PEDESTRIAN TRAFFIC CALCULATIONS AMONG LINEARLY CONNECTED VERTICAL NODES

Gregory T. Kavounas

Lerch, Bates & Associates
Vertical Transportation Consultants
8089 South Lincoln Boulevard, Suite 300
Littleton, Colorado 80122
USA

Blakely Sokoloff Taylor & Zafman
Intellectual Property Law Firm
12400 Wilshire Boulevard, Suite 700
Los Angeles, California 90025-1026
USA

ABSTRACT

Typically escalators and stairs handle pedestrian traffic among vertical nodes that are near to each other, such as department stores, shopping malls, underground railroad, etc. Although the traffic handling parameters of stairs and escalators are individually understood, it is often not appreciated how they work together. A method of calculation is presented that puts together these concepts. Additionally, a software that implements this method of calculation is distributed at a small cost. The designer can enter various combinations of escalators and stair width connecting pedestrian traffic nodes to determine the resulting level of service and arrive at a recommendation.

1. INTRODUCTION

1.1 Background

The behaviour of people in connection with elevator systems is currently being analyzed. Algorithms are known that calculate how many, how big, and how fast elevators should be present to serve a building. The algorithms usually constitute applying the expected passenger demand to the handling capacitites of proposed elevator systems and arrangements, and then computing an anticipated level of service, which determines a recommendation. While elevator systems are being thoroughly studied, however, it is often not appreciated how they will interface with other transportation facilities present in the big picture of pedestrian circulation.

1.2 Definitions

For purposes of this paper, people constituting the demand are called pedestrians, irrespectively of whether they walk, wait in a queue, or are passengers (by being mechanically transported). The mathematical unit of pedestrians is 1P, and fractions thereof are to be tastefully avoided.

Pedestrian transportation facilities are primarily vertical or horizontal. Examples of vertical transportation facilities are elevators, escalators and stairs. Examples of horizontal transportation facilities are corridors and moving walks. All can be simply called facilities. Each facility has an associated pedestrian handling capacity (HC), whose method of calculation and can be found in the literature.

System nodes are defined as places in a transportation system where pedestrians enter and exit the transportation system. (For an elevator system, nodes are the elevator stops.) Consequently, the transportation facilities can be thought of as connecting nodes. The transportation facilities are in the internodal spaces. The internodal spaces can also be thought of as internode (transportation) venues.

Pedestrian demand is expressed in terms of the system nodes. Each pedestrian appears at one node (called the originating node), and wants to go to another node (called the destination node). An insightful formulation was given recently by R. Peters in (1), where pedestrian demand was expressed as a two dimensional matrix. The same formulation is followed here: For a transportation system with n nodes, the pedestrian demand is descibed by an n x n matrix. The column of each entry describes the originating node; the row of each entry describes the destination node. And the value of the number of each entry describes how many people per time unit have those originating and destination nodes. The demand, however, is applied to the internode transportation venues that host the transportation facilities.

1.3 Scope of the Presented Algorithm

The algorithm presented in this paper is applicable to specific situations, and operates thanks to some simplifications and assumptions. Many more extensions of the concepts presented here can be envisioned and implemented.

A first simplification made in this paper is that all nodes of the vertical transportation system are connected linearly. That is, there are two terminal nodes that are each adjacent to only one other node. All other non-terminal nodes are each adjacent to two other nodes.

A second simplification made in this paper is that all nodes are vertically disposed with respect to each other. Therefore, this paper focuses only on vertical pedestrian transportation demand and vertical pedestrian transportation facilities. Accordingly, nodes are the adjacent vertical levels, and the facilities of interest are escalators and stairs. Pedestrians move from an originating level to a destination level that is only a few levels away.

A third simplification is that the transportation system has no facilities that bypass nodes. That is, transportation can only be accomplished between two adjacent nodes at a time. Therefore, each pedestrian must sequentially traverse all nodes intermediate to his originating and destination nodes. As a practical result, elevators are excluded from consideration because they afford users the option to bypass intermediate levels. The HC of one elevator is substantially smaller (5% - 25%) than that of one escalator, for a two stop situation. Therefore, the HC contributed by a two stop elevator will be neglected, with the understanding that solutions are satisfatory to a first order of magnitude only.

Examples of situations this algorithm applies to are: simple two-level interchanges connected by escalators and stairs, situations where escalators transport pedestrians to and from main elevator landings, shopping malls, underground train stations, etc. The usefulness of the algorithm of this paper is for specific situations where large numbers of people have to be transported in short times.

The algorithm of this paper first assumes that there is a building (or generalized structure) with vertical levels that are connected mainly by escalators and stairs. Then, a pedestrian demand matrix is input. The algorithm then suggests how to assign the pedestrian demand between the escalators and stairs. The known parameters of HC and level of service for facilities are then used to compute resulting levels of service for each direction (up and down) of the internode venue of every node pair of the whole vertical transportation system. The designer applies his common sense to the resulting levels of service to determine a recommendation for the proposed system.

It is assumed that pedestrian traffic is uniform, and pedestrian characteristics are relatively homogeneous. Additionally, it is assumed that the total available stair width will be divided uniformly between pedestrians going up and down, which will be the case if both flows are uniform and every pedestrian keeps to the one side or the other (no crossing). (It is not certain that people will always keep to the one side.) Otherwise, pedestrian speeds may decrease, deteriorating the level of service to a value worse than predicted.

The algorithm and software presented in this paper are directed to a specific class of problems. Due to space constraints, only mathematical aspects of these problems will be considered. The designer should not forget his common sense, design principles, or the limitations described above.

1.4 Software

A software has been written that implements the calculation method of this paper. Specifically, it accepts a building and a situation as inputs, and calculates projected levels of service for pedestrians.

1.5 Outline of Paper

In this paper, the known elements about escalators and stairs that are of interest to this paper will be first presented. Subsequently, a model will be presented that describes human behaviour when faced with a choice of the assumed building and system. The behaviour will dictate the algorithm that is presented next. A simple example is subsequently solved. It is simple in that it only has two levels. Then the software functions are described in some detail, and a conclusion is given.

2. ESCALATORS

Escalators are unidirectional (when operating) vertical transportation facilities that connect two nodes. The waiting time to board an escalator is zero, unless there is a queue. A situation where the main direction of pedestrians reverses during some repeating time period (e.g. a day) may call for the escalators to be of reversible direction.

2.1 Dimensions of Escalators

The main escalator dimension of interest is the step width. The most usual widths are 600, 800, and 1000 mm. (Corresponding American escalators have steps that are 24", 32", and 40" wide.) However, these dimensions are not always followed, and escalators of other dimensions can be found.

To complicate matters, sometimes escalators are specified by the width at the hip, which is typically 200 mm wider than the step width for escalators with steel balustrades, making the width dimensions 800, 1000, and 1200 mm respectively. (Corresponding American escalators are 32", 40", and 48" wide at the hip.) Compounding the confusion are escalators with glass balustrades that are vertical, where the hip width almost equals the step width.

To be consistent, in this paper the escalator width is specified as width at the step. The accompanying software also uses width at the step, but further indicates the hip width the escalator would have, if it had steel balustrades.

2.2 Handling Capacity of Escalators

The nominal Handling Capacity of an escalator bank is given by Equation (1):

$$HC = E \,.\, V \,.\, k \,.\, a \,.\, 60 / D \qquad \text{P/min} \quad (1)$$

where:
E = number of escalators operating in the appropriate direction
V = speed of escalator, in m/sec
k = theoretical maximum pedestrian density per step
a = ratio of nominal to theoretical maximum pedestrian density per step
D = depth of step (usually 400 mm - American: 16")
[60 converts from /sec to /min]

The values used for k in this paper are those given in the Elevator Micropedia (3), instead of those implied in Fruin (2). They are 1 for step widths of 600 mm (Fruin: 1.2), 1.5 for step widths of 800 mm (Fruin: 1.6), and 2 for step widths of 1000 mm (Fruin: same).

Equation (1) gives the nominal HC for escalators, by multiplying the theoretical maximum HC by the factor a. The theoretical HC maxima given by escalator manufacturers correspond to highly efficient loading conditions during tests. In actual situations, when there is a queue, pedestrians who are just ready to board on a step sometimes delay boarding slightly, to ensure for themselves a little more space. This pedestrian behaviour prevents escalators from attaining a HC that is much different than the nominal. The ratio a of observed nominal to theoretical maximum pedestrian density per step varies from 0.5 to 0.6, according to Fruin (2). A convenient value of 0.5 will be used.

Further, elevator systems define their HC in terms of P/5min, not P/min. Therefore, escalator HC that are computed for 5 minutes will interface better with elevator systems. For purposes of this algorithm escalator HC will be calculated on a per 5 min basis. Equation (1) then, simplifies to Equation (2):

$$HC = E \,.\, V \,.\, k \,.\, 375 \quad \text{P/5min} \qquad (2)$$

An alternate formulation is Equation (3):

$$HC = E \cdot V \cdot (W-200) \cdot 15/16 \qquad P/5min \qquad (3)$$

where:
E = number of escalators operating in the appropriate direction
V = speed of escalator, in m/sec
W = step width in mm.

It should be noted that the Handling Capacity does not depend on the angle of inclination or on the vertical rise.

2.3 Level of Service of Escalators

No level of service has been defined for escalators based on density of occupancy, as it has been for stairs. Although escalators can be characterized as crowded or not very crowded, the truth remains that they will not be much more crowded than what is required to attain nominal HC. This amount of "crowdedness" can be called "nominal capacity".

3. STAIRS

Stairs are bidirectional facilities.

3.1 Dimensions of Stairs

The main dimension of interest of stairs is the available stair width, because the pedestrian handling capacity of stairs varies linearly with width. Mathematically, then, it is the total stairway width that matters, which can actually be comprised of many adjacent stairways.

Other dimensions of stairs are step height and step depth, which affect the pedestrian speed and therefore the stair handling capacity slightly. In actuality, such dimensions vary little and will not be dealt with any more in this paper.

3.2 Handling Capacity of Stairs

The Handling Capacity of stairs can be found in the Micropedia (3), and is produced as Equation (4):

$$HC = V \cdot D \cdot W \cdot 60 \cdot 0.83 \quad P/min \quad (4)$$

where:
V = pedestrian speed, in m/sec
D = pedestrian density in P/m^2
W = stairway width, in m
[60 converts from /sec to /min]

Pedestrian speeds range from 0.5 to 0.9 m/sec, depending on the type of pedestrians. A density of 0.6 P/m^2 corresponds to threshold free flow, and 2.0 P/m^2 corresponds to full (flow) design. These values approximately match (the inverse: m^2/P of) those in the second column of Table 1 below. (Slight discrepancies are owing to rounding, etc.) This equation is used when the width is being calculated for a known volume and type of pedestrians, and a desired level of service.

However, Equation (4) is not needed for this algorithm. More detailed work by Fruin (2) gives what is needed for this algorithm, namely the levels of service that result when pedestrian demand is applied to stairways of fixed width.

3.3 Level of Service of Stairs

The number of pedestrians per minute applied to the stairs determines the resulting level of service for the stairs. The values and descriptions in the following table are in Fruin (2), calculated at constant pedestrian speeds.

TABLE 1: Stairway Levels of Service

Pedestrians per Minute per Metre Width of Stairway	Inverse Density m^2/P (1/D)	Resulting Level of Service	Description
00 to 16	>1.9	A	Threshold FREE FLOW, convenient passing
16 to 23	1.4 to 1.9	B	Passing and speed restrictions
23 to 33	0.9 to 1.4	C	Crowded but fluid movement, passing and reverse restricted
33 to 43	0.7 to 0.9	D	Severely restricted passing and reverse flow
43 to 56	0.4 to 0.7	E	No passing, intermittent stoppages (FULL DESIGN)
56 to 65(?)	<0.4	F	Flow sporadic with frequent stoppages
>65(?)		X	Impassable (?)

3.4 Acceptable Standards for Stairs

The author does not know of any standards that have been promulgated, or are being widely followed. Considering the descriptions given above, however, the recommendation should probably be to always design for free flow, i.e. level of service A. Worse levels of service (but not "impassable") may be tolerated for the rare contingencies of power failure of escalators. Additionally, the stair width should be at least 1m for each direction.

4. MODEL OF PEDESTRIAN BEHAVIOUR

Pedestrians are assumed to prefer escalators to stairs. Therefore, the mathematical model is that the pedestrians will first try to use the available escalators that are moving in the desired direction. The pedestrians will fill the escalators up to the nominal capacity. If the escalators are full, the remaining pedestrians will take the stairs.

5. THE SUGGESTED ALGORITHM

5.1 Identify the Nodes.

Sometimes, nodes are not exactly building levels, but can be half-levels. The determination is made by what facilities connect which landings. At this time a verification should be made that the nodes are connected linearly to each other, and that no escalator or stairway bypasses any nodes. This is not to say that such bypassing facilities are a poor design choice; it only means that the model presented here and the accompanying software will not be applicable, if there is such a bypassing.

5.2 Write the Demand Matrix.

The demand matrix represents how many pedestrians are going from one level to any other level per five minutes. The flow will be assumed continuous.

5.3 Find the Loads on the Internode Venues.

Every nonzero entry of the demand matrix must be applied to the proper internode venues. For example, if 200 pedestrians are going from the first to the third levels every 5 minutes, there will result 200 pedestrians going from the first to the second levels, and 200 pedestrians going from the second to the third levels. Afterwards, all loads assigned to each direction of each node pair must be summed together. If done manually, this is a tedious task, that the software, however, performs automatically.

5.4 For each Node Pair, and for each Direction.

5.4.1 The escalators take all pedestrians up to the nominal capacity.

First, the nominal escalator Handling Capacities can be calculated, in each direction, using Equation (2). Either all pedestrians for this internode venue will fit on the escalators, or there will be remaining pedestrians who will have to take stairs. If the escalators can handle all the pedestrians, the level of service of the system is "!".

5.4.2 The remaining pedestrians use the stairs.

The remaining pedestrians will take the stairs in both directions. Since stairs are bidirectional, all remaining pedestrians will try to use them. A conceptual simplification is to assign an "UP stair width" and a "DOWN stair width", according to the following equations:

$$\text{UP stair width} = (\text{total width of stairs}) \times \frac{\text{P walking up}}{\text{P walking up and down}}$$

$$\text{DOWN stair width} = (\text{total width of stairs}) \times \frac{\text{P walking down}}{\text{P walking up and down}}$$

This formulation suggests (but does not require) that, for calculation of stair handling capacity purposes, the conceptual simplification is that everybody keeps to the one side or the other, and therefore pedestrians walking in opposite directions do not run into each other. This formulation, however, is subject to the limitations stated above.

5.4.3 Compute levels of service for each direction.

The next step is to calculate the levels of service for each direction, for each node pair. If not all pedestrians can be accommodated by the escalators, the resulting level of service is determined by the pedestrians taking the stairs. This is done by first computing:

No. of P/min /m width of stair = HC (P/min) / total stairway width

Subsequently, the computed No. of P/min /m width of stair is matched with the first column of Table 1 above. In the third column, the corresponding level of service can be looked up. This process also exemplifies the approximateness of this field of inquiry.

A theorem is that, if there are remaining pedestrians taking the stairs in both directions, they will all experience the same level of service.

5.5 Designer makes Judgement.

The designer then makes a judgement from the results. He should not overlook sound design principles or other factors that define a situation. Further, the designer should always consider the contingency of power failure, with the escalators becoming inoperative.

5.6 What the Algorithm does Not do

The algorithm does not calculate pedestrian times to destination. For example, in an application where a theater, after a performance, is emptying out pedestrians in many vertical levels, the software wil not calculate how long it will take to empty out. However, the software can still be used to obtain a schematic representation of the transportation facilities. Further, if an attempt is made to calculate the HC anyway, the numbers appearing on the screen can be used to solve the times to destination problem.

Since continuous flow and averages are assumed, the algorithm does not account for time that pedestrians take to initially fill up escalators and stairs. Further, since the times to destination are not computed, the relative heights of the levels do not matter.

Lastly, the algorithm does not make a judgement as to what is an acceptable level of service and what is not.

6. EXAMPLE

Assume a two level situation, lower level A and upper level B. The pedestrians are uniformly walking commuters. At the heaviest demand time, there will be 400 P/5min going up from A to B, and 150 P/5min going down from B to A. The proposed facilities are 2 reversible escalators at 0.5 m/sec that are 600mm wide at the step, and a total stairway that is 3m wide. Will these facilities be adequate?

Approach: Examine the resulting level of service, under various scenaria. Try with one escalator going up and the other escalator going down (Scenario 1), both escalators going up (Scenario 2), and both escalators out of service (Scenario 3).

6.1 Common to all Scenaria

There are two nodes, A and B, defining two directions in the internode space of A and B, namely up A-->B and down B-->A. Must solve for each node pair.

The demand matrix will be as is shown in this table: ---------------->

DEMAND MATRIX (5min)

	FROM A:	FROM B:
TO B:	400	*
TO A:	*	150

6.2 Scenario 1

Solve for one escalator going up and the other escalator going down.

a) Direction up for the node pair A-->B.

Escalators available: One
Escalator HC (from Eq.2) = E . V . k . 375 P/5min = 188 P/5min

Pedestrian demand = 400 P/5min, therefore, 400-188=212 P/5min will be taking the stairs.
Convert to per minute: 212 P/5min = 43 P/min will be taking the stairs.

b) Direction down for the node pair B-->A.

Escalators available: One
Escalator HC (from Eq.2) = E . V . k . 375 P/5min = 188 P/5min

Pedestrian demand = 150 P/5min < 188 P/5min, therefore none will be taking the stairs.
Level of service for down is !

c) Demand placed on stairs:

Going up + going down = 43 + 0 = 43 P/min

Pedestrians /minute /m-width of stairway = 43 P/min /3m-width = 14.3 P/m m-w

Look up Table 1: Level of service for up is A.

6.3 Scenario 2
Solve for both escalators going up.

a) Direction up for the node pair A-->B.

Escalators available: Two
Escalator HC (from Eq.2) = E . V . k . 375 P/5min = 375 P/5min

Pedestrian demand = 400 P/5min, therefore, 400-375=25 P/5min will be taking the stairs.
Convert to per minute: 25 P/5min = 5 P/min will be taking the stairs.

b) Direction down for the node pair B-->A.

Escalators available: None

Pedestrian demand = 150 P/5min therefore will be taking the stairs.
Convert to per minute: 150 P/5min = 30 P/min will be taking the stairs.

c) Demand placed on stairs:

Going up + going down = 5 + 30 = 35 P/min

Pedestrians /minute /m-width of stairway = 35 P/min /3m-width = 11.6 P/m m-w

Look up Table 1: Level of service for up and down is A.

6.4 Scenario 3
Solve for both escalators out of service (emergency situation)

a) Direction up for the node pair A-->B.

Escalators available: None

Pedestrian demand = 400 P/5min, therefore will be taking the stairs.
Convert to per minute: 400 P/5min = 80 P/min will be taking the stairs.

b) Direction down for the node pair B-->A.

Escalators available: None

Pedestrian demand = 150 P/5min therefore will be taking the stairs.
Convert to per minute: 150 P/5min = 30 P/min will be taking the stairs.

c) Demand placed on stairs:

Going up + going down = 80 + 30 = 110 P/min

Pedestrians /minute /m-width of stairway = 110 P/min /3m-width = 36 P/m m-w

Look up Table 1: Level of service for up and down is D.

6.5 Evaluation
For either scenario, the resulting level of service corresponds to values close to the threshold of free flow, if both escalators are operating, and at least one is going up.

The two scenaria result in almost equivalent solutions. Scenario 1 results in a slightly heavier load on the stairs (14.3), but it is with unidirectional flow of pedestrian traffic.

Scenario 2 results in a slightly lighter load on the stairs (11.6), which, however, reflects bidirectional pedestrian traffic flow, which may not be as efficient as the numbers suggest.

Further, the system will produce poor level of service if both escalators are out of service, according to Scenario 3.

At this point, it is up to the designer to make a recommendation. The author here would personally recommend wider stairways and ideally a third escalator (thus having 2 going up and one going down), although other solutions could be just as acceptable.

7. THE CALCULATIONS SOFTWARE

7.1 Software Specifications

The software has been written in MS-DOS BASIC, and is compatible with IBM-PC or compatible computers. It is given in source code form to facilitate expansion or adaptation to special needs. Many comments are provided within the code. The software is named Traffic - Influenced Design of Escalators and Stairs (T.I.D.E.S.), and implements the algorithm described above, following the assumptions descibed above. TIDES is user friendly and menu driven. Packages are available for Metric and for American units.

7.2 Software Inputs

The inputs can be entered and edited from the master menu. Designing is in two frames of reference, that of the nodes, and that of the internode venues, in which there are facilities connecting adjacent nodes.

7.2.1 Static inputs

Static inputs are the fixed parameters, e.g. the building and its facilities. Specifically, the static inputs include the project name, the number of vertical levels, the names of the vertical levels, and the vertical transportation facilities that connect the levels.

All escalators connecting the same two nodes are assumed to be similar. For each internode venue, the designer can edit the total stair width, and parameters about escalators connecting the two nodes.

7.2.2 Dynamic inputs

Dynamic inputs include the population matrix and the direction of escalators. The population matrix is a collection of numbers of people per five minutes given in terms of originating node and destination node. In going from the originating node to the destination node, the pedestrians will be traversing intermediate (to them) nodes, but the process component of the software will deal with this problem. Additionally, the input program continuously sums how many total people originate from each node.

The direction of escalators can be edited. Another facility allows all escalators to be assumed temporarily disabled, without changing the inputted escalator information about.

7.3 Software Process

The process component of the software solves for the dynamic solution, by applying the demand (pedestrians) to the building facilities. In more detail, the process component of the software reads the population matrix, calculates the pedestrian traffic load for each internode venue, and then determines the adequacy of the vertical transportation facilities for each internode venue.

This determination is by first assigning to escalators their nominal pedestrian load, and then assigning the remaining pedestrians, if any, to the present stairs. The density of pedestrians on stairs determines the levels of service. Outputs are provided on the screen, so the designer can interactively adapt the static facilities (number or parameters of escalators, or available stair width), or the dynamic facilities (direction of operation of escalators) to design for optimum performance, in light of pedestrian demand.

7.4 Software Outputs

The software ouputs are designed to illustrate the problem solved. A printout can be obtained showing the static building with the equipment, to be used for cost assessment. Another printout shows the population matrix of pedestrian originating and destination nodes. Another printout shows the dynamic solution, with achieved levels of service.

7.5 Software Expansion Avenues

The software can be expanded to gradually incorporate situations left out by the assumptions and simplifications. Specifically, the serially connected nodes could also extend horizontally. Walkway widths would come in the picture to accommodate corridors. Ramps, and moving walks could be also added. Then Example 2.1 at page 2-4 of (4) could be also solved.

Another avenue will be to include times to destination, from any originating node to any destination node. Pedestrian speed would have to be included, along with the level to level heights. Also the distances between facilities would start to play a role. The computed time to destination would be the average; different facilities contribute different times to destination for different numbers of people.

A further avenue will be to allow for facilities that bypass nodes. A model of pedestrians choosing facilities will also be needed to augment the demand matrix.

Finally, TIDES can be converted to a true simulation program by allowing for non-uniform time profiles of pedestrian inputs. The demand matrix will have data files for entries.

Additionally, the software could be made to check the proposed equipment against sound guidelines, namely warning if a stairway is less that 1m wide, or 2m wide, if used in both up and down directions.

7.6 To obtain the Software

For information on how to order the software, please write or FAX (*USA 1-(818) 957 4524*) the author an informal request that includes your FAX number.

8.0 CONCLUSION

A model has been presented for pedestrian traffic where there is a large volume of pedestrians, a few vertical levels, and escalators and stairs predominate. Ways to calculate average levels of service are given.

REFERENCES

(1) Peters, R.: "The theory and practice of general analysis lift calculations", Elevator Technology 4, May 1992, International Association of Elevator Engineers.

(2) Pedestrian Planning and Design, by Dr. John J. Fruin, publ. by Elevator World Educational Services Division.

(3) Elevator Micropedia, edited by Dr. George. C. Barney, publ. by IAEE.

(4) CIBSE Guide D: "Transportation systems in buildings", May 1993, Chartered Institution of Building Services Engineers.

BIOGRAPHICAL INFORMATION

Gregory T. Kavounas received a Bachelors of Science degree in Electrical Engineering from California Institute of Technology (Caltech), and a Masters of Science degree and an Engineer's Degree in Electrical Engineering from University of Southern California. He has worked as a Project Manager for Lerch, Bates & Associates Inc., where he wrote design software for and published papers on the subject of elevatoring design. An International Rapporteur for Elevatori and an ELENETter, Mr. Kavounas is a Law Clerk at the Los Angeles Office of the international Intellectual Property Protection firm of Blakely Sokoloff Taylor & Zafman that specializes in Patents and Trademarks.