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ESCALATOR DESIGN FEATURES EVALUATION

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Final Report

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16. Abstract

Rail transit systems make extensive use of escalators at the stations to facilitate efficient patron flow. Escalators are available with design features such as dual speed (90 and 120 fpm), mat operation, and flat steps. This study has evaluated the design features based on the impact of each on capital and operating costs, traffic flow, and safety.

These design features were evaluated on the basis of analyses of data collected from transit properties and manufacturers. A human factors engineering model was developed to analyze the need for flat steps at various speeds.

The study concluded that mat operation of escalators is cost effective in terms of energy savings. Dual speed operation of escalators with the higher speed used during peak hours allows for efficient operation. Minimum number of flat steps required as a function of escalator speed were developed to ensure safety for the elderly patrons.

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PREFACE

This report provides evaluations of special design features associated with escalators used in rail transit systems. Information relating to costs, performance, and safety of escalators was made available to us by several cooperating organizations including transit properties and escalator manufacturers. We acknowledge the contribution from the following individuals and organizations for their cooperation.

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This task was carried out under the guidance of Joe Koziol of Transportation Systems Center, Cambridge, MA. Additional contributors to this task at Jet Propulsion Laboratory included Joel Sandberg, Jim Land, Jack Mondt, and John Cucchissi.

METRIC CONVERSION FACTORS

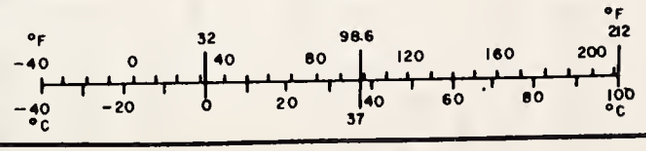
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SECTION 1

EXECUTIVE SUMMARY

1.1 Background

This study provides an evaluation of the effectiveness of several of the special design features associated with escalators in rail transit usage. The study was conducted by JPL for the UMTA/TSC Subsystem Technology Applications in Rail Systems (STARS) program.

The objective of the study was to evaluate the effectiveness of the three escalator design features: (1) mat operation in a single direction and reversible operation, (2) two-speed option (90 or 120 fpm or both), and (3) the use of extended flat steps.

The study was limited to collecting and analyzing readily available transit property data on the use of these features. This was accomplished through discussions with several transit properties including the Port Authority Trans Hudson (PATH), the New York City Transit Authority (NYCTA), the Washington Metropolitan Area Transit Authority (WMATA), and the Bay Area Rapid Transit (BART) district. The properties made available data on accident frequency, capital cost, and energy consumption (primarily BART). However, detailed maintenance costs, station traffic flow rates, and some specific accident data were not readily available from properties for the study.

Escalator manufacturers also contacted regarding these features included Otis and Westinghouse. Other agencies contacted with regard to escalator accidents included the Consumer Product Safety Commission (CPSC) and the National Safety Council (NSC).

1.2 Approach

These design features were analyzed by first collecting capital costs associated with each, and understanding the basic components of each design feature in terms of its function, and its desired effect on the

operation of the escalator. The next step was to understand the failure modes under each feature and see how they are affected by other component failures in the system, and their impact on maintenance.

The primary failures associated with mat operation center around (1) mat activated switches, (2) sensors which monitor embarking passengers, (3) motor degradation resulting from current surges, (4) brake wear caused by intermittent stopping and starting, and (5) step chain wear. It was generally agreed by the transit properties that the 120 fpm (feet per minute) speed accelerated wear on the moving and rotating components compared to escalator operation at 90 fpm. The extended flat step configuration was relatively benign with respect to maintenance since the only additional failure appeared to result from step chain stretch caused when the chain is unsupported under load for the length of the extra flat steps.

The results of the component failure analysis lead directly to the hazard analysis since passengers could be riding at the time of failure. In addition to design or component failures, the study also considered passengers as a contributor to hazards. The analysis did not consider accidental bumps or abuse of the equipment since these result in hazards which cannot be resolved by any of the above design features. Physical limitations were important because these do affect the ability of patrons to cope with higher escalator speeds and achieving balance on moving steps and the number of flat steps.

The results of the accident and injury data analysis confirmed that system failures and a person's physical limitations contribute to many escalator related injuries. In terms of the three design features, it was found that the elderly and handicapped would be affected the most compared to other patrons by these features because most of their accidents were falls resulting from getting on or off the escalators. Since these groups of people usually suffer the most serious injuries on escalators, the evaluation of each design feature was based on its potential impact on reducing injuries to the elderly and handicapped.

1.3 Summary of Findings

1.3.1 Mat Operated Escalators

Mat operation of escalators during off-peak hours is economically feasible for either the up or down direction when the number of escalator starts per hour is less than 30. Life cycle cost analysis of mat operation shows that the capital and operating costs associated with mat operation are more than offset by the cost savings from reduced energy consumption. This assumes that energy costs will increase at a rate higher than the inflationary rate.

At stations with a low patron flow, reversible mat operation of a single escalator may be the preferred alternative compared to two escalators, one for each direction. This is due to the capital cost savings associated with one less escalator. Human factor studies and analyses of subsystem designs currently associated with mat operation indicate that improvements in components and subsystem designs are needed to increase reliability and mitigate hazards associated with these systems.

1.3.2 Escalator Speed

The preferred design is a dual speed escalator. The 120 fpm speed should be used during the peak hours and 90 fpm during the off-peak hours. Even though the hourly capacity is not linearly related to speed, the increase in escalator capacity at the higher speed reduces problems of overcrowding at high volume stations. At low volume stations existing data indicates no real advantages to the higher speed.

Escalators over 40 ft high (three level changes) should utilize the speed of 120 fpm to reduce extended travel time on escalators. Excessive travel times result in movement of passengers resulting in a hazardous operating environment.

Though the extent of maintenance cost differences could not be established in this study, property experience suggests that operation at higher speeds results in increased maintenance costs.

1.3.3 Extended Flat Steps

Extended flat steps increase the safety and improve traffic flow on escalators by allowing patrons to gain balance before the steps separate. Elderly and handicapped coordination and reaction times are major determinants of the minimum number of flat steps required. Analysis of human factors data indicates that the minimum number of flat steps required for safety is 1.5 for 90 fpm escalators and 2.0 steps for 120 fpm.

1.4 Recommendations

Properties installing escalators should require mat operation capability for escalators to save long-term energy costs. Dual speed escalators are recommended in high volume stations instead of the single speed to save energy and reduce maintenance costs. Escalators operating at 120 fpm should specify a minimum of 2.0 extended flat steps to improve the safety of elderly patrons.

Additional studies should be conducted to (1) develop better designs of mat operated escalators to reduce long-term maintenance costs and improve their safety, and (2) to collect and analyze safety and maintenance-related data at 90 fpm and 120 fpm escalator speeds.

SECTION 2

ESCALATOR SPECIAL DESIGN FEATURES

2.1 Introduction

A majority of escalators in rail transit usage in the U.S. were installed in the last decade. The basic escalator technology has generally not changed over the years except for the introduction of the modular escalator concept. The modular drive units in these escalators are located within the truss. The number of drive units required are based on the escalator rise, generally one drive unit for each 20 foot rise. The modular escalator concept allows the use of high-rise escalators in rapid transit station designs at a reasonable cost. Several of the newly built rail systems, including WMATA and MARTA, have utilized the modular escalators in their station designs.

Recent concerns over energy consumption have prompted the introduction of mat operated escalators at NYCTA and Chicago Transit Authority (CTA) on units being replaced. This concept allows escalators to operate only on demand rather than being run continuously. There appears to be no consensus within the transit industry regarding the usefulness of this concept in saving energy. The general opinion within the transit industry is that energy cost savings could be offset by higher maintenance costs due to increased starts and stops. Reversible mat operation allows the use of only one escalator instead of two at low density stations. However, this concept has not been widely employed. Other options specified for escalators in recent years are the use of multiple operating speeds, the reversible operation of escalators on demand, and the use of increased numbers of flat steps.

The use of multiple speeds (90/120 fpm) allows operating the escalators at higher speed during the peak hour. However, none of the operating properties in the U.S. operate escalators at both these speeds based on the hour of the day. Most properties have escalators that can operate only

at one of these speeds. The higher speed allows an increase in capacity, reduced travel time on the escalators, but results in reduced safety for elderly patrons.

The use of flat steps generally enhances the safety of the escalators by allowing more time to become balanced on the steps and thus reduces the chance of accidental falls while stepping on and off the escalators. The use of flat steps increases initial costs.

2.2 Description of Designs

2.2.1 Mat Operated Escalators

The mat operated reversible design allows the system to only operate when passengers activate a mat operated start switch as they board the escalator. This is in contrast to the normal continuous operation. The two basic designs for mat operation are (1) uni-directional mat operation (i.e., the unit is activated to only go up or down, and (2) bi-directional mat operation (i.e., the unit can be activated to go either up or down on demand). BART has experimented with the bi-directional design (Ref. 1) and NYCTA presently operates approximately 40 uni-directional units (Ref. 2). The basic components of the system are as follows (Ref. 1):

- Pressure activated start switches located under a mat which is placed on the walkway leading up to the escalator at both top and bottom.

- Photo cells located in the skirts near the combplates to insure proper sensing of passengers.

- A timing device set to shut the system off after a passenger safely disembarks, and also to reset the running timer if other passengers board while the escalator is still operating,

- A soft start current limiting device which lowers the inrush current to prevent premature motor burnout.

- Precautionary signs informing passengers when it is safe to board.

2.2.2 Escalator Speed

Most of the escalators today offer options for 90 or 120 fpm speeds, or both. Speeds can be easily modified by simply changing gear ratios in the gear reduction unit or main gear drive. This can also be achieved using a motor with two separate windings corresponding to the two speeds.

2.2.3 Extended Flat Steps

The conventional escalators used in department stores and older transit properties such as NYCTA are designed with one-to-one and one-half steps at both the bottom and top landing of the escalators. The measure of the number of flat steps can be determined by counting the number of steps forming a flat surface before the steps articulate, or actually start to rise. Newer designs such as used by BART and WMATA have approximately three to three and one-half flat steps at both the top and bottom landings. This is not a firm design and it appears that the number of additional steps beyond the conventional single flat step can vary from one to three. In actual design, the major components affected are the landings (which must be extended), the step chains (which must be lengthened), and a modified truss network to support extra guide tracks for the step chains and steps.

2.3 Impact on Maintenance and Safety

The first step in the analysis was to collect data from several transit properties relating to component failures. This was accomplished by obtaining maintenance records in the form of maintenance calls and resultant actions required to keep units operational (Refs. 3, 4). The original intent was to gather these data from various properties and perform the maintenance analysis knowing the differences in the designs employed by the properties. For example, both BART and NYCTA used mat-operated units and non-mat-operated

units. In a similar manner, BART and WMATA employ the extended flat steps and operate at 120 fpm, while NYCTA and PATH generally employ the standard single step configuration and operate most of their escalators at 90 fpm. Detailed examination of the records revealed that the differences in reporting formats (primarily in the depth to which the failures were reported) made it extremely difficult to compare component failure rates. Additionally, in order to draw conclusions about failure frequencies it was necessary to examine several months of data. The scope of this effort fell outside the constraints of the study and it was therefore decided to use the failure reporting to confirm the existence of the component failures, and use the experience of the properties to get a relative comparison of failure frequencies (i.e., relative failure frequencies experienced with and without mat operation, operating at 90 or 120 fpm, and with or without additional flat steps). The major failure modes indicated by the maintenance records and experience of the properties are summarized in the subsequent sections.

2.3.1 Mat Operated Escalators

The reported failure modes for the components listed in Section 2.2.1 are as follows (Refs. 1, 2, 3, 5):

- Mat switches fail due to age or corrosion, which is a function of moisture seeping under mats or penetrating mats as they wear and the rubber insulation breaks down. This is further aggravated if escalators are located outdoors.

- Photo cells fail as a result of moisture. Cells located in the lower section of the balustrade at the bottom of the landing are particularly affected because moisture is usually transferred into this area by gravity and trapped (particularly on outdoor escalators). Dirt and grime can also accumulate on the transparent, protective cover and cut down light transmission. The location of the sensors at the lower section of the balustrade also exposes them to damage by passengers carrying umbrellas, shopping carts, or heavy bags.

- Failure of the running timer is primarily a function of mat switch failure. Receipt of an intermittent signal, no signal at all, or a continuous signal would respectively prevent the escalator from operating or cause it to operate continuously.

- Soft start current limiting devices used on present designs offer few problems. However, if mat operation is intended and this device is not employed several problems arise. These center on the circuit overloads caused by not controlling the inrush current.

- Other components besides those listed are affected by the stop-start mode of operation. Constant stopping and starting contributes to brake wear and step chain wear (primarily in the step chain bushings).

- Backlighted caution signs fail resulting in signs not being illuminated.

2.3.2 Escalator Speed

The components affected by increasing escalator speeds from 90 fpm to 120 fpm are the major rotating components such as motor and drive gear bearings, step roller bearings, step rollers, step chains, and drive belts. The failure modes of these components are as follows:

- Increase in speed increases bearing friction which results in skidding and spalling.

- Step roller wear is accelerated by higher speeds due to the greater distances traveled within a given time frame and skidding. This also affects track wear.

- Step chain bushing and link pin wear is greater due to more link rotation and vibration.

- Drive chain or belt wear accelerates because of the higher flex rate.

2.3.3 Extended Flat Step

Though this design feature requires additional structural support, the only component validated by the properties as being affected is the step chain (Ref. 6). On conventional escalator designs the additional flat steps coupled with the track radius and chain tension do not allow the chain to be supported in the track for the length of the steps. Therefore, the chain supports the full passenger load for the length of the steps. BART reports that older step chains which do not hold tension, or new chains in which links are still seating, can stretch under passenger load and trip the lower carriage switch (Refs. 5, 6). This switch senses chain slack and automatically shuts the unit off. Otis confirmed this failure mode and has included step chain support in their latest design (Ref. 5).

2.4 System Failures Resulting in Hazards

Examination of accident data from CPSC, NSC, and the various transit properties confirmed that numerous accidents are caused by design failures or component breakdowns. It is interesting to note that very few accidents involve workers repairing failed units (Ref. 7). The net result of many component failures is that the unit stops in mid flight with passengers in the process of boarding, riding, or exiting. This is often reported as the major cause for accidents. The CPSC investigates cases that result in serious injury (and major litigation) and has accumulated a large file of escalator accidents involving many escalator applications (i.e., department stores, transit stations, hospitals, etc.). These data were studied primarily to determine the kinds of accidents and whether there existed a correlation between age group and accident frequency. The data provided in Table 2-1 show (1) the number of injuries related to three major age groups, (2) the seriousness of the injury, and (3) the basic cause.

TABLE 2-1. REPORTED ESCALATOR INJURIES
(CPSC INJURY DATA, 1979-1980)

Injury Information	Age Groups (Years) 2-13	13-50	50 and over
# Injuries	94	57	81
# Serious Injuries	64	28	61
Typical Injury	Class 4 or greater	Usually Class 2	Class 3 or greater
Typical Cause	Fall/entrapment	Fall	Fall

The severity rating placed on injuries by CPSC is done by class. The general ratings are as follows:

- Class 1 - mild sprain (these injuries are often not reported by patrons)
- Class 2 - Minor contusions
- Class 3 - Minor fractures
- Class 4 - Crushing of extremities, head laceration
- Class 5 - Concussion, fractured neck
- Class 6-7 - Amputation
- Class 8 - Death

Injuries in the less than 13 age group were predominantly due to entrapment (Ref. 8). The middle age group usually suffers the least serious injuries. Injuries occuring in the over 50 age group were predominantly falls resulting in fractures (Ref. 8). Though the under 13 age group suffered a higher number of injuries, a higher percentage of injuries in the over 50 age group were serious (i.e., approximately 75%).

Examination of the transit property accident data revealed the general trend indicating older patrons suffered more fall type accidents and a greater accident rate than the other two age groups. This became an important finding in terms of evaluating the three design features.

Major component failures and hazards related to the less than 13 year old age group are as follows:

- Combplate teeth broken - children's toes and fingers are cut on sharp edges or entrapped between top surface of step and gap in combplate.

- Gap between skirt panel and step is out of tolerance (due to step chain wear) - results in entrapment of fingers or toes (aggravated if wet tennis shoes are worn since rubber is easily extruded).

- Handrail is stretched - allows space for entrapment of fingers.

The major component failures and hazards which appear to be associated with accidents in the over 50 age group are as follows:

- Step chain wear - passengers experience jerky ride which results in imbalance, or chain slack causes immediate shutdown which results in a fall.

- Step roller wear - steps vibrate due to roller skidding causing vibration which causes imbalance.

- Step treads worn or broken - passengers sense uneven surface while riding causing imbalance (aggravated if steps are wet).

- Mat-operated switch fails to activate escalator - passenger falls because he is anticipating forward movement and over-compensates.

- Failure of photo sensor to sense a boarding passenger and timer is not reset - passenger boards and loses balance due to unexpected sudden stop in mid-travel.

- Insufficient number of flat steps (design failure) - steps articulate before passenger has time to obtain balance, causing a fall (aggravated by higher speeds).

It should be noted that sometimes these failures are simultaneous (such as vibration associated with a sudden stop) and further aggravate the balance problems older people experience in boarding and riding escalators.

The above hazards are strictly related to system failures. Human errors are also part of system failures and, where it is practical, should be considered in the system design. Equipment abuse related to passengers hurrying, or vandalism were not considered and accidents associated with these circumstances were removed from the data. Human-induced failures related to children are also difficult to design out of a system because it is not their nature to remain standing and stationary when riding escalators. Subsequently, other than retaining tighter controls over pinch points, it is difficult to incorporate any design features to offset entrapment hazards.

Older people, however, encounter somewhat different problems. Studies done at the University of Texas at Arlington demonstrate that starting around the age of 50, marked degradations in body motor control response start to occur (Ref. 9). These degradations affect a person's ability to compensate for abrupt speed changes, and changes in station orientation when standing on the steps (i.e., vibrations in the step platform) (Ref. 9). These problems, operating in conjunction with escalator speed and the various component failures listed previously, clarify why older people experience a higher frequency of falls. It is also obvious that the design features evaluated relate more closely to falling accidents than other types because they impact boarding, riding, and exiting the escalators. Therefore, the approach taken was to examine the three basic designs from the standpoint of their ability to

mitigate falling hazards related to the older age group. Handicapped people capable of riding escalators suffer the same kinds of problems associated with the older group (Ref. 10). If the proper designs are selected from the alternatives, then escalators will be designed to reduce the number of elderly injuries which contribute the largest portion to total injuries, and therefore will be safer for handicapped and all other age groups.

2.5 Impact on Traffic Flow and Cost

Each of the design features evaluated in the study has an impact on escalator performance. For example, the traffic flow in terms of passengers per hour is slightly increased for an escalator running speed of 120 fpm compared to 90 fpm (Refs. 11, 12).

There is a capital cost associated with the installation of any of these design features. The costs of operation and maintenance are also affected. Of prime concern to transit properties is the impact of these design features on patron safety and on traffic flow.

2.5.1 Mat Operated Escalators

As described earlier, there are two types of mat operation used in conjunction with escalators. These are the uni-directional mat operation and the reversible mat operation. The uni-directional mat operation is utilized primarily to reduce energy consumption during the off-peak hour operation. The reversible mat operation serves two purposes, the first being the ability to utilize one less escalator per station thus reducing capital costs and, secondly, the use on demand to save energy.

Capital Costs

The mat operation involves installation of the pressure-sensitive mats, switches, associated logic and control devices, and caution signs indicating the escalator use directions. The costs of these devices to make

automatic operation of escalators vary from $8,000-$10,000 for uni-directional operation (NYCTA) and $16,000 to $18,000 for reversible escalators (BART).

Traffic Flow

The effect on escalator traffic flow due to installation of mat operation is minimal. This option is generally utilized during the off-peak hours at stations where the traffic is light.

In a reversible operation, some delays may be caused during train movements for passengers desiring to use the escalator because of possibilities of heavier concentration of one-way traffic.

2.5.2 Escalator Operating Speed

The escalator operating practice in U.S. rail transit systems is to utilize either 90 fpm or 120 fpm escalator speeds. Newer properties such as BART and WMATA have chosen the speed of 120 fpm and older properties such as New York and Chicago utilize 90 fpm. Toronto utilizes 120 fpm during the peak hours and 90 fpm during the off-peak hours effectively.

There are three choices in specifying escalator speeds on new procurements. The advantage of dual speed allows an increased capacity needed during the peak hours with 120 fpm, and energy efficient and safer 90 fpm during the off-peak hours. Presently, the technique used to change speed from 90 fpm to 120 fpm is a manual operation.

It should be noted that a majority of escalators in the U.S. utilize the 90 fpm speed. Recently, there has been a trend toward the higher speed to move more people and at higher speeds. The ANSI 17.1 code for elevators and escalators (Ref. 13) specifies a maximum speed of 125 fpm.

The escalator speeds used in the U.S. are generally much lower than those used in Europe. Table 2-2 summarizes escalator speeds used in some representative countries in Europe (Refs. 12, 14). The angle of inclination used in Europe is the same as used in the U.S., namely 30 degrees.

TABLE 2-2. ESCALATOR OPERATING SPEEDS

Country	Subway	Rise in Feet	Speed (fpm)
U.K.	London	40-120	148
France	Paris	15-74	118
Germany	Hamburg	16-46	132
	Berlin	40 (max)	118
Sweden	Stockholm	11-108	148
USSR	Moscow	196 (max)	236
Canada	Toronto	12-40	90/120
USA	Washington	20-96	120
	Chicago	26 (max)	90

Capital Costs

Discussions with escalator manufacturers suggested that there is little difference in the capital cost of specifying either speeds of 90 fpm or 120 fpm. However, there is a slight increase in cost if dual speed operation is specified. The estimates of this cost are about $5,000-$7,000 for a 20 foot escalator including all the control circuitry. The control circuitry can be designed for either manual change of speed or automatic speed change based on a programmable clock. This latter technique is used outside the U.S. (Ref. 12).

Traffic Flow

Generally, an increase in speed results in an increase in capacity. However, this relationship is not linear as shown in Figure 2-1. The theoretical values in Figure 2-1 are based on the assumption of 1.25 passengers per step on the 32 inch and 2.0 passengers per step on the 48 inch wide escalator. The practical capacities are based on field measurements of traffic flows. Studies (Refs. 11, 12, 14) indicate that an actual increase in passenger capacity from 90 fpm to 120 fpm escalator speed is around 12%. This

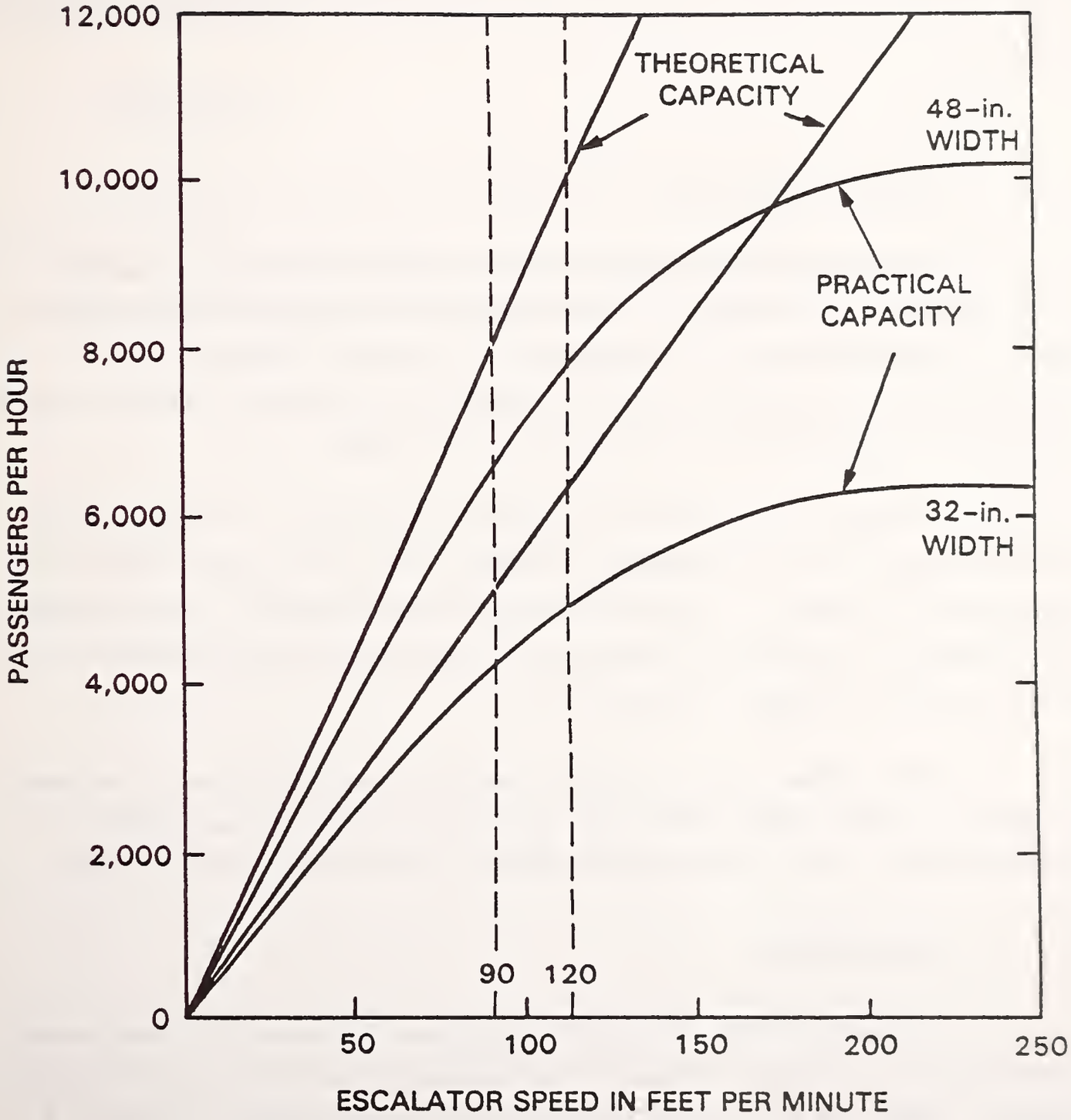

FIGURE 2-1. ESCALATOR CAPACITY AT VARIOUS SPEEDS

increase in capacity is of marginal value at low or moderately loaded stations. However, at stations experiencing high passenger flow rates during the peak hours, a 12% increase in carrying capacity could help clear the station platforms more quickly.

The escalator capacity in practice is lower than the theoretical at higher speeds due to hesitation of passengers at higher speeds to get on an escalator (Refs. 12, 14). This hesitation delays a patron's first step onto an escalator and results in several steps being empty to cause the capacity reduction.

2.5.3 Extended Flat Steps

Extended flat steps allow the patron time to adjust his balance during the horizontal movement of the escalator while making the transition from a stationary platform to moving steps. In general, the extended flat steps are designed to increase inherent safety of an escalator and help reduce the impedance to traffic flow due to patron hesitation.

Extended flat steps have been used in the U.S. in recent years at new properties such as BART, WMATA, and MARTA. There is no specification for flat steps in the ANSI 17.1 code for escalators and elevators. There seems to be an impetus to use extended flat steps on escalators utilizing speeds of 120 fpm and escalators having rises over 20 ft.

There appears to be a certain degree of variability as to how many of these flat steps really need to be specified so that they serve both the intended purpose (safety and patron movement) and are also cost effective.

Capital Cost

The installation of extended flat steps increases the total costs associated with escalators because of an increase in hardware and structural elements. There are two types of costs in this design feature. There is a

tooling set-up cost for the manufacturer, distributed over the number of escalators ordered. The second cost, which is minimal, relates to the structural elements and space required for the additional flat steps.

It was difficult to estimate the precise cost of each additional step because of several variables. On low rise (20 ft) escalators, the proportion of the cost due to an additional three steps could be 10-15% of the escalator cost. However, this proportion appears to drop substantially as the escalator rise increases.

Traffic Flow

Extended flat steps are generally used to improve safety during the boarding and exiting of escalators. However, their use results in an improved traffic flow also. By reducing hesitation during boarding, the flat steps help achieve a higher hourly capacity associated with the 120 fpm escalator speed.

SECTION 3

DESIGN EVALUATION

3.1 Mat Operated Escalators

3.1.1 Maintenance and Energy Cost

Mat operated escalators not designed properly (without soft stop and start controls) will stress standard components such as motors, brakes, and step chains to a greater degree than simply operating escalators continuously. The mat operation requires additional components (such as switches, photo sensors, and sign lighting) which are particularly susceptible to failure as a result of transient on-off switching, and moisture (Refs. 5, 6). Mat operated escalators are not widely used at this time and it is therefore difficult to evaluate the relative frequency of failure of these systems compared to the standard constant running mode of most existing escalators. The theory of installing mat-operated systems to conserve energy was tested by BART. The test was conducted by essentially attaching a current-voltage integrator to the power switch on the escalator. Power output was measured for constant operation as well as for mat operation. The other variable monitored on the mat system was the frequency of starts. The results of the test are shown in Table 3-1.

The energy consumption of a mat-operated escalator is generally lower than that of a continuously operating escalator because the escalator is used only when demanded. Energy consumption can approach that of a continuously operated escalator if frequency of starts per hour is over 30. BART is currently investigating the implications of the "Mat Operated Reversible" escalator at its Bayfair Station. BART has installed prototype solid-state current-limiting devices in the starter to reduce energy consumption associated with escalator startup.

TABLE 3-1. AVERAGE DAILY ESCALATOR POWER CONSUMPTION
(TEST DATA PROVIDED BY BART)

Escalator Feature	Daily Power Consumption/Escalator (kWh)
Dual directional mat-operated (with soft starts)	
a. Starting mode (3 second in-rush at 10.46 kW)	
-highest no. of starts (741)	6.5
-average no. of starts (525)	4.6
-lowest no. of starts (434)	3.8
b. Running mode (average of 49 seconds/start at 3 kW up and 1.5 kW down)	
-highest no. of starts (741)	30.24
-average no. of starts (525)	21.44
-lowest no. of starts (434)	17.7
Range of Total Consumption	21.5-36.7
Continuous Operation for 18 hrs at 3kW usage	54

The data on the escalator motor used at the Bayfair Station is as follows.

19 HP, 460 V, 3 Phase 60 Hz

1170 RPM, Frame Type 280

Lock Rotor KVA Code H (6.3-7.09)

20.1 Amp, Full Load Current

The energy savings associated with mat operation is related to the number of starts/hour used in the operation. The demand for mat usage can vary from about 5 starts/hour to about 30 starts/hour. If the starts per hour exceed 30, the startup energy consumption offsets any energy savings from mat operation. Utilizing the experimental BART energy consumption data, the energy savings in constant dollars of an escalator running continuously and under mat operation are estimated.

For an escalator rise of 30 ft, a patron would be on the escalator for 34.6 seconds at 90 fpm and about 26 seconds at 120 fpm. As a safety measure, the BART system is set up to run an additional 10 seconds to insure all passengers have exited. Thus, allowing for multiple users, it is assumed for analysis purposes that an escalator will run approximately one minute on an average each time it is started.

For the four daily peak hours, it is assumed that the escalator will be used continuously. Thus, for a 24-hour operation, the escalator would run in the mat-operated mode for 20 hours. The energy consumptions are calculated for four different levels of demand: 5, 10, 20, and 30 starts/hour. The energy consumption data are summarized in Table 3-2.

TABLE 3-2. ENERGY CONSUMPTION AT VARIOUS DEMANDS

No. of Starts Per Hour	Daily Startup Energy kWh	Daily No-Load Energy kWh	Daily No-Load Consumption kWh	Yearly No-Load Consumption kWh	Mat Operation as Percent of Continuous Operation
5	.86	4.98	5.84	2,131	9.7
10	1.72	10.00	11.72	4,277	19.5
20	3.44	20.00	23.44	8,555	39.1
30	5.16	30	35.11	12,833	58.5
Continuous	*	60	60	21,900	100.0

*Negligible

Under load, energy consumption for both types of operation is identical. The yearly no-load consumption in Table 3-2 shows differences in energy consumption between continuous and mat-operated modes.

Energy Cost Implications

The cost of electrical energy has almost doubled in the last five years. The projections made by forecasters, including Data Resources, Inc.

(Ref. 15), indicate that energy costs will increase at a 4.1% relative inflation rate over the next decade. This means that if the annual inflation rate is 10%, the cost of energy will rise at an annual rate of 14.1%.

The cost of electrical energy in terms of dollars per kWh varies depending on the region of the country. An average cost of $0.05 per kWh will be used in the calculations (transit property costs of electrical energy may be slightly different). Annual cost savings of mat operation compared to continuous operation are shown in Table 3-3.

TABLE 3-3. ANNUAL ENERGY COST SAVINGS USING MAT OPERATION

Escalator Starts/Hour	Annual kWh Saved	Annual Cost Saving at $0.05/kWh (1981 Dollars)
5	19,769	$988
10	17,623	$881
20	13,345	$667
30	9,067	$453

Life Cycle Costs

Discussions with properties indicated that annual maintenance costs for mat operation are between $500 to $550 higher than for continuously-operated escalators.

The capital recovery factor at 10% interest rate and 20 years is 0.117. The additional capital cost of $10,000 for installation of mat and related devices results in an annual cost of $10,000 x 0.117 = $1,170. The total annual, exclusive of energy costs, to a property of operating a mat-operated escalator is $1,170 + $530 = $1,800.

It appears that if energy and maintenance costs stay at the present rate, the energy cost savings of mat operation of escalators is not economically practical.

However, as indicated earlier, the costs are projected to rise indicating potential exists to save on energy costs. Also, substantial maintenance cost reductions are possible by utilizing better components and technologies. An annual maintenance cost of $300 is possible with improved equipment. Thus, the present worth of maintenance cost of $300 annually at 10% interest rate and 20 years would be $2,550.

The long-term energy cost savings given that energy costs are increasing at 5% over the mat life of 20 years results in cost savings shown in Table 3-4.

TABLE 3-4. LIFE CYCLE ENERGY COST SAVINGS

Escalator Starts/hr	Energy Cost Savings at $.05/kWh	Present Worth of Cost Savings
5	$988	$32,604
10	$881	$29,073
20	$667	$22,011
30	$453	$14,949

Thus, under all cases, a total present mat operation cost penalty of $10,000 + $2,550 = $12,550 is easily offset by energy savings utilizing the mat operation for escalators. Figure 3-1 shows the life cycle energy cost savings at various escalator demand levels during the off-peak hour and at relative inflation rates of 1, 2, 3, 4, and 5% for electricity cost.

If escalators are operated continuously under no load conditions, there is little difference in the energy consumption between that of an escalator going up or down. Under load, however, the escalator going down consumes less energy than that going up. Westinghouse test data (Ref. 16) indicate under a load of five passengers, the consumption in the up direction is 2.8 kW, but drops to 0.764 kW in the down direction. As the load increases, the down direction escalator starts consuming less energy. Westinghouse test

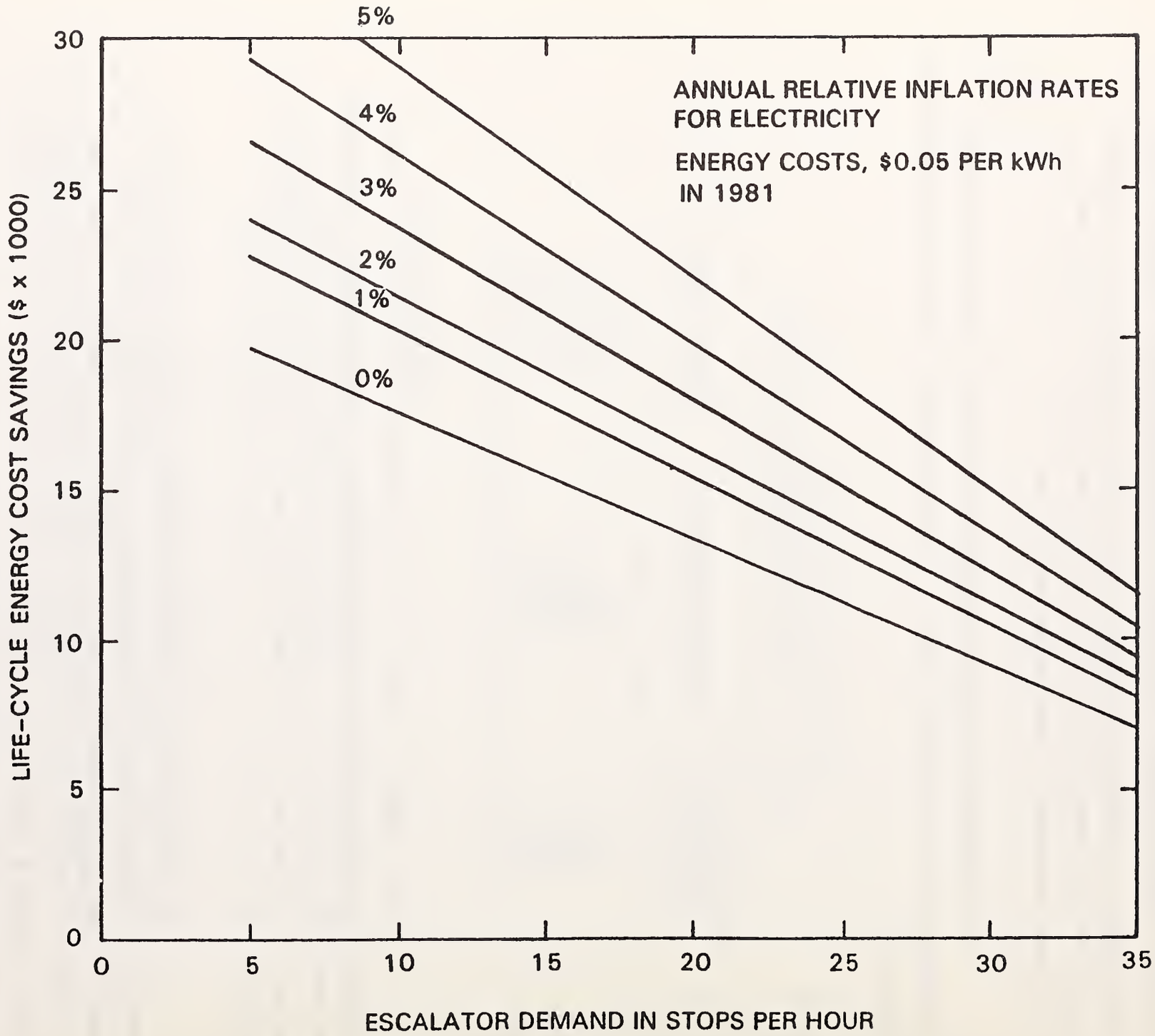

FIGURE 3-1. LIFE CYCLE ENERGY SAVINGS USING MAT OPERATION

data also show that the down escalator becomes regenerative for loads more than 10 passengers. OTIS (Ref. 5) test results show similarly that a load of 30 passengers travelling in the down direction provides sufficient regeneration to allow enough energy to power an escalator going up carrying five passengers. The calculations shown in this report are applicable for escalators operating in either direction.

Considering the possibility of lower component life resulting from cyclic fatigue, it appears that some of the wear on equipment can be offset by limiting the number of hourly starts (i.e., the escalator continues running for a period of time regardless of whether passengers are riding). NYCTA has found reasonable success in reducing component stress by limiting escalator starts to no more than 30 per hour (Refs. 1, 2). Though this is adequate for uni-directional operation, serious problems arise with multi-directional systems. CTA reported that passengers queued to use their dual directional systems were unwilling to wait in excess of 8 seconds (after a passenger deboarded) for a unit to stop and change direction (Ref. 1). This resulted in an extremely high number of maintenance calls since patrons would push the stop-start button hoping it would change the escalator's direction. High numbers of maintenance calls result in substantial labor costs.

A major conflict which recurs throughout the above discussion appears to be the problem of trying to conserve energy, lower installation and maintenance costs, and still provide optimum patron service. The best way to offset energy costs, and faster component degradation due to cycling, is to allow escalators to only experience a minimal number of starts. The two scenarios which meet this criteria are as follows:

- In stations with multiple escalators in each direction, operate escalators continuously in the desired direction only during peak usage hours and selectively shut escalators down during off-peak hours. This would accomplish several things:

  - No modification costs would be incurred for mat operation.
  - Additional mat system components such as mat switches, sensors and signs would not be required.
  - Energy would be conserved.

- Potential accelerated component degradation would be mitigated (i.e., cycling units on and off four times a day does not significantly affect component wear).
- By selectively shutting escalators down, stations can still meet patron demands (i.e., shutting low rise escalators down does not seriously inconvenience patrons; or, operating one of several high rise escalators can still handle the off-peak patron flow).

o It appears that the mat-operated applications should be limited to uni-directional mat-operated escalators at stations where patron flow is low. This would accomplish the following:

- Significantly reduce energy consumption.
- Cycle the components at a stress level perhaps lower than continuous operation (i.e., if the unit hardly operates it will experience a considerably longer life).
- Alleviate patrons pushing the stop button while waiting to board as might occur in bi-directional mode.

3.1.2 Safety of Mat Operated Escalators

As indicated earlier, the over 50 age group is affected largely by falls as related to escalator hazards. The two largest safety problems with mat-operated systems are (1) the hidden failures of the mat switches and photo sensors, and (2) the possibility that patrons can enter without being properly sensed by the system (Ref. 5). Some suggestions for mitigating hazards are as follows:

o Ensure soft stop (glide to stop) is incorporated to prevent sudden stop.

o Allow no deadspace where patrons may stand and not be sensed. This means that the pressure-sensitive mat must extend to the combplate, with photo sensors located in line with the step side edge of the combplate.

- Provide several system redundancies to insure operation on demand (i.e., several sets of mat switches connected with the photo sensors such that if the mat switches have failed, the photo sensor immediately activates the start switch).

- Signs must be designed to allow all important caution information to be seen by patrons (some having poor eyesight) in sufficient time to allow the right decision to be made (i.e., stop and wait, or proceed). Poor eyesight considerations might make an audible signal a viable addition to the signing.

The importance of resolving design hazards of mat operation cannot be emphasized enough. The number of potentials for injury which may result in lawsuits could offset energy cost savings to an even greater extent than yearly installation and maintenance costs.

3.2 Escalator Speed

3.2.1 Maintenance Aspects

It was stated in Chapter 2 that the general experience of the properties indicated greater wear on components such as bearings, step rollers, step chains, and drive belts. Wear on these components can be offset to a certain extent through (1) use of high quality lubricants, (2) either a lower interval between scheduled inspections and lubrication, or incorporation of an automatic lubricating system that is timed to lubricate each link as it passes (Refs. 6, 4). Experience suggests that maintenance costs on higher speed escalators are greater because (1) scheduled maintenance calls are made at a greater frequency, and (2) if scheduled maintenance is done at the same rate regardless of speed, parts will experience a higher wear out rate. Both of these scenarios will result in somewhat higher maintenance costs.

3.2.2 Safety Comparison

The choice of the 120 fpm speed over 90 fpm stems from properties wanting to increase the passenger carrying capacity of escalators. Empirical data gathered in this area indicates that the actual increase in load carrying capacity is very slight (only 12%) (Refs. 4, 5). In addition to this, accident rates (measured in yearly accidents per million passengers) gathered from properties using predominantly 120 fpm speeds are significantly higher than properties using 90 fpm speeds. Older properties such as NYCTA and PATH (operating at 90 fpm), incorporate stairs in the stations instead of escalators to a larger degree than newer properties such as BART or WMATA (operating at 120 fpm). Since passenger loading affects the accident rate greatly, a conservative estimate of 50% load factor was assumed for PATH (estimated by PATH officials) and 10% for NYCTA, and 100% usage for the newer properties. In a similar manner, it was extremely important to separate design related accidents from accidents caused by carelessness (such as running, or carrying heavy packages), or vandalism (such as children kicking the skirt and activating the skirt switches). This was done to the extent possible by noting the accident cause in the accident summaries. The final comparison is shown in Table 3-5.

TABLE 3-5. COMPARISON OF ACCIDENT RATES FOR PROPERTIES EMPLOYING 120 FPM and 90 FPM ESCALATORS (ACCIDENT DATA FROM BART, WMATA, NYCTA, AND PATH)

Transit Properties (yr)	Escalator Speed (fpm)	Avg. Yearly Accid. Rate (Accid./10^6 Passengers)		
		2-13	13-50	50 and over
WMATA (79)	120	2	12.2	13.9
BART (79-80)	120	3	8	13.7
NYCTA (78-79)	90	.35	.35	.30
PATH (77-78)	90	.3	.4	1.9

Table 3-5 shows that accident rates associated with 120 fpm operation are an order of magnitude higher than the 90 fpm rates. It is appropriate to note that, even though escalators compose the majority of station accidents, only a small percentage of escalator accidents actually result in serious injuries. The above conclusion should be interpreted as indicating that passengers have more problems in dealing with boarding and riding escalators operating at higher speeds. It appears appropriate to suggest that the 90 fpm speed is the best alternative for effecting a lower accident and injury rate in the selected "worst case" population, namely the older age group and the handicapped. This is adequate for low rise escalators (less than 40 ft high), but introduces a new problem on high rise escalators. A Hitachi escalator study (Ref. 12) suggests that high rise escalators operating at low speeds induce passengers to move while riding to cut down the ride time. This is not advisable since numerous accidents are caused by passengers accidently bumping other passengers. High rise escalators (over 40 ft high) thus require the higher speed with adequate number of flat steps to enhance safety.

3.3 Extended Flat Steps

3.3.1 Maintenance Aspects

As stated earlier, the addition of extra flat steps at both the top and bottom of escalators has a relatively benign effect on maintenance. The major effect is the possible increase in maintenance calls due to the step chain (either old or new step chains) tripping the lower carriage shut-off switch. This is due to excessive chain deflection, which is caused by the chain not being supported under passenger load for the length of the additional flat steps (Ref. 2). Nevertheless, existing experience suggests that this design feature does not present any appreciable maintenance problem.

3.3.2 Safety Impact

Additional flat steps provide patrons an extra measure of safety when boarding. This occurs through allowing more time to adjust balance before starting to rise or descend. As described earlier, given the coordination and balance degradation in the older age group, this is a feature worth considering. However, the cost of incorporating several extra flat steps is sizeable. Whether this is a reasonable investment or not was studied by first examining motor control and balance requirements in terms of the time required to become stable, and then determining how many flat steps were actually required to meet the time needed to gain station balance. Again, the older group and the handicapped are the key concern in choosing the safest configuration.

Studies done by the University of Texas at Arlington (Ref. 9) indicate that starting at age 50, there is an overall reduction in faculties. The results of these studies are summarized in Table 3-8. All of the affected faculties shown in Table 3-6 are used in boarding, riding, and exiting

TABLE 3-6. PERCENT REDUCTION IN MOTOR CONTROL AND STRENGTH AS A FUNCTION OF AGE (REF. 9)

Physical Faculty Affected	% Degradation in the 50 Yrs. & Over Age Group
Hand strength	21-23
Hand Force Control Steadiness	63
Hand Reaction Time	17
Hand Speed (tracking)	43-51
Overall Coordination	19.4
Foot Reaction	19
Foot Speed	24
Station Balance	32
Gait (with hand-arm aid)	18

escalators. This process can be modeled using a human engineering approach. Fruin (Ref. 11) demonstrates that the mean boarding time for the average non-handicapped person is approximately one second. This is the elapsed time required for a person to cross from the combplate onto the center of the first step. Considering the data from Table 3-6, an older person's foot speed time would then be 24% (0.24 seconds) slower. Since the escalator is traveling at constant speed, this delay can be transferred into distance. An escalator traveling at 120 fpm would travel 5.8 inches further before an older person would actually place his foot on the step. Since the center of the step is 7.8 inches from the edge, this distance puts the foot position very close to the step edge enhancing the chance for a fall. As faculties required to board an escalator are coupled together, we can assume a worst case condition in determining the time frame required to achieve balance. Stepping usually occurs before reaching, so the worst case would be the coupled effect of foot reaction, foot speed, and station balance. In speaking with individuals conducting research in physical motor control and response (Potvin, 1980), it appears that the foot reaction and foot speed response occur simultaneously, followed by station balance. Therefore, the actual lag time experienced by an older person stepping onto an escalator would only be the lag time in the foot speed (i.e., 0.24 seconds). This would be followed by the lag time in achieving station balance. Furthermore, the stepping sequence composes the majority of the total motion (approximately 70%), leaving the station balance to consume 30% of the total physical activity. Using the lag times shown in Table 3-6, and knowing that the average, non-handicapped person takes one second for the whole stepping and balance activity, the response time (RT) for an older person would be approximated as follows:

$$RT = 0.7\ (1) + (0.24\ (0.7)) + 0.3\ (1) + (0.3\ (0.32))$$
$$RT = 1.3 \text{ seconds.}$$

The total motor control time lag experienced by an older individual boarding an escalator would then be 1.3 seconds. Table 3-7 indicates the required number of flat steps to offset this total reduction in stepping and station balance ability by converting this total lag time into distance.

TABLE 3-7. CALCULATED NUMBER OF FLAT STEPS TO COMPENSATE FOR MOTOR CONTROL AND BALANCE REDUCTIONS

Escalator Speed (fpm)	Horizontal Distance Step Travels in 1.3 sec. (inches)	Equivalent Number of Flat Steps
90	23.4	1.5
120	31.2	2

The requirement to allow a higher boarding time for older passengers is validated by Fruin's study where boarding hesitation was observed with regular frequency in the general population (Ref. 11). This same consideration applies to handicapped patrons as well. Studies show that handicapped people with disabilities still enabling them to use transit systems, use these systems at the same rate as non-handicapped people (Refs. 10, 17). The time required to achieve station balance for these "worst case" populations is subsequently the major driver behind matching flat steps with speed. It should be noted that the design of extra flat steps at both the top and bottom landings of escalators can also be assisted by slightly increasing the track radius for the steps. The key point in either of these configurations is to allow the steps a greater horizontal travel before they start to rise. In addition to the extended flat steps, it is advisable that steps be properly delineated to assist patrons in gaining station balance. Demarcation strips and foot markings provide patrons with a rapid means of differentiating between steps and also provide target positions for the feet to insure maximum balance.

SECTION 4

NEW PROPERTY CONCERNS

One of the tasks associated with this project was to delineate the concerns of new rail transit properties regarding the special design features. At least two properties, Miami and Baltimore, are in the process of buying the first set of escalators for their systems. Baltimore has selected the contractor, but no escalators have yet been installed. At Miami, the Requests for Proposals were issued in December, 1980, but no contractor had been chosen as of January, 1981.

4.1 Summary of Specifications

A summary of the specifications of special design features evaluated in this document, as used by both properties, is summarized in Table 4-1.

TABLE 4-1. SPECIFICATIONS OF SPECIAL DESIGN FEATURES

Design Feature	Baltimore	Miami
Mat Operation	Not Specified	Not Specified
Speeds (fpm)	90-100	120
Flat Steps	h < 20', 1 Step h > 20', 3 Steps	h < 20', 1.5 Step h > 20', 3 Steps

In terms of the automatic escalator operation using mats, it appears neither properties considered the trade-off of potential energy savings and the maintenance cost associated with mat operation. Neither of the properties specified any control circuitry to be installed in case they desire automatic operation in the future. Most stations have at least two escalators each, so mat operation with the reversible feature has not been utilized.

Substantial differences of opinion exist, however, regarding the speed of escalators. Miami, after extensive deliberations, has apparently specified 120 fpm, whereas Baltimore has utilized the 90 fpm. The major criteria for the higher speed choice at Miami was the higher capacity associated with 120 fpm compared to 90 fpm. The Baltimore choice of the lower speed was due to a concern over accident frequency at the higher speed.

Both properties tended to agree on the use of three flat steps on escalators over 20 ft rise. The general feeling at both properties is that, due to the higher rise, patrons would be safer with more flat steps, allowing them time to adjust their balance on the escalator step.

4.2 Recommendations

The analysis contained herein suggests substantial energy savings associated with mat operation and this capability should be specified for future escalator procurements. Dual-speed escalators give the flexibility to match the demand and speed. In the long run, properties utilizing dual-speed operation of escalators will realize improved safety, efficient traffic flow, and lower operating and maintenance costs compared to operating at either speed of 90 fpm or 120 fpm for low rise escalators. High rise escalators should be designed for the 120 fpm speed.

SECTION 5

FINDINGS AND RECOMMENDATIONS

5.1 Findings

5.1.1 Mat Operated Escalators

The analysis conducted in this study shows that the use of mat operation is desirable in saving energy and reducing energy costs. Safety of existing mat-operated designs can be improved considerably by utilizing fail-safe designs. For example, the failure of a mat switch, should it occur during operation, should result in a gradual stop. The failure of a mat switch in uni-directional operation should result in a continuous operation. Redundant patron sensing devices should be used. In addition, there should be no deadspace where a patron could stand and not be sensed; and, proper visual (and auditory) caution signals should be provided.

The bi-directional escalator design is suited for a low demand station (less than 20 starts per hour) because of the large savings in capital cost of avoiding the use of an additional escalator. Safety in mat operation should be assured; for example, the bi-directional design should eliminate the potential for a patron to enter onto an escalator moving in the opposite direction.

5.1.2 Escalator Speed

Most U.S. rail transit properties utilize escalators which are limited to one of the two operating speeds, 90 fpm or 120 fpm. The use of dual-speed escalators with an operating policy resulting in 120 fpm during the peak hours and 90 fpm during the off-peak hours results in maximizing escalator energy efficiency. Off-peak operation at the lower speed reduces the energy consumed and results in less wear on the mechanical components. In addition, the desired higher speed is available at peak hours. The advantages

of dual-speed escalators generally outweigh the increased additional capital cost for dual-speed operation.

The analysis in this study has shown a higher maintenance cost and accident involvement rate at the higher speed. Detailed analysis of these data to identify whether these accidents occurred during peak or off-peak hours was not possible. But, off-peak operation at the lower speed would be expected to substantially reduce this accident rate and maintenance cost.

As pointed out in the report, high-rise escalators should generally operate at the higher speed to reduce passenger movement on the escalator. A large segment of the population shows a tolerance of rides up to 45 seconds (Ref. 8) before passenger movement begins and results in a hazardous environment.

5.1.3 Extended Flat Steps

The human factors engineering analysis in this study has shown the relationship between the minimum number of flat steps and the escalator speed. Extending flat steps, or increasing the track radius, is justified by the improvement in safety. The effects on maintenance costs of this design feature are minimal.

Extending the flat steps substantially more than the minimum shown in this study may be justified for high-rise escalators to increase the safety of the escalators. This has to do more with controlling the vertigo sensation, a feeling of disorientation often induced when standing on a steep incline.

5.2 Recommendations for Further Analysis

The analysis shown in this study is definitive on at least two aspects of the special design features that were evaluated. The uni-directional, mat-operated escalator saves energy and operating costs. The minimum number of flat steps corresponding to the two escalator speeds has been conservatively established. There are uncertainties in the design

feature associated with escalator speed with regard to both hourly carrying capacity and maintenance costs. Also unresolved in our analysis was the extent of annual maintenance costs associated with mat operation.

To get more definitive guidelines in these unresolved areas, we recommend the following studies to collect additional data and disseminate information among the transit properties.

5.2.1 Mat Operated Escalator Study

The cost effectiveness of uni-directional mat operation can be soundly established by conducting a study over a period of at least a year which would compare both energy consumption between continuous and mat operation as well as maintenance costs associated with them. The mat design feature for this study should be selected after an extensive survey of existing equipment in use.

The year-long study would provide sufficient data for comparisons of maintenance costs associated with mat operation and continuous operation. Analysis of accident records should help establish additional safety criteria for future implementation.

It is understood that cyclic stresses may affect the life of several of the rotating components subjected to intermittent loading. A study to establish this effect would be of a long-term nature and could be conducted at some future date after mat operation is extensively used in rail transit systems.

5.2.2 Escalator Speed Study

A controlled study is necessary to firmly establish the hourly capacity of escalators, impact of speed on maintenance, and safety of higher speed (120 fpm) operation of escalators. The hourly capacity could be easily established by comparing traffic flows under both speeds. The accident and maintenance data should be collected for at least a year to determine the safety and costs associated with the higher speed.

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APPENDIX A

Report of New Technology

This study evaluated the effectiveness of special design features associated with escalators used in rail transit systems. Results of the study can be utilized by transit properties to choose the appropriate design features in escalator procurements. A methodology was developed to estimate the minimum number of flat steps for an escalator based on its speed.

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