DEFORMABLE MESH MOVING BELT AS AN ACCELERATING-DECELERATING DEVICE

Robert U. Ayres, International Research and Technology Corporation, Washington, D.C.; and
Robert Malone, Pratt Institute, Brooklyn

•ONE OF the most vexing sociotechnological problems of today is that of public transportation, especially in the densely populated centers of major cities and at major transportation termini such as airports. The class of systems that seems to offer the greatest promise for filling this gap encompasses a variety of continuously accessible, continuously moving systems. The people conveyor idea is hardly new; it has been proposed many times in the past (1, 2, 3, 4). However, the key to practical embodiment of the system lies in the method used for getting people on and off the moving element. The speeds of the entry or exit ramps, and the conveyor belt itself, must be matched as closely as possible at the point of transfer. Yet, because the conveyor is to be used by people of all ages and physical conditions, the accelerations and decelerations must be effected smoothly and with as nearly absolute safety as possible. Past proposals usually have entailed a pair of adjacent parallel moving platforms, one with a slightly higher speed than the other, or a car running slowly along a track for loading and unloading, after which it accelerates to a higher speed between stations. Either method implies a considerable amount of mechanical complexity, and, of course, at each speed-change interface there are opportunities for mechanical breakdowns or accidents.

PRINCIPLES OF OPERATION

An ideal entry-exit technique should achieve the necessary speed change smoothly and gradually, preferably with no sharp stepwise discontinuities at all. Although it would be very difficult to eliminate all such discontinuities completely, it is possible via the technique described here to achieve a reasonable final speed (8 to 12 mph) smoothly with only a single velocity-interface point involving a discrete speed change of 1.5 to 2.5 mph in the forward direction only (as with an escalator).

The problem of achieving effective acceleration is essentially to simulate, through mechanical means, the flow of a fluid. If a stream is forced through a narrow constriction, the speed of the flow increases, and vice versa; in aerodynamics this is the well-known Bernoulli effect. One simple means of accomplishing this speed-constriction trade-off in 2 dimensions is by means of a strip of a mesh, constructed like a fish net (5). The unit cells of this mesh are roughly parallelopipeds whose sides are inextensible (i.e., not stretchable) but bendable and whose joints (or vertices) are flexible. In short, the mesh can be distorted by extension along one axis and simultaneous contraction along an orthogonal one, as shown in Figure 1. If a belt constructed in this fashion is forced through a funnel-shaped constriction, the gradual narrowing and elongation of each cell along the line of motion will gradually increase the speed of anything riding on its surface. Thus, where the belt is wider it moves more slowly, and where it is narrower it moves more rapidly: the ratio of cell lengths along the direction of motion is equal to the ratio of speeds.

$$V_1/V_2 = \ell_1/\ell_2 = \sin\theta_1/\sin\theta_2$$

For a parallelogram mesh, the ratio of widths is given by the ratio of cosines.

$$W_1/W_2 = \cos\theta_1/\cos\theta_2$$

However, in the case of the hexagonal mesh, we again have

$$V_1/V_2 = \ell_1/\ell_2 = \sin\theta_1/\sin\theta_2$$

while

$$W_1/W_2 = (1 + \cos\theta_1)/(1 + \cos\theta_2) = [1 + \cos\sin^{-1}(\ell_{1/a})]/[1 + \cos\sin^{-1}(\ell_{2/a})]$$

For small values of θ_1 and θ_2, it can be shown that the ratio of speeds may be quite large with only a slight change of width. For example, suppose $\theta_1 = 0.02\,\pi$ and $\theta_2 = 0.10\,\pi$. Then,

$$\sin\theta_1/\sin\theta_2 \cong 1/5$$

whereas

$$\cos\theta_1/\cos\theta_2 = 1 - 0.002/1 - 0.05 \cong 1.05$$

and

$$(1 + \cos\theta_1)/(1 + \cos\theta_2) \cong (1 + 1 - 0.002)/(1 + 1 - 0.05) \cong 1.025$$

Thus, a 5:1 speed change requires only a 5 percent change in belt width for a quadrilateral mesh and a 2.5 percent change in belt width for the hexagon mesh. For larger values of θ_1 and θ_2, however, arbitrarily great lateral distortions can be introduced in the quadrilateral case, but the hexagonal mesh can never increase (or decrease) in width by more than a factor of 2.

When the speed is maximum (in practice, perhaps 8 to 12 mph), the accelerating-decelerating strip can be made to run immediately adjacent to, or even on top of, a continuously moving (main) beltway. Not only is the interface easy to control but also it is possible to ensure a zero velocity differential across it; thus, the acceleration from walking speed to that of the belt can be made with almost complete smoothness after the initial entry (which would be similar to a conventional escalator). The exit procedure is, of course, essentially the same procedure in reverse. Two configurations in which a single variable-width belt serves both purposes are shown in Figure 2.

The entry-exit ramp strip, of course, is returned to its starting point in a continuous belt fashion, either underground or, alternatively, via a loop underneath the main conveyor. Exits and points of entry and of egress would normally be paired, possibly as shown in Figure 2. For shorter point-to-point links, however, the variable-width beltway might function as a self-contained relatively high-speed people-mover system in itself, with its own built-in accelerating and decelerating mechanisms at each end. Note that either the quadrilateral or hexagonal meshes are capable of lateral curvatures; i. e., they can turn corners.

The continuous velocity-changing strip described above can, in principle, be cascaded if it is found that a single stage is inadequate to achieve the desired final speed. However, there are practical upper limits for standing passengers imposed by the apparent wind caused by motion and the greater complexity of multiple-staging for entrance and egress.

It is also possible, at least in principle, to operate a deformable-mesh conveyor belt in a demand-activated mode. Thus, one can envision a closed loop normally moving at a constant uniform speed. Suppose, however, that such a loop consists of alternating regions of high and low density, similar to those shown in Figure 1. As viewed from a fixed external frame of reference both high and low density regions move at the same constant speed; whereas from a frame of referenced fixed to the conveyor belt, the density variations (or density waves) appear to be stationary.

However, suppose a passenger wishes to enter (or exit) the system at some point along the loop. Then, following an appropriate signal to the control mechanism, one region of high density accelerates in the conveyor frame of reference and decelerates in the external frame of reference until it is stationary in the latter frame. A low-speed section is then momentarily available for the passenger to step onto (or off of). Subsequently, the sequence is reversed and the high-density region accelerates with respect to the external frame of reference and moves in the opposite direction along the moving belt until it regains its original position with respect to the rest of the loop. The sequence is shown schematically in Figure 3.

THE MESH

Although it is not necessarily obvious from an examination of Figure 1, it can be shown easily that the desired speed-change function must be accompanied by some slight distortion of the structural members of the mesh. This distortion may take the form of either stretching or bending or both, but we shall assume inextensibility (no stretching) would be characteristic of most long-wearing structural materials.

It is obviously desirable that the joints or vertices connecting neighboring cells of the mesh should offer minimal resistance to angular flexing of the scissors type. A quadrilateral mesh (whose cells consist of equilateral parallelograms), such as the one shown in Figure 1, will have the necessary angular deformability, but this is not the only possible geometrical configuration with appropriate topological characteristics. Hexagons are probably more desirable because they involve less lateral distortion, as already pointed out.

It is apparent also that the mesh need not be homogeneous or uniform. It can, for instance, consist of a heavy-duty macromesh designed to carry the lateral and longitudinal stresses, plus a finer secondary micromesh designed to support a load-bearing surface (Fig. 4a). For the latter, there are a number of possible options, including a woven wire fabric, a solid mesh constructed of thin metal strips (Fig. 4b) having substantial rigidity in the vertical dimension while remaining flexible in the horizontal plane, or a tufted carpet of metallic or glass fiber yarn (Fig. 4c). Or, instead of tufted metal or glass fibers as such, short sections of thin fiber-stiffened plastic tubes might be utilized. The concept of a deformable carpet would be applicable to either a quadrilateral or hexagonal mesh.

As for the heavier tension-carrying elements of the macromesh, the members may consist of flexible rods, braided cable, metal strips, heavy wire, or any other material with high tensile strength and some stiffness (in regard to bending) but without rigidity. The vertices should have absolute rotational freedom as needed to ensure the requisite deformability of the mesh. The simplest form of hinge would probably be a simple rivet, perhaps utilizing a nylon grommet to minimize friction.

PROPULSION

There are several possibilities for propulsion, but at this stage it seems likely that the external driving force would be applied via a series of spaced externally driven belts or rollers. Several variant approaches, such as a rotating Archimedes screw with an appropriately variable pitch or a pair of counter-rotating cones placed axially to the direction of motion, may also be used. In the future, however, it is expected that some sort of linear induction motor (LIM) would be the optimum means of propulsion.

ANCILLARIES

Desirable ancillaries—mostly related to or considerations of safety or comfort—are as follows:

1. A hand grip or backrest or (preferably) both, traveling with the conveyor surface. An accordion-like handrail could be moved in phase with the feeder (mesh) belt by linking it directly to the main drive mechanism. The requisite degree of expansion or contraction or both could be provided by means of a segmented tubular structure.

Figure 1. Extension and contraction of mesh belt.

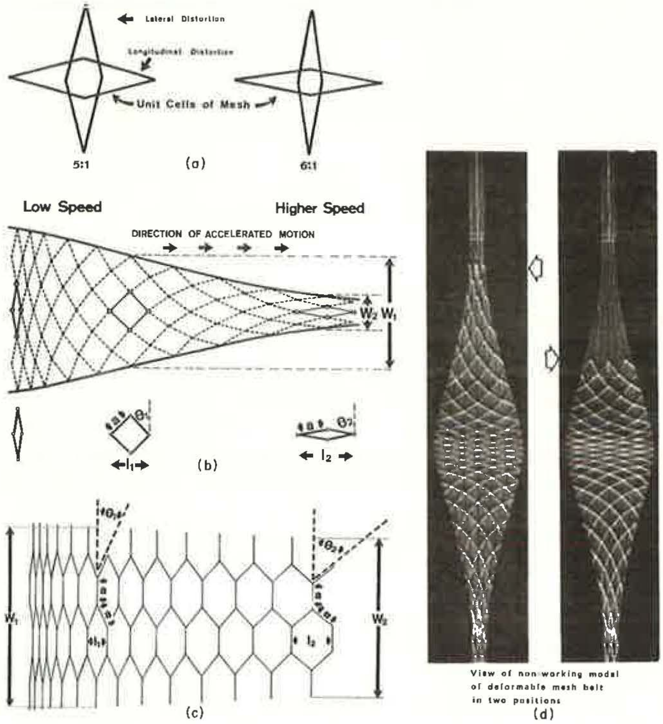


Figure 2. Mating of entry-exit ramps.

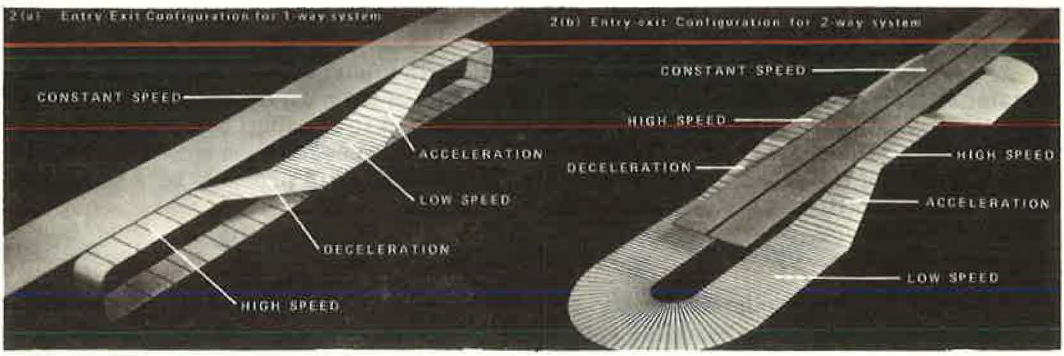
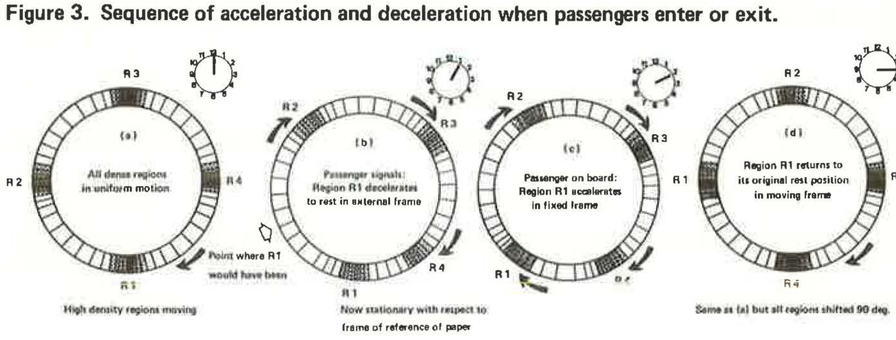


Figure 3. Sequence of acceleration and deceleration when passengers enter or exit.



It is not envisioned that passengers would sit down during the acceleration or deceleration phase (although seats would probably be provided on the main conveyor), but form-fitting backrests offering additional support and stability could be provided in the same way as handgrips.

2. A device to prevent loose items of clothing or baggage from being snagged at points where the moving conveyor passes under a stationary platform. For instance, a high pressure jet of compressed air might be forced through the moving mesh at such points to ensure that no article of clothing or personal property could possibly be caught and accidentally dragged under the edge of the stationary platform or between the feeder belt and the main conveyor (Fig. 5).

3. A system to discourage people from debarking onto the exit strip too close together so that there is no uncomfortable crowding during deceleration. Signs, flashing lights, and taped loud-speaker instructions could be used to stress the importance of this precaution. Properly spaced handgrips would be most effective in discouraging bunching at points of egress.

4. A suitable gate to permit one entrance-exit to be shut down and withdrawn from service for maintenance or other reasons without affecting the main conveyor system.

5. A suitable arrangement for surveillance and supervision, presumably via closed-circuit TV. An alarm system permitting passengers to call for assistance should also be considered.

6. Facilities for emergency entrance and exit (for guards, police, first aid, or maintenance) possibly via suitable slides or chutes, or possibly wheeled electric mini-cycles.

URBAN DESIGN IMPLICATIONS

The fact that either of the deformable mesh configurations is capable of curving and turning corners, in contrast to conventional conveyor belts that require a line-of-slight ight-of-way, is of critical importance. Evidently, a curvilinear conveyor system would be extraordinarily flexible, accommodating itself easily to irregular terrain and existing structures. For instance, it is quite possible to envision a people mover utilizing the deformable mesh principle passing through individual buildings or even through a series of adjacent structures, and resulting in an internal arcade.

The implications of such a system for urban architecture and city planning are profound. The nature of the system permits it to be introduced on a small scale and expanded gradually, without the major upheavals that usually accompany a significant advance in transportation technology.

The advantages of the system fall into 2 major categories: scale and flexibility. The scale advantages are of several kinds. In the first place, the belt and its bed are the only hardware involved; there are no extra parts such as cars or cabs to be moved, stored, repaired, and so on. The only probable accessories might be a signal system and an automatic cleaning system. This creates a very low profile, adds almost nothing to the scene, and uses no additional real estate. Because the belt itself is like a sidewalk or hallway floor, the people or objects being moved are the only visible moving parts.

This obviously reduces not only the maintenance and design problems but also, perhaps most important, the energy problem. When the containers (cars, cabs, and so on) used by conventional systems are eliminated, most of the weight being moved is automatically eliminated as well. This reduces the energy requirements proportionately—an important ecological consideration. Moreover, in terms of the passengers' own immediate environment, both noise and fume emission are eliminated; by contrast with any existing mode of travel, this belt system would be both clean and silent, having nearly no pollutant side effects within the channel of movement.

The flexibility of the system makes possible another whole category of change in the urban environment. The variable speeds and rhythms along the system create an adaptability to all scales. The system and its controls do not get more cumbersome as they get larger; they just ramify like a tree, still completely integrated. This makes it possible to design and install the system at any scale.

The system can also be made responsive to automatic electronic control (programmed automation) and is particularly adaptable to this type of control because, no matter how extensive, it is organically one system. There is great compatibility between a possible control system and the nature of the belt system itself, for it is completely integrated and flexible virtually down to the cellular level. The system is not strained by additional loops and can operate at any scale, large or small, with no loss of efficiency.

From a human-factor point of view, the system can be made totally responsive: Passenger stops can be created at command, on the principle of the push-button walk lights now in use. Moreover, the belt system can interpenetrate and connect both outdoor and indoor spaces. It would no longer be necessary to think of exterior and interior transportation as separate design problems. Clearly, this would open up city planning and architecture in the directions of multiple-level access and use of space and tend to reduce the problems of jamming and congestion designers now have to cope with at each point where the mode or direction of travel changes. If a belt system such as this is used, the direction could change in 3 dimensions without a change in mode having to be forced.

DESCRIPTION OF VARIFLEX MODEL

The variflex model exhibits in reduced scale a continuously moving surface that varies in speed (and density) as it moves around a closed circuit. The model consists of 4 major components: hexagonal mesh belt, support for the belt, speed-changing system, and drive motor.

The belt consists of aluminum strips bonded together to form a cellular matrix—when fully extended—similar to honeycomb. Unlike the latter, of course, the cells of the aluminum mesh remain flexible as long as the plastic limit of the material is not exceeded. The material is thin (0.002 in.) so that longitudinal extension by a factor of 5 still corresponds to a very small angular distortion and, consequently, a small change in belt width.

The support mechanism consists of a secondary fabric belt having a suede-like surface that interlocks with the cellular structure of the belt to maximize sliding resistance. All constant speed movement by the belt whether fast or slow is controlled by secondary belts.

Each transition zone between fast and slow sections of the loop requires a speed-changing mechanism. This is accomplished in the model by a pair of counter-rotating conical rollers that have axes of rotation nearly parallel to the direction of motion of the belt. The slight angle ϕ between the cones and the belt produces a driving component in the direction of motion proportional to sec ϕ.

The drive consists of a $\frac{1}{40}$-hp, 110-volt motor connected to a sprocket and chain transmission (Fig. 6). The transmission drives a set of flexible shafts at speeds compatible with the requirements of the primary and secondary belts.

VARIFLEX MODEL SPECIFICATIONS

Specifications are as follows:

Model: 24 by 36 by 60 in. irregular
Belt surface: $4\frac{1}{2}$ by 60 in. ($4\frac{1}{2}$ by 122 endless)
Speed ratio: 5 to 1 (2.0 in./sec to 0.4 in./sec)
Drive: $\frac{1}{40}$-hp, 110-volt motor
Transmission: chain and sprocket with flexible shafts to belt surface carrier
Acceleration: 0.122 in./sec^2 each direction

The potential impact of a pedestrian-oriented people mover on an archetypal urban activity center—downtown Lower Manhattan—has been investigated in a study sponsored by the U. S. Department of Housing and Urban Development (6).

For purposes of analysis, a moving sidewalk was "implanted" (hypothetically) along Broadway, Water Street, and Fulton Street to form a loop around the Lower Manhattan Financial District, as shown in Figure 7. The conveyor was assumed to be free of

Figure 4. Alternative mesh configurations.

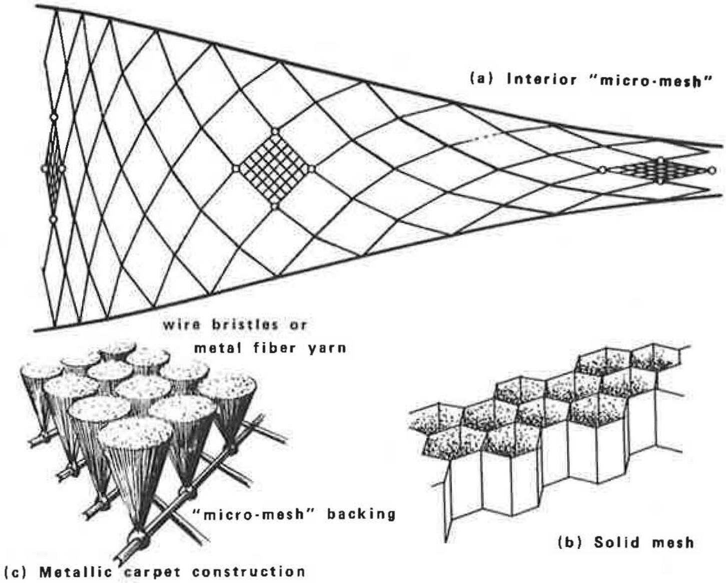


Figure 5. Device to prevent material from being caught at stationary platforms.

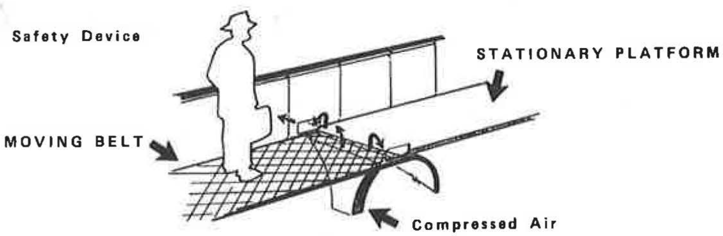


Figure 6. Transmission drive of working model.

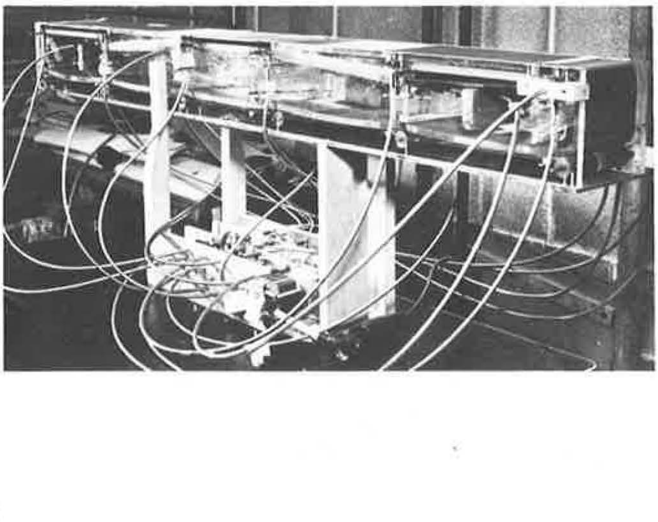


Figure 7. Implanted moving sidewalk in Lower Manhattan.

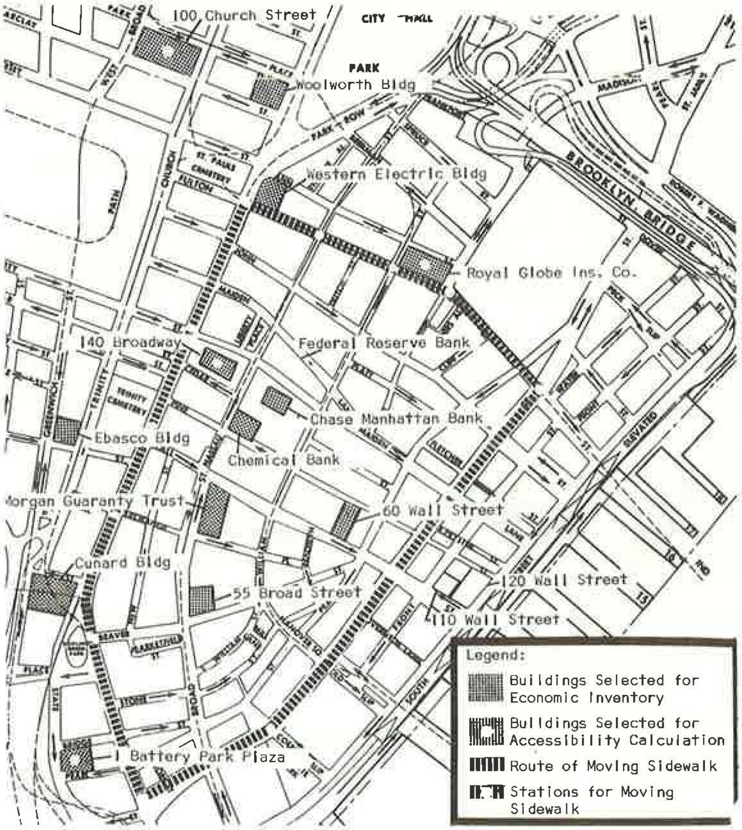
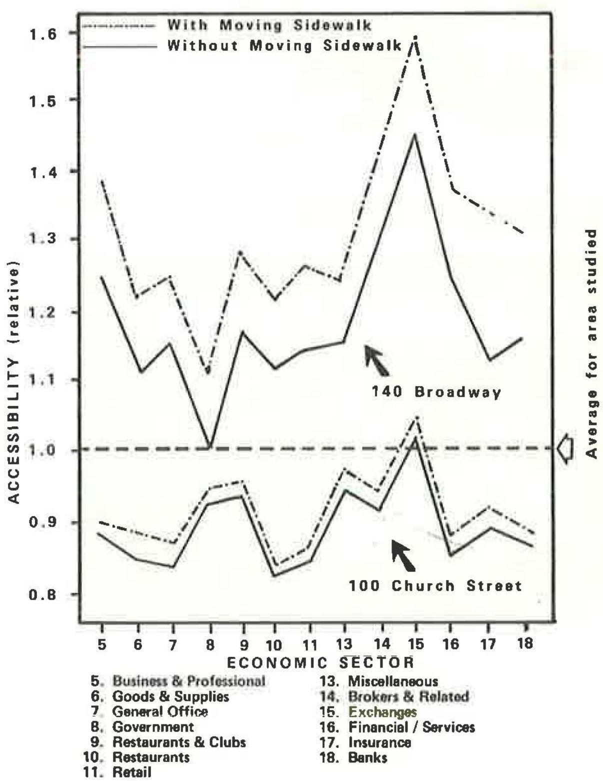


Figure 8. Changes in sector accessibility due to moving sidewalk.



charge, to move at 8 mph, to be covered against the elements, and to be elevated above street level. The system could be boarded at each stop for transportation in both directions and did not require slowdowns at intermediate stations. It was assumed that suitable means for accelerating onto and decelerating off of the conveyor were available.

The principal effect of this implantation was to alter the accessibilities of various locations in the immediate area, relative to their accessibilities without the conveyor system. Accessibility for a point location is defined as the sum of all destinations reachable from that point by all modes of transportation (including walking), weighted inversely by a measure of the difficulty of reaching each destination (a function of cost, time, and stress involved in making the trip), multiplied by the intrinsic frequency of interaction between a given activity located at the origin and a given activity at the destination, and weighted by the number of people engaged in each economic activity at each point. To compute this index quantitatively requires that specific data be obtained on the geographical possibilities for transportation, detailed characteristics of the transportation network, optimum routes and modes linking all pairs of points, distribution of employment by activity and by location, and probability of interaction (i. e., trip-making) among different economic activities. Such a data bank has been collected for downtown Lower Manhattan, and the necessary calculations were carried out (6).

A comparison of sectoral accessibilities with and without the conveyor system is shown in Figure 8 for 2 building locations, 140 Broadway and 100 Church Street. The accessibility of 140 Broadway, already much better than average, is markedly improved further by the new transportation system, whereas 100 Church Street, not very accessible to begin with, is not much benefited by the conveyor belt, which, at its point of closest approach, is 3 blocks away. The effect of the implantation is to increase accessibility by a minimum of 1 percent to a maximum of 13 percent, depending on sector and location.

As far as the economic impact is concerned, a change in accessibility implies an increased demand for space at the same rent or—with space constrained to remain the same in the short run—an increased equilibrium rental value.

The data so far obtained support the conclusion, tentative at this time, that the equilibrium demand for space (with rents held fixed) is a very strong function of accessibility. Thus, a 5 percent increase in accessibility would seem to result in close to 50 percent more demand for space at the same price. Because the accessibility change is sector dependent, external changes in transportation, land use, or improvement can cause shifts in demand for space by different sectors and can engender new patterns for space use and employment skills.

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