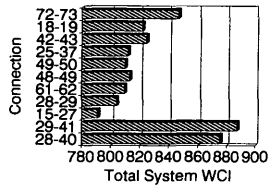

FIGURE 6 Different placements of additional link and effect on system WCI.

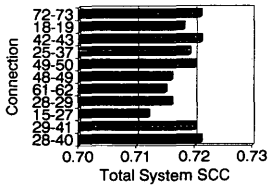

FIGURE 7 Different placements of additional link and effect on system SCC.

first or second according to the WCI and SCC criteria. Both these links are situated around the middle of the north core subnetwork and fill the gap in the east-west direction in which the subnetwork has developed.

CASE STUDY 2: ADDITIONAL LINK FOR CALGARY PLUS 15 SYSTEM

In 1993, Link CR15-CR16 and two others were in place, and there were 50 bridges distributed among four different subnetworks in the north, south, east, and west cores of downtown Calgary. The new PLUS 15 schematic is shown in Figure 5. The total system WCI is 786, and the SCC is 0.711.

To investigate the best location for an additional link for the entire PLUS 15 system, 14 alternative locations are considered for comparison. From Figures 6 and 7, it may be seen that Links CR29-CR41 and CR28-CR40 are the best alternatives. Both of these links will combine the north and south subnetworks into one large subnetwork. Link CR29-CR41 has a slightly higher WCI because it directly connects larger office areas. Link CR28-CR40 has a small edge in SCC because it is closer to the middle of the north and south subnetworks.

DISCUSSION OF RESULTS

Two indexes, WCI and the network circuity coefficient (NCC), were developed as indicators of the efficiency of alternative pe-

destrian networks. WCI is an indicator of the potential for travel between blocks via the alternative network given measures of land use in the blocks and separation between the blocks. NCC is an indicator of the portion of trips that may use the alternative network for the entire trip or a segment of a trip given the circuity of routes in that network relative to the street level.

It is worthwhile to note that the city of Calgary has added Link CR15-CR16 (Table 4), which was selected in the 1989 study on the basis of the indexes as a suitable addition to the PLUS 15 network.

The WCI could be improved by choosing a better function to describe the resistance to travel between two blocks. For example, an exponential travel-time function could be investigated, though a significant additional data collection effort would be needed to collect travel-time data.

A basic problem associated with having two indicators is the dilemma that occurs when they give different rankings of options. The possibility of combining the two indicators is worth consideration. An example is an indicator obtained by summing the product of WCI for a block pair and a function of NCC for that pair over all block pairs as an indicator of the propensity for travel in an alternative network.

The indexes proposed here can be used to evaluate the addition of k-links (instead of one link) to an alternative network. In such a case, the indicators are calculated for all possible partitions of k-links out of a feasible set of K-links, $K!/k!\ (K - k)!$.

A third index that has been suggested to the authors as worth considering is one that indicates the propensity for pedestrian-vehicle conflicts if the alternative network were not available.

In general, the indicators provide a low-cost microcomputer-based method for evaluating alternative pedestrian networks.

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