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 circuity. 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 use, particularly in cities with severe climates. Other concerns are personal safety, particularly in tunnels, and the difficulty of way-finding indoors.

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 type has 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.
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network connects land uses between which there is likely to be travel-can be defined as follows:

between two blocks will essentially depend on the type and extent of land use in the two blocks and the separation between them.

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:

\[
WCI = \sum_{i,j} \left[ \frac{K_{mn}A_{mi}A_{nj}}{D_{ij}^2} \right]
\]

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:

\[
SNCC = \frac{1}{n} \sum_{i,j} \left[ \frac{SD_{ij}}{GD_{ij,i}} \right]
\]

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:

\[
SCC = \frac{1}{n} \left[ \sum_{i,j} SD_{ij} \right]
\]

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

\[
CD_{ij} = GD_{ij} + \delta_1 SD_{ij} + \delta_2 LC_{ij}
\]

where \( SD_{ij} \) and \( GD_{ij} \) 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 \( \delta_1 \) (\( \geq 1 \)) is a penalty factor that represents the relative unattractiveness of the street travel (e.g., extra travel time because of pedestrian signals), and \( \delta_2 \) 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.

Further research is required to determine behaviorally validated values for \( \delta_1 \) and \( \delta_2 \).

**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 \( \delta_2 \) 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.
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 $\delta$, 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 $\delta$ 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 circuitry 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 between 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

<table>
<thead>
<tr>
<th>Subnetwork</th>
<th>No. of Blocks</th>
<th>No. of Bridges</th>
<th>CR</th>
<th>WCI</th>
<th>SNCC</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
<td>14</td>
<td>0.875</td>
<td>55.090</td>
<td>0.876</td>
<td>0.899</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>19</td>
<td>0.731</td>
<td>378.382</td>
<td>0.766</td>
<td>0.856</td>
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<tr>
<td>3</td>
<td>7</td>
<td>6</td>
<td>0.750</td>
<td>87.567</td>
<td>0.870</td>
<td>0.909</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>8</td>
<td>1.000</td>
<td>228.189</td>
<td>0.975</td>
<td>0.975</td>
</tr>
<tr>
<td>Total</td>
<td>49</td>
<td>47</td>
<td>0.331</td>
<td>749.228</td>
<td>0.697</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 3  PLUS 15 pedestrian walkway system, Calgary, Alberta, Canada.
**FIGURE 4** PLUS 15 network: 1989.

### TABLE 2 K-Values

<table>
<thead>
<tr>
<th>Destination</th>
<th>Office</th>
<th>Residential</th>
<th>Hotel</th>
<th>Parking</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office</td>
<td>10</td>
<td>1</td>
<td>14</td>
<td>4</td>
<td>16</td>
<td>45</td>
</tr>
<tr>
<td>Residential</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Hotel</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Parking</td>
<td>12</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>Other</td>
<td>10</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Total</td>
<td>40</td>
<td>2</td>
<td>18</td>
<td>11</td>
<td>29</td>
<td>100</td>
</tr>
</tbody>
</table>

### TABLE 3 Existing System

<table>
<thead>
<tr>
<th>Subnetwork</th>
<th>No. of Blocks</th>
<th>No. of Bridges</th>
<th>CR</th>
<th>WCI</th>
<th>SNCC</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>East (1)</td>
<td>14</td>
<td>14</td>
<td>0.875</td>
<td>55</td>
<td>0.876</td>
<td>0.899</td>
</tr>
<tr>
<td>North (2)</td>
<td>20</td>
<td>19</td>
<td>0.731</td>
<td>376</td>
<td>0.766</td>
<td>0.856</td>
</tr>
<tr>
<td>West (3)</td>
<td>7</td>
<td>6</td>
<td>0.750</td>
<td>87</td>
<td>0.870</td>
<td>0.909</td>
</tr>
<tr>
<td>South (4)</td>
<td>8</td>
<td>8</td>
<td>1.000</td>
<td>228</td>
<td>0.975</td>
<td>0.975</td>
</tr>
<tr>
<td>Total</td>
<td>49</td>
<td>47</td>
<td>0.331</td>
<td>748</td>
<td>0.697</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 4 North Core Subnetwork

<table>
<thead>
<tr>
<th>Link</th>
<th>Subnetwork WCI</th>
<th>SNCC</th>
<th>SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR13-CR14</td>
<td>391</td>
<td>0.785</td>
<td>0.868</td>
</tr>
<tr>
<td>CR05-CR15</td>
<td>389</td>
<td>0.778</td>
<td>0.864</td>
</tr>
<tr>
<td>CR15-CR16</td>
<td>404</td>
<td>0.836</td>
<td>0.890</td>
</tr>
<tr>
<td>CR15-CR27</td>
<td>384</td>
<td>0.796</td>
<td>0.867</td>
</tr>
<tr>
<td>CR26-CR27</td>
<td>391</td>
<td>0.838</td>
<td>0.893</td>
</tr>
<tr>
<td>CR28-CR29</td>
<td>395</td>
<td>0.788</td>
<td>0.883</td>
</tr>
<tr>
<td>CR17-CR18</td>
<td>388</td>
<td>0.805</td>
<td>0.879</td>
</tr>
</tbody>
</table>
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 subnetwork 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 circuitry coefficient (NCC), were developed as indicators of the efficiency of alternative pe-
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.

REFERENCES


Publication of this paper sponsored by Committee on Pedestrians.