1. Introduction

1.1 Background Information

Over the years the escalator industry and the National Elevator Industry, Inc. (NEII) have worked toward reducing escalator entrapments between the steps and the skirt (side) panels of moving escalators. To reduce step/skirt entrapments, the ASME (American Society for Mechanical Engineers) A17.1-1996 [1] specifies the following requirements relative to the step/skirt interface:

- Step/skirt clearance to be no greater than 3/16" on either side
- Skirt panel to deflect no more than 1/16" @ 150 lbf load
- Exposed skirt panel surfaces to be smooth and made of a low friction material

At the time this study was commissioned, the industry lacked a standard methodology and the necessary tools to assess this entrapment potential. A performance standard would provide a common measurement metric to evaluate the relative entrapment potential of escalators in the field.

As a result, NEII decided to conduct a comprehensive study to assist in developing proposed technical revisions that could be submitted to the ASME A17 Committee. NEII contracted Arthur D. Little, Inc. (ADL) to help develop a standard test method for evaluating the potential for entrapment between the steps and the skirt (side) panels of moving escalators.

Arthur D. Little conducted a preliminary assignment (April 1997 to June 1998) to develop an understanding of the step/skirt entrapment process and the parameters that contribute to this process. The results of that assignment were summarized in a report, "Escalator Step/Skirt Performance Study," dated July 2, 1998. [2]. This report supercedes the July 2, 1998 report.

1.1.1 Program Objective

The primary objective for this assignment was to develop a step/skirt performance standard based on the potential for step/skirt entrapments. This index (i.e., a measurable quantity) would also provide a means of evaluating escalators. In addition, Arthur D. Little identified several other tasks necessary to support the primary objective. As a result, ADL completed the following objectives:

- Identified and summarized common accident scenarios involving step/skirt.
- Determined escalator design parameters contributing to object entrapment in the step/skirt interface.
- Developed a Step/Skirt Index derived from laboratory tests to evaluate step/skirt entrapment potential.
- Correlated the Step/Skirt Index with both laboratory and in-field entrapments.
- Measured the Step/Skirt Index of four in-field escalators.
- Developed hardware and a procedure for in-field measurement of the step/skirt entrapment Index.

1.1.2 Program Approach

The overall program approach was based on reviewing step/skirt entrapment scenarios and escalator designs, conducting laboratory entrapment tests, deriving a Step/Skirt Index, and correlating the Index with entrapment potential in the laboratory and in the field. In addition, a measurement protocol, inspection tool requirements, and concepts for inspection tools were developed as input to the recommended step/skirt performance standard. This program approach is summarized in Figure 1-1.

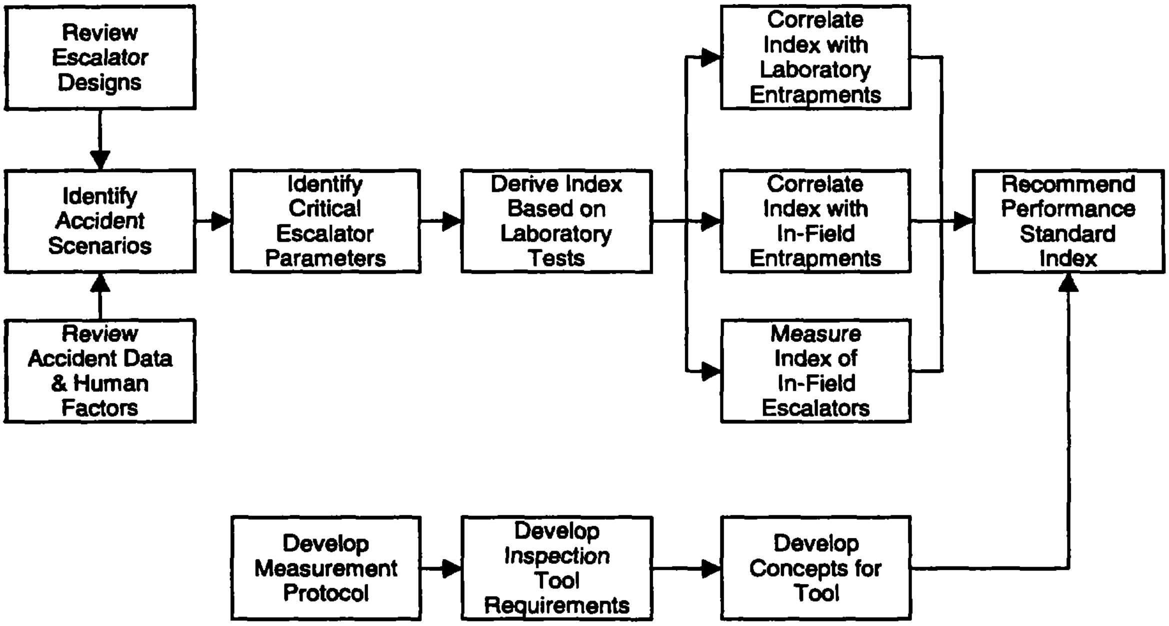


Figure 1-1: Program approach

Numerous meetings were held with members of NEII and with the US Consumer Product Safety Commission (CPSC) staff to provide periodic progress updates.

1.2 Accident Scenarios Investigated

Accident scenario development required understanding two fundamental factors: the manner in which a given escalator is ridden and the condition of that escalator. Both these factors contribute to the likelihood of a step/skirt entrapment. Consequently, ADL recognized the importance of understanding how accidents occur from the perspective of human-machine interaction. Human factors data were collected from NEII members, local and federal government reports, a literature search, and a human interaction study conducted by ADL.

1.2.1 Step/Skirt Incidence Considerations

ADL examined the following documentation for relevance to step/skirt entrapment:

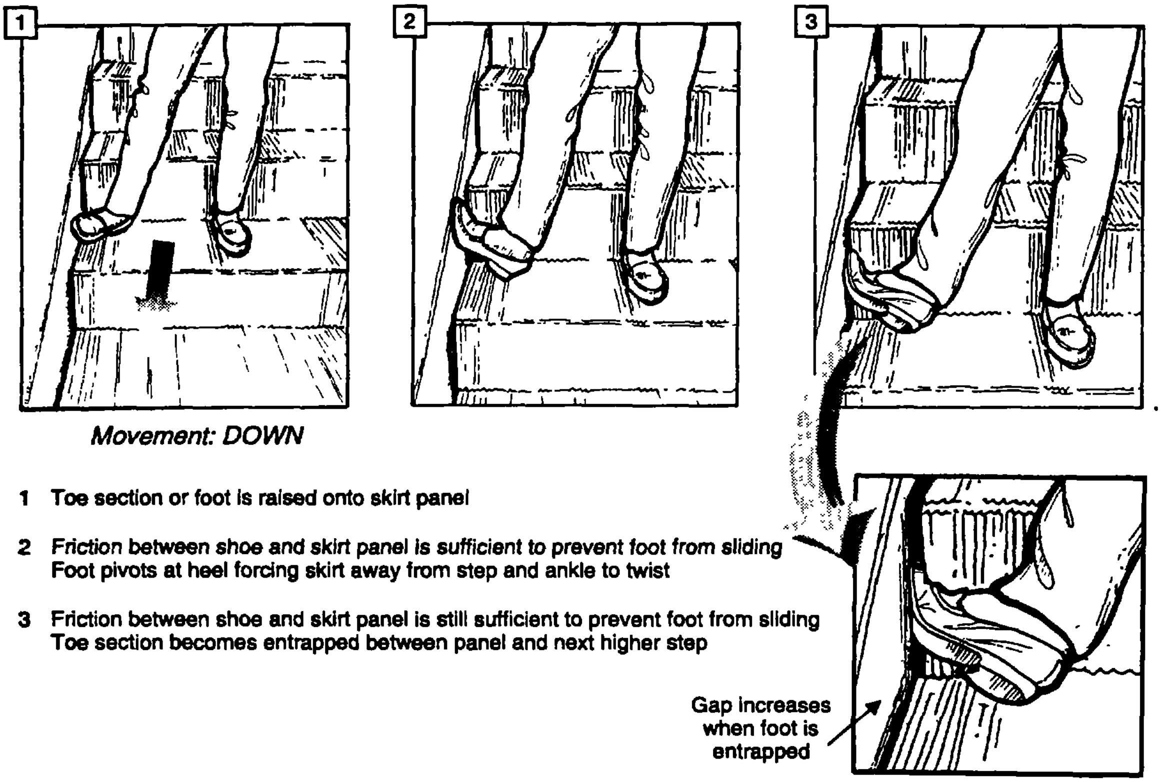
- Information supplied by several escalator manufacturers
- Data supplied by the US Consumer Product Safety Commission [3]
  - National Electronic Injury Surveillance System (NEISS)
  - Injury or Potential Injury Incident File (IPII)
  - Death Certificate File (DCRT)
  - In-Depth Investigation File (INDP)
- Records maintained by the State of Massachusetts Department of Public Safety
- Literature search conducted by ADL

The above information was useful in furthering a general understanding of escalator accidents.

1.2.2 Human Factors Considerations

Building on previous discussions with the manufacturers, ADL conducted an escalator field investigation to define human interaction with the step/skirt interface during an accident. This investigation took place within the Boston metro area subway system.

ADL visited several escalator units at different stations within the subway system. A stopped unit was examined at Porter Square station (Cambridge, MA) where ADL simulated and photographed possible step/skirt accident scenarios using project participants and passersby as models. The photographs were used as a baseline to illustrate several accident scenarios, illustrated in Figures 1-2 through 1-5.



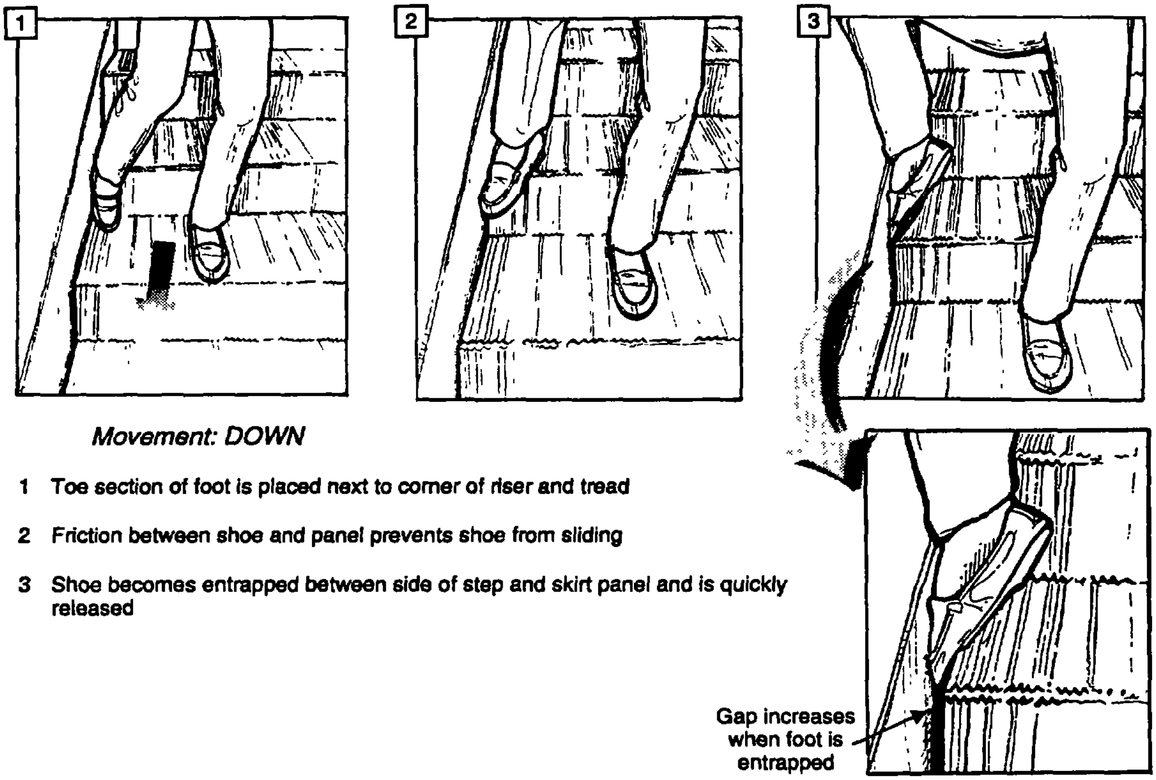
Movement: DOWN

1 Toe section or foot is raised onto skirt panel

2 *Friction between shoe and skirt panel is sufficient to prevent foot from sliding*
Foot pivots at heel forcing skirt away from step and ankle to twist

3 Friction between shoe and skirt panel is still sufficient to prevent foot from sliding
Toe section becomes entrapped between panel and next higher step

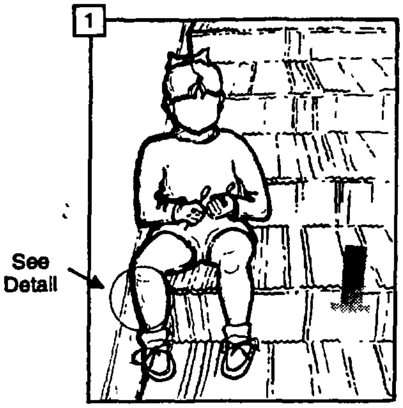
Figure 1-2: Foot and toe entrapment scenario for a down escalator



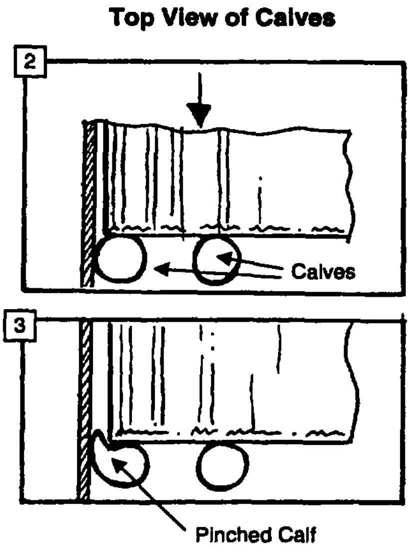
Movement: DOWN

1. Toe section of foot is placed next to corner of riser and tread
2. Friction between shoe and panel prevents shoe from sliding
3. Shoe becomes entrapped between side of step and skirt panel and is quickly released

Figure 1-3: Toe entrapment and release scenario for a down escalator



Movement: DOWN

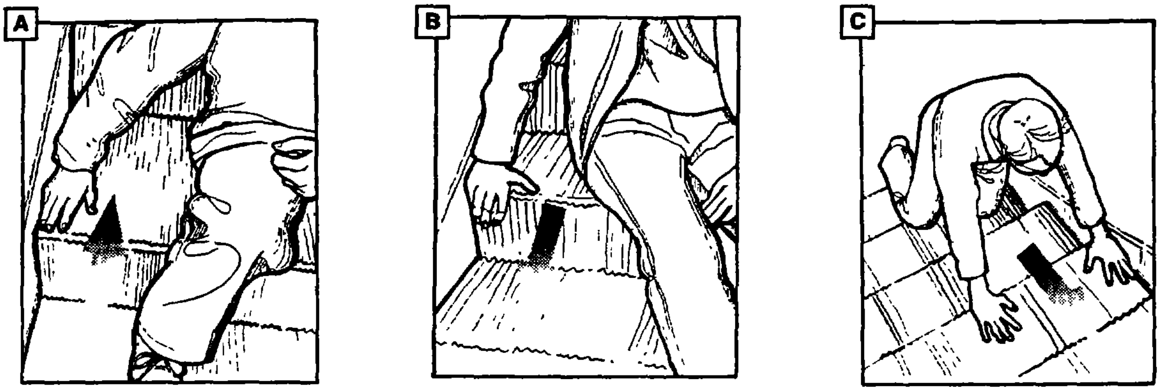


1 Child backs up and stands or sits too close to step immediately behind him/her such that calf is in contact with riser portion of that step

2 Friction between calf and skirt panel is sufficient to prevent calf from sliding on the panel

3 Calf becomes entrapped between riser and skirt panel

Figure 1-4: Calf entrapment scenario for a down escalator



Movement: UP *Movement: DOWN* *Movement: UP*

A Child sits on step and hand/forearm/thigh is placed on step next to gap (or finger in gap)

B Child sits on step and hand/forearm/thigh is placed on riser next to gap

C Adult falls and finger/hand/forearm/thigh or arm land next to step riser and skirt panel

C1 Friction between hand/forearm/thigh and skirt panel is sufficient to prevent hand from sliding on the panel. In case of a finger, the friction between finger and skirt panel is larger than the friction between finger and step

C2 Hand/forearm/thigh becomes entrapped between step tread and skirt panel. For the down direction, the fingers are entrapped between the step riser and the skirt panel.

Figure 1-5: Hand and finger entrapment scenarios for both escalator directions

1.2.3 Accident Scenario Summary

Table 1-1 identified in ADL's Human Factors Study [2] summarizes the most likely accident scenarios that could occur at the step/skirt interface.

Accident Scenario	Direction	Entrapment Interface	See Figure
Foot/Toe Entrapment	Down	Riser/Skirt Panel	1-2
Toe Entrapment/Release	Down	Riser/Skirt Panel	1-3
Calf Entrapment	Down	Riser/Skirt Panel	1-4
Hand/Finger Entrapment (Subject Sitting)	Up	Tread/Skirt Panel	1-5
Hand/Finger Entrapment (Subject Sitting)	Down	Riser/Skirt Panel	1-5
Hand/Finger Entrapment (Subject Kneeling)	Up	Tread/Skirt Panel	1-5
Note: The investigation focused on limb entrapment and did not consider the possible entrapment of shoe laces, clothing or hair			

Table 1-1: Summary of accident scenarios

1.3 Mechanics of Entrapment

Characterizing the mechanics of step/skirt panel entrapment is a major factor in determining which escalator parameters contribute to the entrapment process. This process involved understanding the analytical requirements for each of the developed scenarios, understanding escalator designs, and performing an appropriate mechanical analysis. The objective of the analysis was to focus on the initiation of entrapment rather than the mechanics after entrapment has already occurred. The details of the entrapment process itself (when an object was already in the gap) were not germane to the primary goals of this assignment. The primary goal was to understand how to prevent initiation and identify escalator parameters contributing to entrapment.

The mechanics of entrapment analyses identified some fundamental parameters that govern the initiation of entrapment. The results are summarized below:

- The coefficient of friction (COF or μ) between the object and the skirt panel is a key parameter that leads to entrapment initiation.
- The skirt panel stiffness and the step lateral stiffness contribute to gap size changes under load.
- The step deadband (free side-to-side motion) also contributes to the overall gap size.
- A "loaded gap" (gap dimension under load) term was introduced to account for the step lateral stiffness, the step deadband, and the skirt panel stiffness.

A summary of the mechanics of entrapment analyses is presented below.

1.3.1 Escalator Design Considerations

Illustrations provided by NEII highlight the components most often found in escalators. Although the actual design may vary for each escalator type, these components represent the major components that impact the step/skirt interface. The following analyses were based on this generic escalator design. (See Figure 1-6)

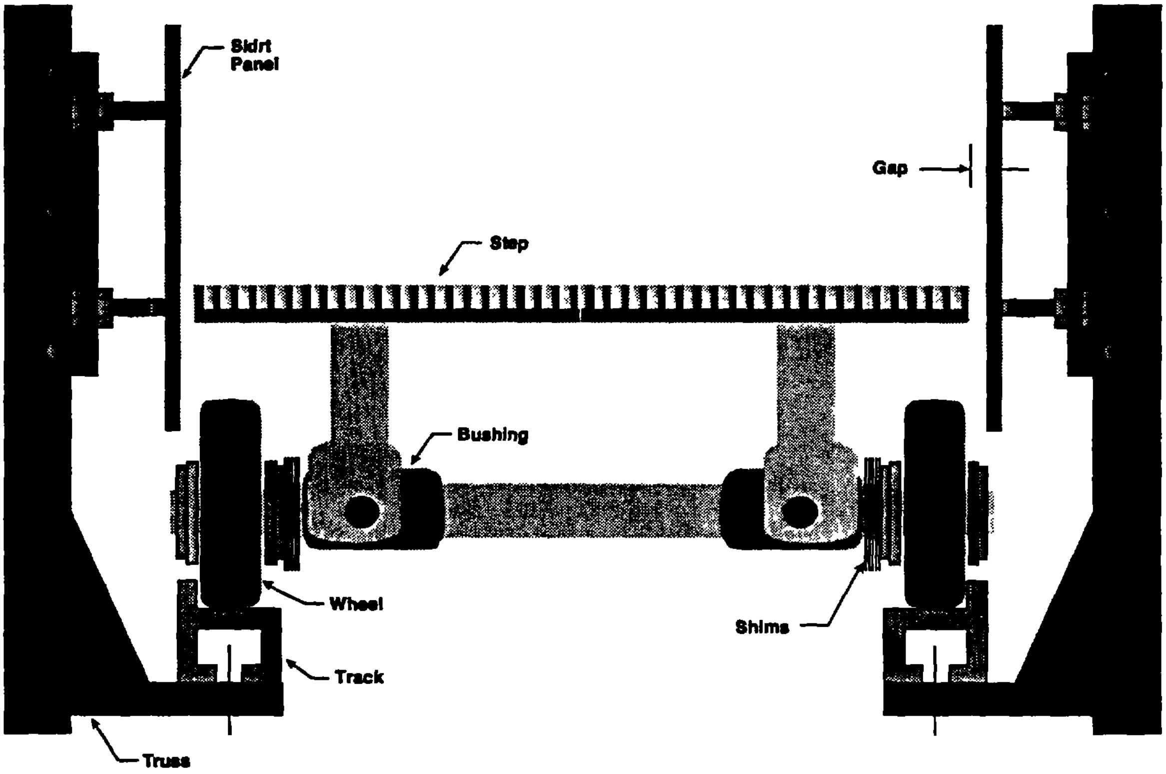


Figure 1-6: Escalator cross sectional view

Based on discussions with escalator manufacturers and a limited review of escalator designs, sources of gap variation were identified and are illustrated in Figure 1-7.

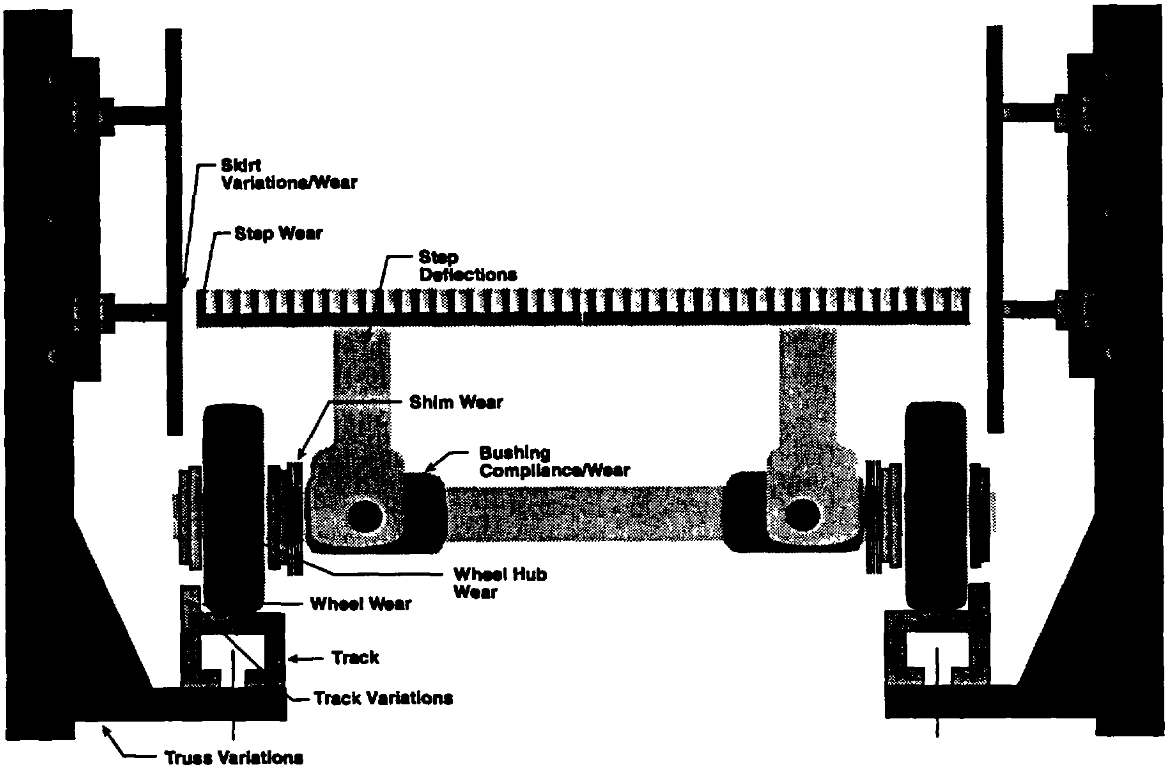


Figure 1-7: Step/skirt gap variation sources

These gap variation sources can be grouped as side panel, step, or truss. The following options tree (Figure 1-8) provides a roadmap of this grouping.

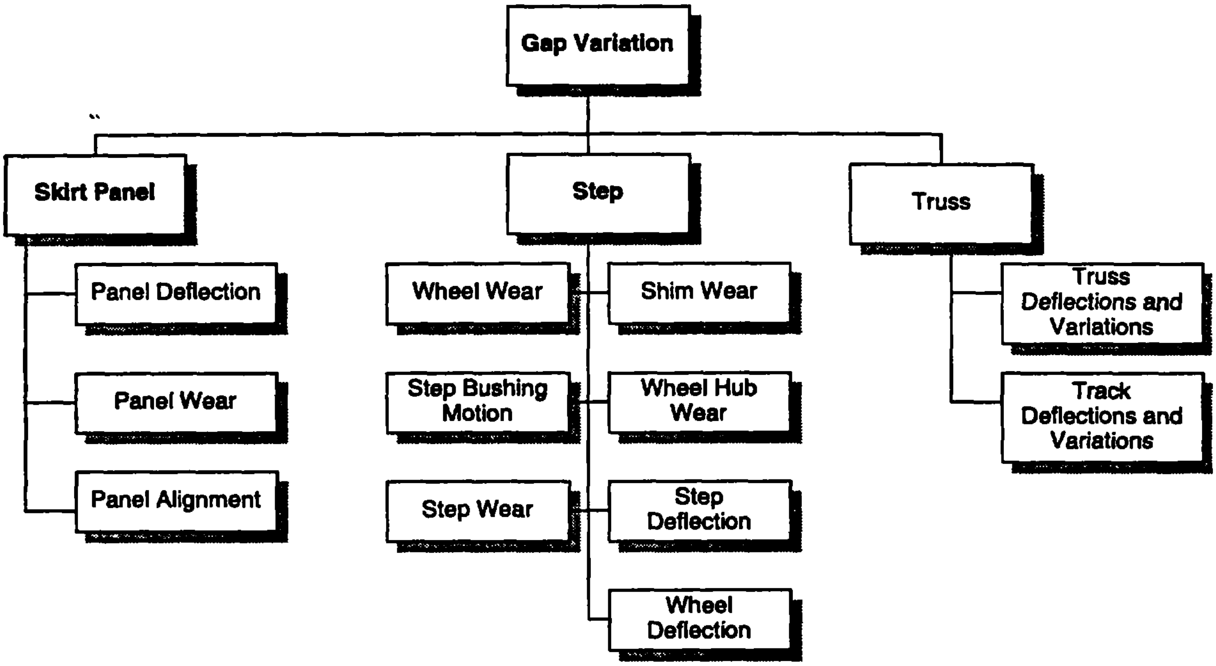


Figure 1-8: Factors in gap variation

It is clear that not all of these variations are of equal magnitude. Additional discussions with manufacturers and review of a lumped mass modeling approach revealed that the major contributors to the mechanics analysis should include the following variables:

- *Gap* consisting of nominal gap, skirt panel variations, truss variations, and worn components
- *Skirt panel stiffness*
- *Step lateral stiffness* consisting of track, truss, and wheel/components
- *Coefficient of friction* between the object and the skirt panel

1.3.2 Entrapment Analysis

In order to analyze the entrapment initiation potential for each scenario and to determine the escalator parameters responsible for this initiation, it was necessary to define the entrapment analysis problem at the outset.

Entrapment Analysis Definition. The three major entrapment scenarios considered were foot/toe entrapment, calf entrapment, and hand/finger/forearm/thigh entrapment. Although these scenarios involve different parts of the body, the required analyses are similar. Figure 1-9 shows that in each scenario a body part is placed on the skirt panel, and a friction force is generated which is large enough to decelerate the body part or actually stop the body part from sliding. Then entrapment initiation may occur.

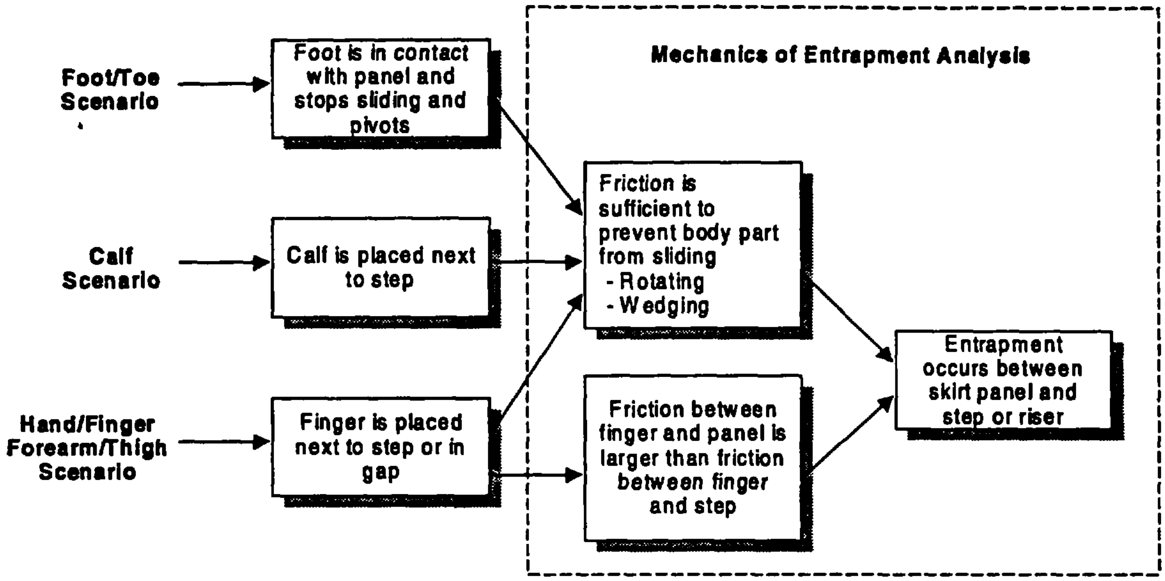


Figure 1-9: Entrapment analysis definition

The two resulting conditions are object rotating into the gap and object wedging into the gap. The condition for a body part inside the gap was not evaluated since the assumption was made that the gap would be made small enough to prevent "casual" placement of a body part in the gap. The two conditions analyzed are illustrated in Figure 1-10.

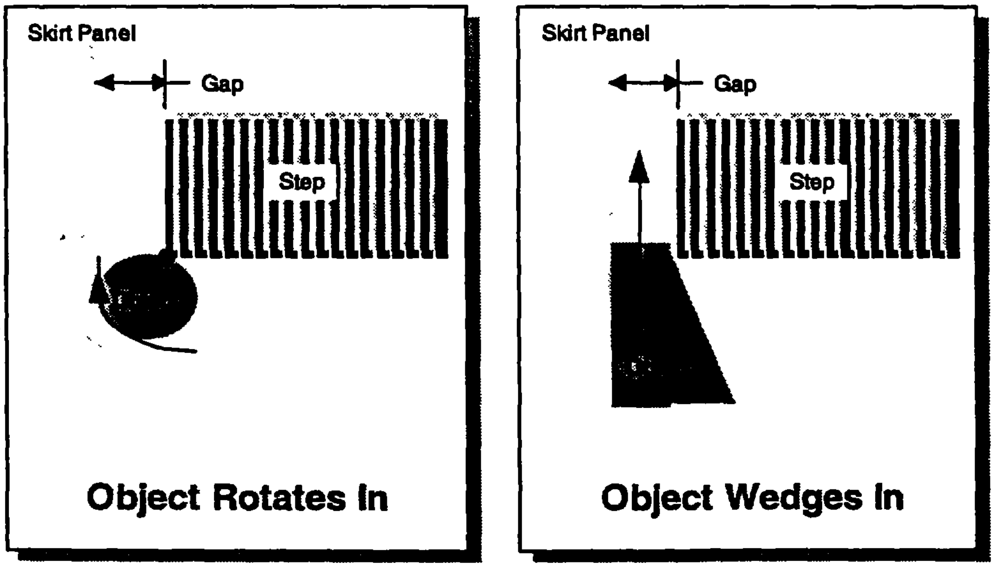
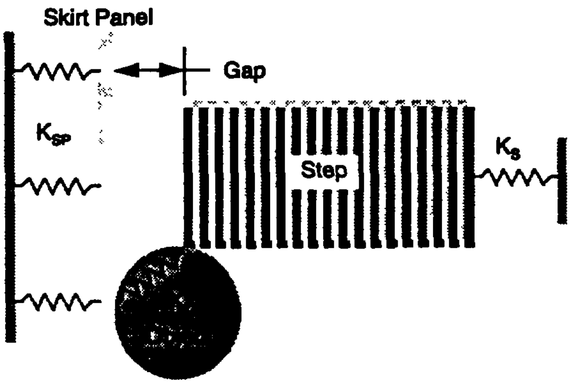


Figure 1-10: Entrapment diagrams (plan view)

The entrapment analysis was based on a lumped mass approach. Given the above escalator design considerations highlighting which parameters should be included in the analysis, the following system diagram was generated for an object rotating into the gap:



where:

Gap = *f* (variations, deflections)

variations include:
- component locations
- worn components
- track and truss

deflections include:
- panel
- track and truss
- wheel

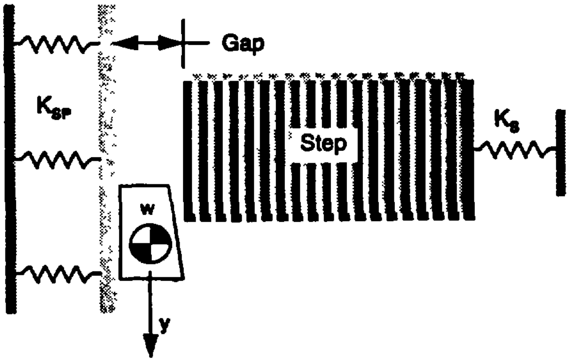
and

K_s = lateral step stiffness (this is combination of all step support components such as wheels, collars, shims, springs, etc.)

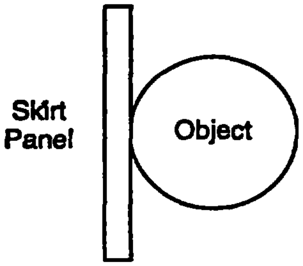
K_{SP} = skirt panel stiffness

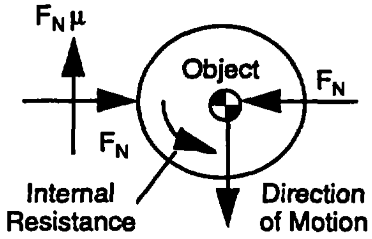
K_o = object stiffness

For an object wedging into the gap, a similar system diagram was generated.



Coefficient of Friction Considerations**.** Determination of the parameter relationships for a rotating object requires evaluation of a free body diagram as illustrated below:





By considering the equilibrium equations about the center point of the object, the rotational acceleration can be expressed as:

$$F_N \mu \text{ (Radius)} - T_{\text{Internal}} = I\theta'' \tag{1}$$

where: T_{internal} is the resisting torque
I is the inertia
θ'' is the angular acceleration
F_N is the normal force
μ is the coefficient of friction

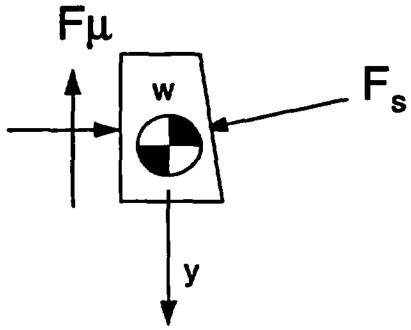
When the left side of this equation is greater than 0, then the object no longer slides—it sticks or chatters on the skirt panel. Therefore, for the object to continue slipping,

$$F_N \mu \text{ (Radius)} < T_{\text{internal}} \tag{2}$$

or

$$\mu < \frac{T_{\text{Internal}}}{F_N \text{(Radius)}} \tag{3}$$

T_{Internal} will vary based on various body parts and individuals. Thus, experimentation is required to understand the range for μ. Similarly, for an object wedging into the gap, a free body diagram helps determine the coefficient of friction relationships.



The equations of motion yield:

$$\Sigma F = my'' \tag{4}$$

or

$$F_S \sin\theta - F_S \cos\theta\, \mu = my'' \tag{5}$$

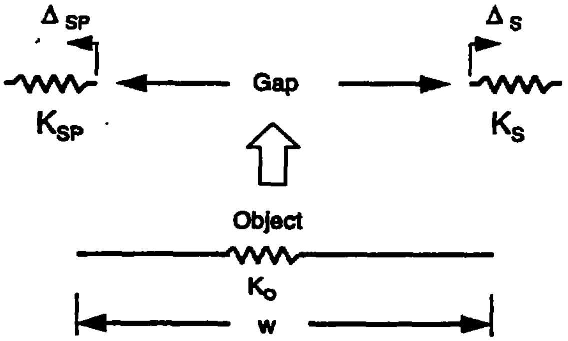
where:

μ is the coefficient of friction
F_s is the normal force on the surface of the wedge
y'' is the wedge acceleration
θ is the angle of the wedge surface

Wedging begins when $y'' < 0$. Thus, for the object to continue slipping (and not wedge)

$$\mu \leq \tan\theta \tag{6}$$

Compliance Analysis. A compliance (or stiffness) analysis can be used to theoretically estimate the forces imparted to the object during an entrapment event.



where:
o = object
s = step
sp = skirt panel
w = free width of object

Thus, the force equations are:

$$w - Gap = \Delta_o + \Delta_s + \Delta_{sp} \tag{7}$$

and

$$F_i = K_i \Delta_i \qquad (8)$$

Combining these two equations leads to the following compliance relationship:

$$w - \mathrm{Gap} = F\left[\frac{1}{K_O} + \frac{1}{K_S} + \frac{1}{K_{SP}}\right] \qquad (9)$$

Thus, the generated force can be determined, given values for w, gap, and the relevant stiffness. It is then possible to estimate the potential damage to an entrapped object. Although this equation implies that less damage is generated with more compliant systems (i.e., skirt panel or step stiffness is low), there are disadvantages to compliant systems, such as:

- Step stiffness is inherently non-linear.
  - Very low stiffness or even deadband may be present followed by very high stiffness.
  - Extremely low stiffness can exist due to deadband (free side-to-side motion) in the system.
  - Step stiffness may change as conveyor parts wear (making this measurement ideal for maintaining quality).
- Gaps can be enlarged.
  - A compliant system will allow larger gaps, promoting further entrapment and eventually increasing stiffness, resulting in high damage forces.

High lateral step stiffness allows the design of smaller gaps, thereby minimizing the size of entrapped objects and minimizing the likelihood of steps contacting the skirt panel.

Also, the first-order model for an object entrapped in the step/skirt gap shows that the object deflection is given by

$$\delta = w - G = F[1/K_{TOT}] \qquad (10)$$

where the reciprocal of the combined system stiffness is

$$[1/K_{TOT}] = [1/K_o + 1/K_s + 1/K_{sp}] \qquad (11)$$

In these expressions, w is the free object width, K_O is the object stiffness and F is the force generated. It is important to note that in the above equation, the object stiffness K_o is nonlinear in the case of human tissue.

2. Index Formulation

2.1 Overall Approach

The entrapment simulation tests described in [2] established that the step/skirt entrapment process could be observed under an array of experimentally controlled conditions in a laboratory setting. Although quite complex and clearly dependent on many escalator and object characteristics, it was demonstrated that the likelihood of step/skirt entrapment could be derived empirically using a statistically designed experiment.

By explicitly relating the likelihood of entrapment of test specimens to experimentally controlled escalator characteristics, a quantifiable index could be developed in a laboratory environment. Since the intent was to *induce* entrapments, test conditions were necessarily configured as extreme (i.e., severe, accelerated, high-stress) situations; that is, the placement of, and forces imposed on, test objects are considered quite rare and highly unlikely to occur in practice. However, test conditions characterizing escalator attributes (e.g., gap size, stiffness measures, etc.) were intended to be reasonably representative of field installations.

In order to derive and validate a Step/Skirt Index, the following tasks were performed:

- Laboratory entrapment experiments were designed, conducted and analyzed using a selected array of test specimens.
- The estimated likelihood of entrapment (i.e., the Index derived from test specimens) was compared to actual entrapment percentages observed when testing under severe conditions with objects shaped like body parts.
- Appropriate measurements were performed on field installations to demonstrate that the Index can be ascertained in an actual field-use environment.

Each of these tasks is described in the remainder of this section.

2.2 Laboratory Index Formulation Experiment

2.2.1 Objective

The primary objective of the laboratory index formulation experiment was to derive an explicit cause-and-effect functional relationship between measurable escalator characteristics and the occurrence of an entrapment in a controlled laboratory environment.

2.2.2 Approach

To achieve this objective, it was necessary to consider several fundamental issues; namely:

1. Identify *escalator characteristics* based on the mechanics of entrapment analysis that could be both measured in the field and experimentally controlled in the laboratory;

2. Specify *relevant ranges* and/or test levels for each characteristic identified in (1).
3. Select an array of *test specimens* (object size, shape, compliance, and imposed force) that adequately represented a wide array of entrapment scenarios.
4. Develop a *test protocol* for measuring and controlling key parameters.
5. *Design an experiment*; that is, select specific escalator/object combinations to test for entrapment.
6. Determine appropriate *measurements* to be compiled in each test run.
7. Prescribe sound *statistical procedures* to estimate a functional relationship between escalator characteristics and the observed number of entrapments; and
8. Establish an independent test procedure to *validate* the relationship derived in (7).

Each of these issues is described in greater detail in subsequent sections.

2.2.3 Experimental Considerations

Escalator Characteristics and Relevant Test Levels. Many variables were previously identified in the study of entrapment mechanics (described in Section 1.3) and in the conduct of preliminary laboratory testing [2]. As a result, the list of candidate variables and corresponding test levels depicted in Table 2-1 was prescribed for further investigation. Table 2-1 includes a brief description of the rationale for selecting each test level. The two different escalator designs (denoted as "A" and "B") represent laboratory units located at two different manufacturer facilities.

Variable	No. of Levels	Specific Test Levels	Rationale
Design	2	A B	Practical limitation and limited availability
Coefficient of Friction	3	Low Medium High	0.2 is the test escalator lower limit 0.5 is a mid-range value 0.8 is the practical upper limit
Step Stiffness	3	2000 lbf/in. 4000 lbf/in. 11000 lbf/in.	11000 is the practical upper limit 2000 was lowest achievable
Skirt Panel Stiffness	2	2400 lbf/in. 5000 lbf/in.	2400 is the present code minimum 5000 was the value at skirt panel support in preliminary lab testing
Step/Skirt Gap	3	1/16 in. 3/16 in. 3/8 in.	Test escalator lower limit Current A17.1 code A17.1 and A17.3 historical maximum
Travel Direction	1	Down	Test equipment facilitates down direction testing, and analytical model is independent of direction
Travel Speed	1	100 fpm	Will be A17.1 code value

Table 2-1: Escalator characteristics controlled in laboratory entrapment experiment

Test Specimens. The array of objects that were tested is given in Table 2-2. The circular object sizes were based on finger and calf sizes established in the human factors task [2]. The rectangular object sizes approximate the range of typical shoe sole thickness for children and adults. The wedge size is the same as that used in the preliminary laboratory entrapment simulation task [2].

The forces imposed on each object were calculated from observing actual test subjects exerting various forces in a variety of standing and sitting positions in a controlled laboratory environment. A statistical probability model[2] was then selected to characterize the human force measurement data. The model was then used to estimate a "one percentile" force; that is, a value that is likely to be exceeded only one percent of the time under similar experimental conditions. These one-percentile values are given in Table 2-2.

Simulated Scenario/Part Entrapped	Object Shape	Object Size	Object Force
Child Sitting (Finger)	Circular	¼" D x 3" Long	10 lbf
Adult Sitting (Finger)	Circular	¾" D x 3" Long	20 lbf
Child Sitting (Calf)	Circular	1-¼" D x 3" Long	25 lbf
Child Standing (Foot)	'Rectangular	¼" Th x 3" x 3"	20 lbf
Adult Standing (Foot)	Rectangular	½" Th x 3" x 3"	70 lbf
Adult Standing (Foot)	Rectangular	1 " Th x 3" x 3"	70 lbf
Preliminary Tests (Wedge)	Wedge	1 " Th x 20° Taper	53 lbf

Three object stiffness levels were tested (100, 1000, and/or 10,000 lbf/in.); these values are typical of body parts as determined in prior experimental work [2].

Table 2-2: Seven test specimens used in laboratory entrapment experiment

Test Protocol. The test procedure consisted of two preliminary steps. The first step involved an evaluation of the initial escalator parameters and an assessment of the modifications required to span the entire range of test levels given in Table 2-1. In the second step, an entrapment simulation was performed, whereby each test scenario was set up, and test sample specimens were run on the escalator. These two steps are described in greater detail below.

Test Apparatus. A portable test device was used for laboratory and in-field testing. The device consisted of a compressed nitrogen supply, two linear variable differential transformers (LVDT), a data acquisition system, and a pneumatic cylinder. A load cell was used to measure the normal force on the skirt panel. When required, an additional load cell was fitted to measure the frictional force on the test specimens. An on board data acquisition system collected sensor measurement data for download to a PC for analysis. A schematic of the test equipment is shown in Figure 2-1.

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[2] Extreme Value Probability Distribution described in Nelson[4]

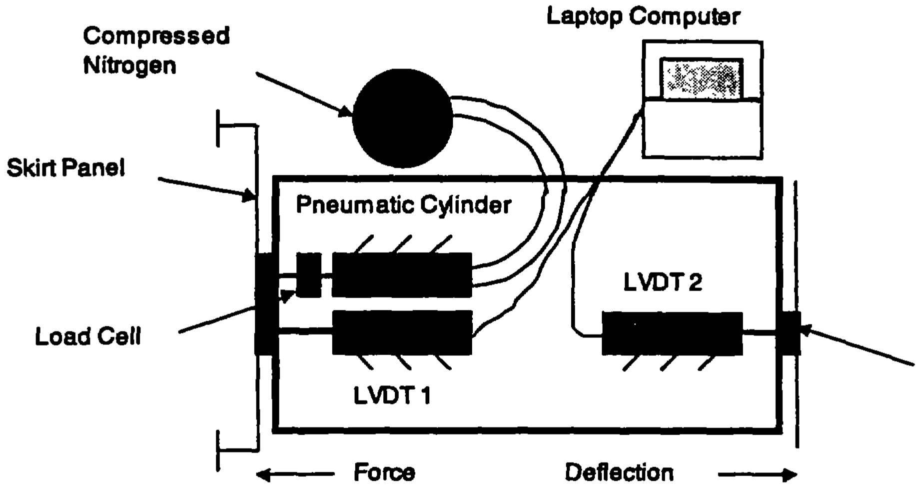

Figure 2-1: Test apparatus

Parameter Assessment

Coefficient of Friction. The initial COF value was measured using the test apparatus documented previously [2] and samples of all candidate test specimen materials. To assess COF consistency, COF profile data for each material were acquired for the length of the escalator skirt panel. Using the same test apparatus and a choice of lubricants, the COF values were modified as required by the test plan.

Skirt Panel Stiffness. The escalator design was reviewed to determine which points along the skirt panel offer the range of desired stiffness values. Using the test apparatus, a static load was applied to the skirt panel in 20 lbf increments up to 220 lbf. An LVDT measured the panel displacement and a load cell measured the applied load. Typically, rigid zones were located near the vertical structural members, while compliant zones were located at the mid-point between these members. If the measured values did not approximate the test plan targets, modifications to the escalator were made.

Step Stiffness. The initial step stiffness of the escalator was determined using the most rigid portion of the escalator structure for load reaction. A load was applied from the step to the skirt panel, and displacement was recorded using two LVDT's on the test apparatus, one LVDT located on each side of the step. The load was applied in 20 lbf increments up to 220 lbf. The value of the load applied and the difference between the two displacement readings yielded the step stiffness. Step stiffness was modified as required. Prior to the start of the test, the step deadband was removed by applying, then removing, a moderate load.

Step/Skirt Gap. The initial gap was measured with a feeler gauge. The gap was modified, as the test plan required, by physically changing the step position on its axle.

Object Properties. Object stiffness was assessed for different candidate materials at Arthur D. Little laboratories prior to testing. Materials were generally elastomeric. Shapes and sizes were prepared as required by the test plan prior to testing.

Entrapment Simulation

For each unique condition prescribed by the test plan, the escalator was modified as required. Changes made to the escalator were minimized between tests (for example, all tests requiring the same step stiffness were performed in succession). The following general steps were taken to conduct each entrapment simulation:

1. Prepare and test skirt panel surface and object material for desired COF value.
2. Determine location along skirt panel for desired skirt panel stiffness.
3. Modify and test step for desired step stiffness.
4. Modify and measure escalator for required gap.
5. Orient the test sample adjacent to the test step riser and apply the test load.
6. Begin escalator travel in the down direction.
7. Observer #1 detects if/when entrapment occurs.
8. Observer #2 determines entrapment location along the skirt panel.

Provisions were made to monitor object loading and gap variation throughout each test run.

Experimental Design. Inspection of Tables 2-1 and 2-2 reveals that there are 2,268 unique conditions or combinations that could have been tested (i.e., 7 object configurations, at each of 3 stiffness levels, could have been tested at each of 108 escalator variable settings). Since it was neither practical nor necessary to test all possible combinations, statistical experimental design principles were invoked to select an appropriate, scientifically sound subset to be tested.

Using procedures described in the statistical literature [5], a subset of only sixteen of the 108 possible escalator configurations was sufficient to achieve the experimental objective of identifying escalator variables that have a significant impact on the likelihood of entrapment. The test plan (known in statistical design of experiments as a Fractional Factorial Plan) is given in Table 2-3. Since actual test values were expected to (and subsequently did) vary somewhat from the target values appearing in Table 2-1, only general notation (L = low, M = medium, H = high) is used in Table 2-3 to categorize the test levels intended for each condition.

	Escalator Variables				Escalator/Object Interactive Variable
Test ID No.	Location (Design)	Step Stiffness	Skirt Stiffness	Gap	COF
1	A	L	L	H	L
2	A	M	L	M	H
3	A	H	H	M	M
4	A	M	H	L	M
5	A	M	L	M	M
6	A	L	L	L	M
7	A	M	H	H	H
8	A	H	H	M	L
9	B	H	L	L	H
10	B	M	L	M	L
11	B	L	H	M	M
12	B	M	H	H	M
13	B	M	L	M	M
14	B	H	L	H	M
15	B	M	H	L	L
16	B	L	H	M	H

Table 2-3: Experimental design (Fractional Factorial Plan)

Test Measurements. Prior to performing the experiment, the decision was made to test all seven objects at each of the sixteen escalator configurations given in Table 2-3. Furthermore, the intent was to replicate each trial and obtain two separate outcomes at each test condition. Due to practical constraints, each of the seven test specimens was configured and tested at the same object stiffness level, resulting in a total of 14 separate trials performed at each escalator configuration.

After completing the round of testing at the first selected location, it was noted that each repeat test yielded the same outcome (entrapment or no entrapment) in all but one of 52 replicate test conditions. Based on the high degree of repeatability observed in these entrapment outcomes, the decision was made to revise the plan at the second location. Instead of repeating the test run performed with each object, consideration of a wider array of potential object configurations would be more informative. This was accomplished by testing each of the seven test objects at two different stiffness levels, resulting, once again, in 14 separate trials being conducted at each escalator configuration. Subsequently, 32 test conditions were also replicated at the second location.

Object entrapment was determined visually. Most entrapments were clearly apparent. The objects had a frictional force large enough to draw the object into the gap, which then resulted in larger normal loads and larger frictional forces. This process continued until the escalator was stopped or the object, skirt panel, and lateral step stiffness was large enough to prevent any additional deflection. In most cases, the objects would have permanent deformation and markings of being entrapped.

2.2.4 Experimental Results and Data Analysis

Test Results. The outcome of each test run is summarized in Table 2-4. As indicated in the table footnotes, cell entries signify when the corresponding object was entrapped ("1") or not entrapped ("0"); two entries in the same cell indicate replicate test outcomes. A small number of combinations were not tested, in which case an ("x") appears in the cell. A total of 242 test runs were conducted; 158 were unique escalator/object trial configurations, and 84 of these were replicated.

Test ID No.[c]	Object Stiffness [illegible]	Shape Size Force[b]						
		Circular 0.25" 15	Circular 0.75" 20	Circular 1.25" 25	Rect. 0.25" 20	Rect. 0.5" 70	Rect. 1" 70	Wedge 20° 53
1	100	x	1, 1	0, 0	x	0, 0	0, 0	x
2	1000	1, 1	0, 0	0, 0	0, 0	0, 0	0, 0	1, 1
3	12000	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0
4	1000	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0
5	1000	1, 1	0, 0	1, 1	0, 0	0, 0	0, 0	0, 0
6	100	0, 0	1, 1	1, 0	0, 0	1, 1	0, 0	x
7	1000	1, 1	1, 1	1, 1	1, 1	0, 0	0, 0	1, 1
8	12000	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0
9	12000	0	0	0	0	0	0	x
9	100	0, 0	0, 0	0, 0	0, 0	0, 0	0, 0	x
10	12000	1	0	0	0	0	0	0
10	1000	1	0	0	0	0	0	0
11	12000	1	0	0	0	0	0	1
11	100	0	0	0	0	0	0	1
12	12000	1, 1	1, 1	0, 0	1, 1	0, 0	0, 0	x
12	1000	1, 1	0, 0	0, 0	1, 1	0, 0	0, 0	x
13	100	0	0	0	1	0	0	1
13	1000	0	0	0	0	0	0	0
14	1000	1, 1	0, 0	0, 0	1, 1	0, 0	0, 0	1, 1
14	12000	1, 1	0, 0	0, 0	1, 1	0, 0	0, 0	1, 1
15	12000	0	0	0	0	0	0	x
15	100	0	0	0	0	1	0	x
16	1000	0	0	0	1	0	0	1
16	12000	1	0	0	0	0	0	0

(a) "1" denotes object entrapment; "0" denotes no entrapment; "x" indicates no test performed.
(b) One-percentile lbf values derived from preliminary tests.
(c) Corresponds to experimental conditions depicted in Table 2-3.

Table 2-4: Object characteristics and test outcome of laboratory entrapment experiment

Entrapment outcomes were also demonstrated to be repeatable at the second test site. In all, 83 of the 84 repeat tests performed in the laboratory entrapment experiment yielded the same outcome; that is, entrapment occurred in both or neither of the two replicate test runs. Of the 242 individual test runs, 58 resulted in a step/skirt entrapment event. It should be emphasized that this entrapment percentage (24%) is relative to the severe entrapment-induced conditions imposed in a controlled laboratory setting. It should not be interpreted in an absolute (i.e., "real world" or in-field usage) sense; it is applicable to only (1) *these seven* test objects, (2) exposed to *this array of 16* test conditions, (3) at *these two* laboratory facilities, and (4) tested under *extreme* positioning *and severe* object force conditions.

Data Analysis. Experimental results were analyzed in several ways. Test outcomes were summarized separately for each escalator characteristic controlled in the experiment; summary results are displayed in Table 2-5.

Since no difference was observed in the percentage of entrapment events at the two test locations, there is experimental evidence of reproducibility at different laboratory environments (and, equivalently, for different escalator designs).

Variable	Test Level	# Tests	# Events	% Events
Location	A	104	25	24%
	B	138	33	24%
Step Stiffness	Low	48	13	27%
	Medium	120	33	28%
	High	74	12	16%
Skirt Panel Stiffness	Low	122	31	25%
	High	120	27	22%
Gap	Large	74	34	46%
	Medium	112	18	16%
	Small	56	6	11%
COF	High	60	17	28%
	Medium	134	36	27%
	Low	48	5	10%
All Test Runs		242	58	24%

Table 2-5: Tabulation of entrapment events

As indicated in Table 2-4, each test outcome was measured as a binary event; either entrapment occurred (the response variable = 1) or entrapment did not occur (the response variable = 0). A standard statistical technique known as Logistic Regression [6] is appropriate for analyzing binary response data. A Logistic Regression analysis yielded the following key results:

- Except for the two-level "Location" variable, all other escalator variables given in Table 2-3 yielded significantly different outcomes when varied over the levels controlled in the experiment.

- Analytical results are commonly expressed as "Odds Ratios;" for example, under the conditions considered in the laboratory entrapment experiment, a test object in a large (3/8") gap was approximately 11 times more likely to be entrapped than in a small (1/16") gap; the difference between a medium (3/16") and a small gap was not significant (i.e., the Odds Ratio was approximately 1). Odds Ratio estimates are given in Table 2-6.

Variable/Level	Odds Ratio[a]	Comment
Step Stiffness		
Low	8.9[b]	Compared to **High** stiffness Value
Medium	4.7	Compared to **High** stiffness Value
Skirt Panel Stiffness		
Low	3.0	Compared to **High** stiffness Value
Gap		
Large	11.2	Compared to **Small** gap size
Medium	1.3	(Medium not significantly different from Small)
COF		
High	7.3	Compared to **Low** COF
Medium	5.0	Compared to **Low** COF

[a] Odds Ratios are relative to the conditions imposed in the experiment; they are not applicable to actual field use environments.

[b] For example, the Low Step Stiffness setting (2,000 lbf) is 8.9 times more likely to yield a laboratory entrapment than the High Step Stiffness setting (11,000 lbf)

Table 2-6: Logistic regression results (Estimated Odds Ratios)

2.2.5 Derivation of Step/Skirt Index

As a final step in the analysis of the laboratory entrapment experimental data, a statistical model was derived to serve as a Step/Skirt Index measure. Here again, a Logistic Regression model was used to relate the occurrence or non-occurrence of test object entrapment to known escalator characteristics. This analysis involved a three-step process; namely:

1. Define specific independent variables that are presumed to influence the entrapment process;
2. Perform the analysis step; that is, use the experimental data to estimate the terms in the assumed (Logistic Regression) model; and
3. Test the derived model; determine whether or not the model adequately describes (or "explains") the data from which it is derived.

Independent Variables. Based on the findings presented in Section 2.2.4, the occurrence of entrapment was related to step stiffness, skirt panel stiffness, gap size, and coefficient of friction (COF). The first three variables are physically related, and a new variable (denoted as the "Loaded Gap") was introduced.

$$\textit{Loaded Gap} = \text{Gap}_{\text{initial}} + \frac{\text{Object Force}}{K_{\text{combined}}}$$

$$K_{\text{combined}} = \left[\frac{1}{K_{\text{skirtpanel}}} + \frac{1}{K_{\text{step}}} \right]^{-1}$$

where K represents the subscripted stiffness value.

Furthermore, as indicated in Table 2-7, entrapment was more likely to occur with the three smaller objects used in the experiment. Therefore, a qualitative term (called an indicator variable and defined in the bottom of Table 2-7) was included in the model.

Object Shape	Object Size	Force (#)	No. of Trials	No. of Entrapments	Percent Entrapments
Circular	ϕ ¼" x 3" long	15	35	18	51%
Circular	ϕ ¾" x 3" long	20	37	8	22%
Circular	ϕ 1¼ " x 3" long	25	37	5	14%
Rectangular	¼" x 3" x 3"	20	35	12	34%
Rectangular	½" x 3" x 3"	70	37	3	8%
Rectangular	1" x 3" x 3"	70	37	0	0%
Wedge	1" x 20°	53	24	12	50%

▨ defined as "small" objects (indicator variable = 1)
☐ defined as "large" objects (indicator variable = 0)

Table 2-7: Laboratory-induced entrapments by object

In summary, the analysis consisted of expressing in an explicit functional form the relationship between the occurrence of an entrapment and the COF, Loaded Gap, and Indicator variables.

Statistical Analysis. The data set contained 242 observations; each observation included an observed outcome ("1" if entrapment, "0" if not), along with the test conditions (i.e., COF, Loaded Gap, and Indicator values) at which each outcome was observed.

The actual data set used, and the analytical output [7] are given in the Appendix. Diagnostics given in the Appendix indicate model adequacy; that is, the model demonstrably "explains" the data. Results are summarized by the two mathematical expressions given below:

Regression Estimate

$$y = -6.26 + 2.37(\text{COF}) + 9.30\ (\text{Loaded Gap}) + 2.49(\text{Object Size})$$

Step/Skirt Index Calculation

$$\text{Index} = \frac{e^y}{e^y + 1}$$

The Index ranges between zero and one; lower values correspond to lower likelihood of an entrapment in the laboratory experiment. The three numerical examples given in Table 2-8 illustrate the calculation of the Index, and its relationship to test outcomes obtained in the experiment.

Test Object	Test ID No.	Location	Step Stiff-ness	Skirt Stiff-ness	Gap	COF	Loaded Gap	Indicator (size)	y	Index	No. of Tests	No. of Entrap-ments
0.25" Circular 15 lbf	6	A	2000	2300	1/16	0.6	0.08	1	-1.60	0.17	2	0
0.25" Circular 15 lbf	7	A	4000	5000	3/8	0.8	0.38	1	1.67	0.84	2	2
0.75" Circular 20 lbf	4	A	4000	5000	1/16	0.6	0.07	0	-4.18	0.02	2	0

Table 2-8: Calculation of Index (illustrative examples)

A graphical depiction of the Index is given in Figure 2-2.

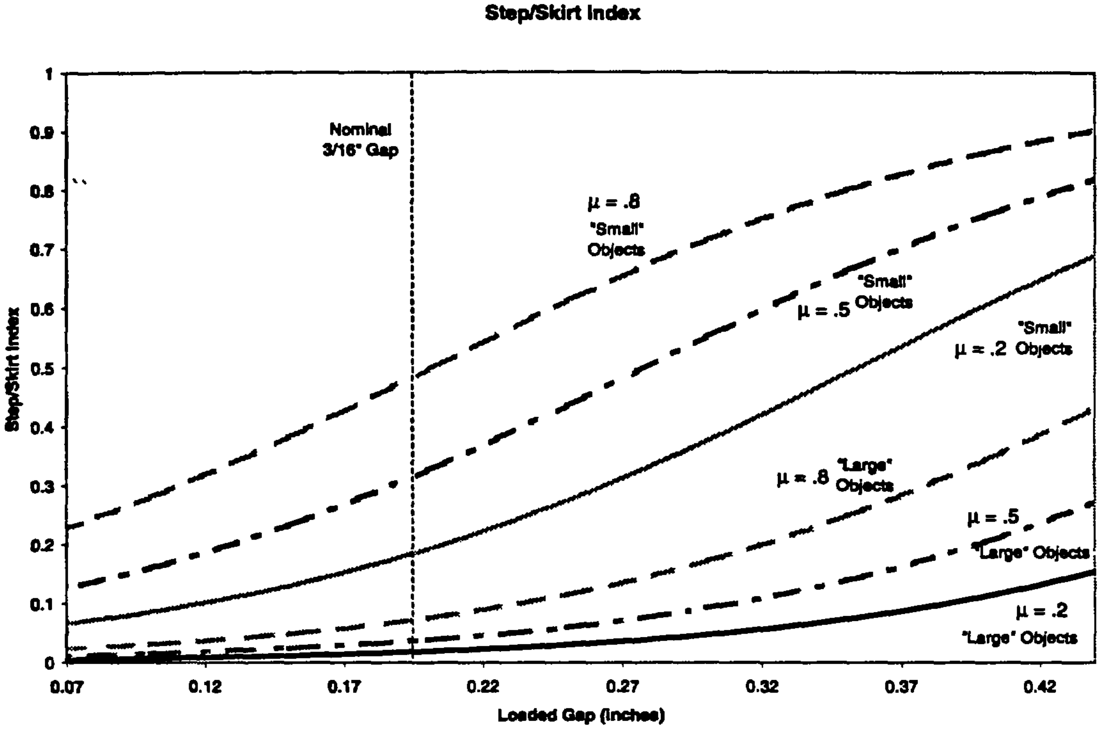

Figure 2-2: Step/Skirt Index

The ranges in the graph correspond to values included in the experiment. The dashed vertical line highlights the current code specification (gap not to exceed 3/16").

2.2.6 Index Sensitivity

A sensitivity study was conducted to determine how the derived Index responds to measurement noise (i.e., error). This study showed that the Index is more sensitive to measurement errors for larger Index values, with an expected precision of ± 5% for an Index of 0.2 and typical measurement accuracy. Figure 2-3 shows the error band.

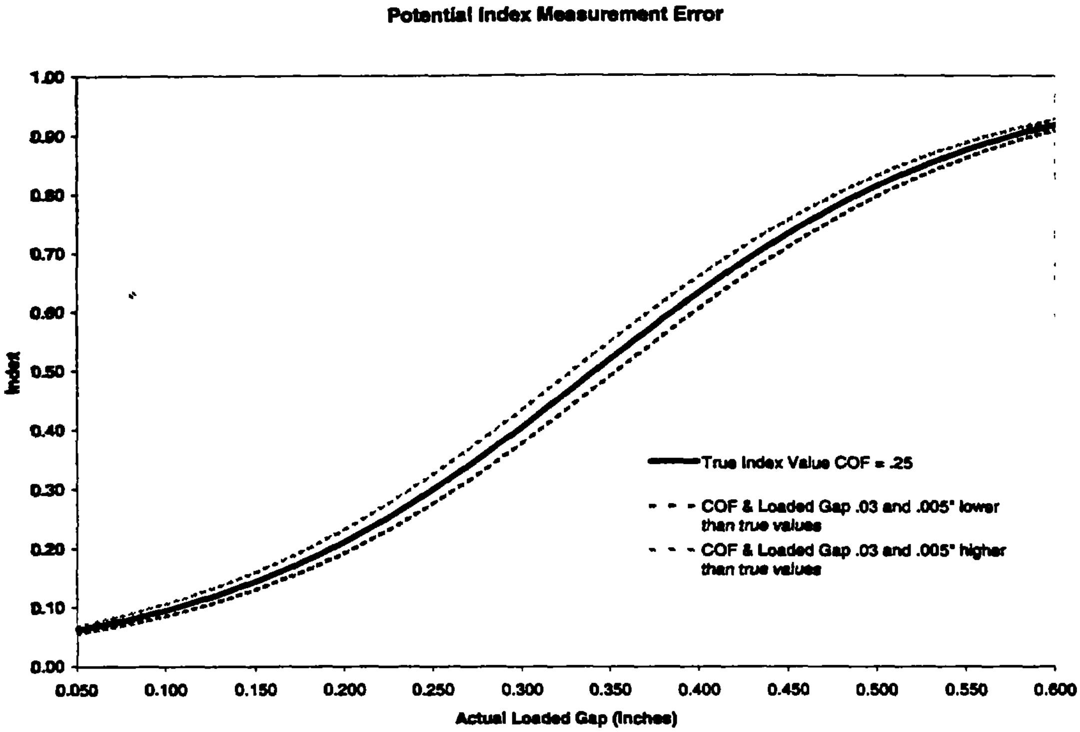

Figure 2-3: Index Sensitivty Study

The results indicate that for all parameters, except loaded gap, the Index "dampens" measurement error. Although loaded gap will impact the Index most, the loaded gap is also the measurement that can be executed with the most precision.

The sensitivity analysis also considered the impact of each parameter. This analysis was conducted for the following conditions:

Loaded gap = 0.20 inches
Force = 25 pounds
Stiffness = 800 pounds/inch
COF = 0.25
Index = 0.19

Parameter	% Change in Parameter	% Change in Index
Coefficient of Friction	1%	0.4%
Loaded Gap	1%	1.5%
Force	1%	0.2%
Stiffness	1%	0.2%

Table 2-9: Index Sensitivty Study

2.3 Step/Skirt Index Validation Test

2.3.1 Objective

As stated in Gunter [8], a model is essentially a framework with which to make predictions. The intended use of the Step/Skirt Index model is to classify escalators according to their relative resistance to the step/skirt entrapment hazard. Therefore, the objective of the validation tests was to demonstrate that the model performs as intended; that is, it predicts entrapment if/when an entrapment is likely to occur.

To do this, additional tests were conducted both in a laboratory environment and in the field for the purpose of validating the model by using replicas of actual body parts. The objective was to assess the predictive capability of the Index by correlating the Index to the likelihood of entrapment of objects that more closely resemble body parts.

2.3.2 Approach

The test was initially configured as outlined in Table 2-10. The coefficient of friction and loaded gap of the test escalator was controlled to yield a known, pre-determined Index level. The range of values considered is displayed in Table 2-11. For subsequent analytical purposes, the intent was to perform an equal number of tests in each of three non-overlapping Index level ranges; ranges were arbitrarily designated as low (Index < 0.2), medium (0.2 to 0.5) and high (> 0.5).

The plan was to test each of the seven object/scenario conditions within each of the three Index ranges; each of the 21 test runs would be repeated three times, yielding 63 outcomes in all. Results would then be tabulated within each Index range, and compared across the three ranges. Test results were anticipated to show that the highest percentage of entrapments would correspond to the highest Index range, and so forth.

Entrapment tests were conducted with artificial body parts. These parts were manufactured by Pacific Research Laboratories, Inc. (Sawbones) and consisted of individual polymer bones, foam representing muscle, and a separate foam layer representing skin. These parts were manufactured from molds made from castings of human parts. Some measurements in ADL laboratories showed that Sawbones parts have reasonably comparable compliance to human parts, but friction characteristics are higher than human skin.

Variable	No. of Levels	Value	Rationale
Step/Skirt Index	3	Low (< 0.2) Medium (0.2 to 0.5) High (> 0.5)	Based on escalator characteristic combinations as identified in Laboratory Entrapment Experiment
Real Object/ Object Force/ Scenario Combination	7	Adult foot/70 lbf/Foot/Toe Entrapment Adult foot/30 lbf/Toe Entrapment/Release Adult hand/20 lbf/Hand/Finger Entrapment Child foot/20 lbf//Foot/Toe Entrapment Child foot/20 lbf/ Toe Entrapment/Release Child calf/25 lbf/Calf Entrapment Child hand/15 lbf/ Hand/Finger Entrapment	Based on accident scenarios identified and outlined in Section 1.2

Table 2-10: Index validation test conditions

Escalator Variable (Units)	Range
Coefficient of Friction	0.2 to 0.8
Step/Skirt Gap (inch)	1/16 to 3/8
Skirt Panel Stiffness (lbf/inch)	2300 to 5000
Step Stiffness (lbf/inch)	2000 to 11000

Table 2-11: Ranges of escalator variables used to create step/skirt indices

The conduct of the test consisted of two steps. The first step involved an evaluation of the initial escalator parameters and an assessment of the modifications required for the desired Index level. The second step involved an entrapment simulation where each test scenario was set up and test objects were run on the escalator. All simulations were performed to minimize the number of system changes between each test.

Parameter Assessment

Coefficient of Friction. The initial COF value was measured using the test apparatus documented previously [2] and samples of all candidate test specimens. This initial value was acquired using a dry skirt panel. Lubricating the skirt panel modified COF values; however, the surfaces of the test samples were not modified. When tests were replicated using the same test specimen, all residual lubrication on that test specimen were removed prior to running it a second time.

Skirt Panel Stiffness. The escalator design was reviewed to determine what points along the skirt panel offered the range of desired stiffness values. Using the test apparatus, a static load was applied to the skirt panel point. An LVDT measured the panel displacement and a load cell measured the load applied. Typically, rigid zones were located near the vertical structural members, while compliant zones were located at the mid-point between these members. If the measured values did not approximate the test plan targets, modifications to the escalator were made.

Step Stiffness. The initial step stiffness of the escalator was determined using the most rigid portion of the escalator structure for load reaction. A load was applied from the step to the skirt panel, and displacement was recorded using two LVDT's on the test apparatus, one LVDT located on each side of the step. The load was applied in 20 lbf increments up to 220 lbf . The value of the load applied and the difference between the two displacement readings yielded the step stiffness. Step stiffness was modified as required. Prior to the start of this test, the step deadband was removed by applying, then removing, a moderate load.

Step/Skirt Gap. The initial gap was measured with a feeler gauge. The gap was modified, as the test plan required, by physically changing the step position on its axle.

Entrapment Simulation

For each unique condition prescribed in Table 2-9, the escalator was modified as required. Changes made to the escalator were minimized between tests (for example, all tests requiring the same step stiffness were performed in succession). The following general steps were taken to conduct each entrapment simulation:

1. Modify escalator characteristics to achieve desired Step/Skirt Index.
   a. Prepare and test skirt panel surface and object for desired COF value.
   b. Determine location along skirt panel for desired skirt panel stiffness.
   c. Modify and test step for desired step stiffness.
   d. Modify and measure escalator for required gap.
2. Position the test object within ½" but not in contact with the test step riser.
3. Apply the test load.
4. Begin escalator travel in the down direction.
5. Observer #1 detected if and when entrapment occurs.
6. Observer #2 determined the entrapment location along the skirt panel.

Test Results. In most cases, the objects had permanent deformation and markings of being entrapped. These observations were applicable to the sample test specimens, the artificial Sawbones hand and calf, and shoes. The calf was the only exception, in which it was difficult to positively state the entrapment condition. Some of these recorded calf entrapments were closer to pinches than entrapments. When the escalator was stopped and the normal force removed, the calf became free due to its own resilience. ADL opted to be conservative and classified these events as entrapments.

After conducting the validation tests and reviewing the results, further testing was suggested. Although the results indicated a strong correlation between the Index and percent entrapments (as expected), several new issues emerged. For example, none of the shoes (adult or child) were entrapped, even though 45 test runs were performed. Furthermore, the relatively small number of small object tests (scenarios characterizing child entrapment) needed to be augmented with additional tests to balance the test matrix and achieve greater precision in the derived estimates.

Consequently, additional tests involving children's shoes, and replicas of children's hands and calves were conducted.

These additional tests resulted in a total of 78 entrapment test runs using child-size objects. Results of these tests are displayed in Table 2-12. As indicated in the table, most tests were performed with hands and calf replicas. Shoes were entrapped only at high Index values (above 0.9) due to large loaded gaps equal to or larger than 0.5 inches. Exploratory testing was also conducted to identify the lowest Index value needed to entrap shoes. These tests were conducted at Index values between 0.3 and 0.9, and no shoe entrapments were observed.

Index Level	Child's Shoe		Child's Hand	Child's Calf	Total # Entrapments	Percent Entrapment
	Toe Entrapment	Entrapment and Release				
.9-1	2/3	0/3	--	--	2/6	33%
.8-.9	--	--	3/3	3/3	6/6	100%
.7-.8	--	--	--	--	--	--
.6-.7	--	--	--	--	--	
.5-.6	--	--	2/3	3/3	5/6	83%
.4-.5	--	--	1/3	3/3	4/6	66%
.3-4	--	0/3	0/6	2/6	2/15	13%
.2-.3	0/3	--	0/9	3/9	3/21	14%
.1-.2	0/3	0/3	0/6	1/6	1/18	6%

Note: Entries above indicate number of entrapments/number of trials; dash (--) indicates no test.

Table 2-12: Step/Skirt Index validation test results (based on object COF; child objects only)

Although entrapment percentages are not strictly comparable from row to row due to the varying type and number of tests, a general trend is readily apparent. There is a clear indication that the lower the Index, the less likely entrapment will occur under laboratory-controlled conditions.

2.4 Step/Skirt Index Using a Standard Test Specimen

Approach

The test results presented in Section 2.3 were based on coefficient of friction for each specific object against the skirt panel. However, measuring the coefficient of friction for various objects that could conceptually be entrapped in an escalator is impractical in the field. As a result, a standardized coefficient of friction test specimen must be used. Section 3.3 presents test results for various test specimens, and was the basis for selecting polycarbonate test specimens to measure the coefficient of friction when calculating the Step/Skirt Index.

Consequently, coefficient of friction values for polycarbonate test specimens were also measured during the entrapment tests presented in Section 2.3. These validation test results

(Table 2-12, referenced the object coefficient of friction) were recalculated based on measurements using the coefficient of friction for polycarbonate test specimens.

Results

As described above, a polycarbonate test specimen will be used to measure the COF (and, consequently, the Step/Skirt Index) for field installations.

The relationship between an Index calculated from a polycarbonate specimen and the corresponding Index calculated from specimens used in the Index validation test (Section 2.3) is illustrated in Table 2-13.

Object/Scenario	Object Index	Polycarbonate Index	No. of Trials	No. of Observed Entrapments
Child's Shoe/Entrap Release	0.92	0.88	3	0
Child's Shoe/Toe Entrap	0.91	0.88	3	2
Child's Hand	0.87	0.59	3	3
Child's Calf	0.86	0.59	3	3
Child's Hand	0.54	0.20	3	2
Child's Calf	0.52	0.20	3	3
Child's Calf	0.45	0.19	3	3
Child's Hand	0.45	0.19	3	1
Child's Hand	0.35	0.16	6	0
Child's Calf	0.35	0.16	6	2
Child's Shoe/Entrap Release	0.31	0.22	3	0
Child's Shoe/Toe Entrap	0.28	0.22	3	0
Child's Hand	0.25	0.12	6	0
Child's Calf	0.25	0.12	6	0
Child's Hand	0.25	0.07	3	0
Child's Calf	0.23	0.07	3	3
Child's Shoe/Entrap Release	0.12	0.08	3	0
Child's Shoe/Toe Entrap	0.10	0.08	3	0
Child's Calf	0.10	0.08	6	1
Child's Hand	0.10	0.08	6	0

Table 2-13: Comparison of polycarbonate-based Index and object-based Index

Inspection of Table 2-13 reveals that the test specimen Index is lower than the object-based Index due to coefficient of friction differences.

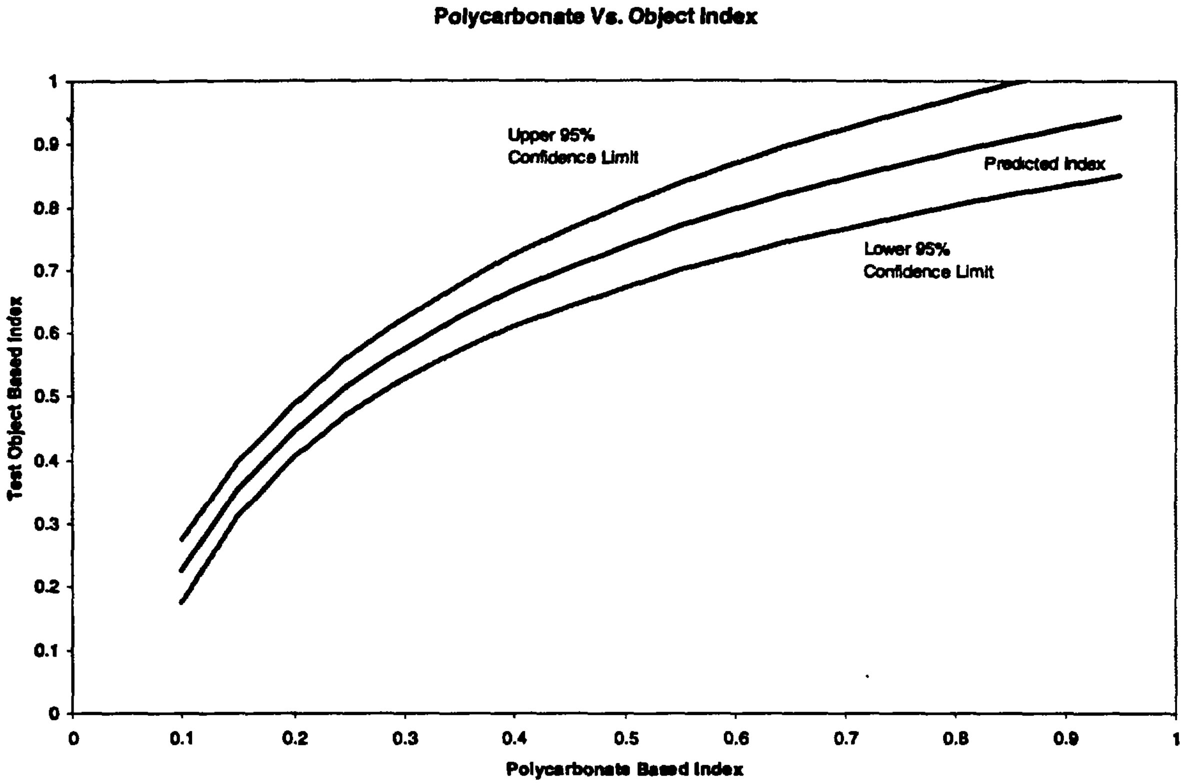

Figure 2-4: Comparison of polycarbonate-based index and object-based index

The relationship can also be expressed according to a linear regression model. The analysis, given in the Appendix, indicated a strong pairwise correlation (a), and a credible statistical model (b) that relates a measured polycarbonate-based Index to the child-specimen Index. The derived relationship, including 95% confidence interval estimates, is displayed in Figure 2-4. The confidence interval is included since it is useful for making inferences about an overall (i.e., population) *mean Index* for test objects at a given polycarbonate-based Index value; it is not intended to characterize the prediction error associated with any individual object.

For example, if the polycarbonate test specimen COF yields an Index of 0.20, the corresponding Index calculated from child-like specimen COF is expected to be about 0.45 (on average). The upper and lower bounds of the confidence interval quantify the degree of uncertainty associated with this estimate. Inspection of Figure 2-4 indicates that it is unlikely the *average Index* using child's (Sawbones) hands/calves, and/or shoes would be below 0.41 (or above 0.49). Stated

---

(a) Estimated correlation coefficient is 0.95
(b) Child-Specimen Index = 0.96 + 0.73 log (Polycarbonate Index)

another way, observing an Index of 0.20 in the field using a polycarbonate specimen corresponds to an Index of 0.45 using the Sawbones hand/calf specimen.

In summary, the intent here is simply to demonstrate a definitive relationship between indices computed from child-like and polycarbonate test specimens. Since the relationship holds in a relative (not absolute) sense, the lower the polycarbonate-based Index, the more resistant to entrapment the escalator is likely to be. Consequently, the use of polycarbonate to measure coefficient of friction does not compromise the validity or interpretation of the Step/Skirt Index.

In practical applications, the Index will be calculated using a polycarbonate test specimen. Therefore, the results of the validation test, based on child test specimen and displayed in Table 2-12, are not strictly applicable to Index measurements to be obtained on field installations. Consequently, the results of the laboratory validation tests are also displayed in Table 2-14 using the polycarbonate COF-based Index instead of the actual child-object COF in the calculation.

	Child's Shoe					
Index Level	Toe Entrapment	Entrapment and Release	Child's Hand	Child's Calf	Total No. of Entrapments	Percent Entrapment
.9-1	--	--	--	--	--	--
.8-.9	2/3	0/3	--	--	2/6	33%
.7-.8	--	--	--	--	--	--
.6-.7	--	--	--	--	--	--
.5-.6	--	--	3/3	3/3	6/6	100%
.4-.5	--	--	--	--	--	--
.3-4	--	--	--	--	--	--
.2-.3	0/3	0/3	2/3	3/3	5/12	72%
.1-.2	--	--	1/15	5/15	6/30	20%
.0-.1	0/3	0/3	0/9	4/9	4/24	16%

Note: Entries above indicate number of entrapments/number of trials; dash (--) indicates no test.

Table 2-14: Index based on polycarbonate test specimen COF

Statistical Analysis. A more rigorous analysis of the data given in Table 2-14 confirmed the correlation between Index and percent entrapments. This analysis, which is given in the Appendix, does account for the variation in the number of test runs from row to row. Since only child hand and calf data were used in the analysis, an equal number of tests were performed for both objects, thus assuring an unbiased comparison.

Here again, a statistical model was derived from the experimental data given in Table 2-14. The model, depicted graphically in Figure 2-5, clearly exhibits a relationship between the Index and the percentage of entrapments expected (i.e., predicted) to occur under the laboratory test procedure.

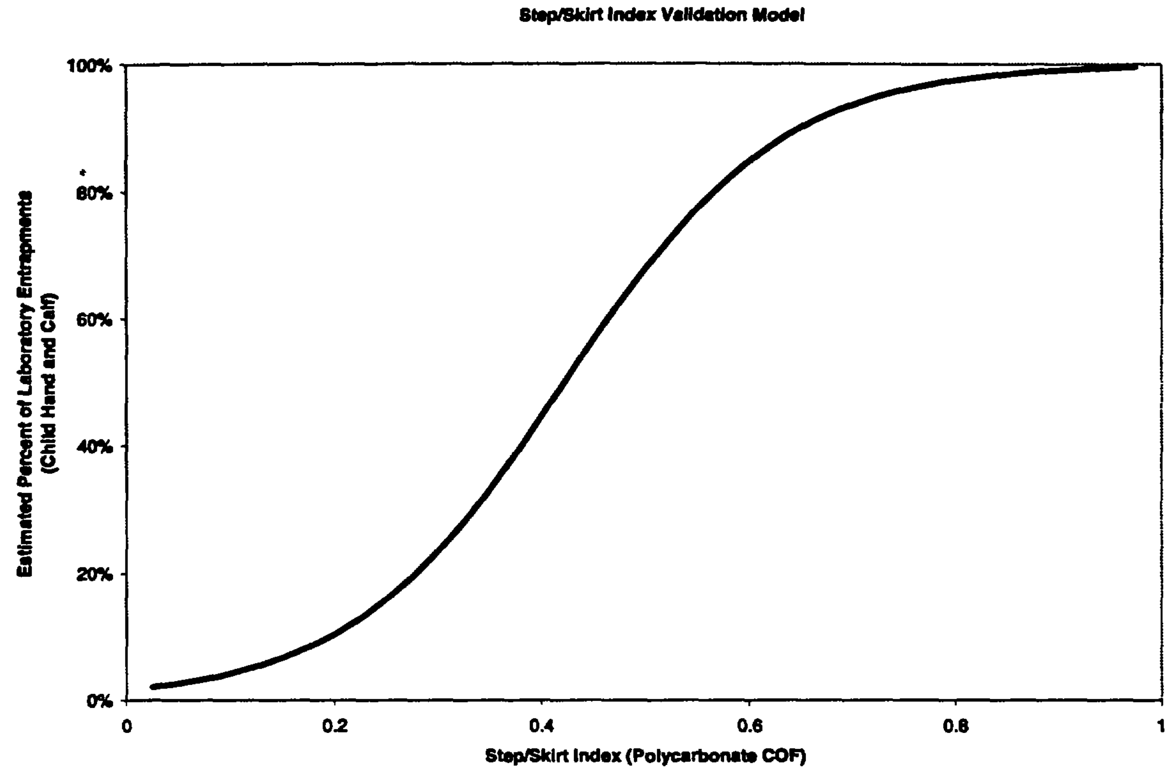

Figure 2-5: Step/Skirt Index Validation Model

2.5 In Field Entrapment Verification

2.5.1 Approach

A measure of an escalator's step/skirt entrapment potential (the Index) was developed and validated on laboratory escalators. In order to demonstrate that these laboratory conditions were consistent with in-field conditions, tests were conducted on an installed escalator. An escalator was selected, and the laboratory entrapment tests with artificial hands, calves, and athletic shoes were duplicated for the selected escalator.

2.5.2 In Field Entrapment Tests

Tests on the in-field escalator were conducted without making any modifications to the escalator. A brief description of the test escalator follows in Table 2-15.

Location	Skirt Panel Condition	Installation Date	Measured Index (polycarbonate COF)
Office Building	Dry Teflon Coated Aluminum	~1978	0.22

Table 2-15: In Field Escalator Characteristics

The entrapment tests consisted of two distinct parts.

First, the escalator's Index was measured and calculated. Coefficient of friction and loaded gap were evaluated along the length of the inclined portion of the escalator, and the measurement data were analyzed to generate a Step/Skirt Index for the test escalator. The measurement equipment was the same as was used during the laboratory testing.

Second, artificial body parts were used to simulate entrapment scenarios. The same artificial body parts and test fixtures that were used in the laboratory entrapment testing were used for this test. Consistent with NEII's desire to focus on small objects, only the child scenarios were tested. A comparison of the results of in-field and laboratory testing are summarized below in Table 2-16.

	Index Level*	Child's Shoe		Child's Hand	Child's Calf	Total No. of Entrapments
		Toe Entrapment	Entrapment and Release			
Field Escalator	0.22	0/3 (0.74**)	0/3 (0.62**)	6/6 (0.66**)	6/6 (0.66**)	12/18
Laboratory Escalators	0.2-0.3	0/3 (0.28**)	0/3 (0.31**)	2/3 (0.54**)	3/3 (0.52**)	5/12

*Index level was calculated using a polycarbonate test specimen
** Index level was calculated using test object coefficient of friction
Entries indicate number of entrapments and number of trials

Table 2-16: In Field Entrapment Test Results

Results indicate a reasonable agreement between laboratory and in-field entrapment tests.

3. Measurement Procedure

3.1 Objective

The analysis and laboratory experimentation described in Section 2 resulted in a Step/Skirt Index that estimates the conditional probability of step/skirt entrapment potential for given levels of loaded gap and coefficient of friction. However, in order to use the Index to classify escalators in the field, a method for measuring the Index in the field was required. Tests were conducted on installed escalators to demonstrate the feasibility of measuring the Index in the field, identify the range of Index values of escalators in the field, and develop a reliable measurement procedure. A material for the coefficient of friction test sample was also selected for Index measurements as a result of testing in-field escalators.

3.2 In-Field Measurements

Four escalators were tested in the Boston area. The equipment used in laboratory testing was also used for the measurements in the field tests. A variety of candidate measurement approaches was considered and the measurement approach was gradually refined as testing progressed.

Parameters evaluated in this test program were:

- Coefficient of friction between test specimen and skirt panel
- Unloaded or initial step/skirt gap (in.)
- Loaded step/skirt gap (in.)
- Combined step/skirt stiffness (lbf/in.)

These characteristics were evaluated for each escalator. Measurements were made continuously along the length of the escalator while the escalator was moving, as well as in several discrete locations on a stationary escalator. The Index was then calculated for the escalator based on the model given in Section 2.

3.2.1 Escalator Selection Criteria and Test Procedure

Escalators were selected to cover a wide range of Index values using the following criteria:

- New (installed after 1996)
- Average age (installed between 1980-1995)
- Old (installed prior to 1980)
- Old (installed prior to 1980) and slated for replacement

First, each escalator was visually inspected to note any unusual damage to the skirt panel, the steps, or inconsistent gap sizes. In addition, each escalator's characteristics were recorded:

- date of installation
- applicable code
- step guidance design
- skirt panel material

The test procedure consisted of evaluating the escalator parameters necessary to calculate the Index. These parameters were evaluated on an initial "as found" basis, with no modifications made to the escalator. The Index parameters were assessed as follows:

Coefficient of Friction. The initial COF value was measured using the test apparatus documented previously with three different test specimens. These test specimens were made from materials meeting the following criteria shown in Table 3-1:

Type	Color	Durometer (Shore A)	Finish	Length (in.)	Width (in.)	Thickness (in.)	Specification
Neoprene	Black	60 ± 5	Smooth	3.0	1.5	0.25	MIL-R-6855-D CL II GR 60 (or equivalent)
Acetal	White	N/A	Smooth	3.0	1.5	0.25	Delrin AF (or equivalent)
Polycarbonate	Clear	N/A	Smooth	3.0	1.5	0.23	GE Lexan 100 with no fillers (or equivalent)

Table 3-1: Frictional Test Sample Specification

The skirt panel was tested as found; panels were not cleaned or lubricated prior to testing. A load of approximately 25 lbf[3] was applied, and the step was advanced the entire length of the incline. Data for each run were collected and evaluated for maximum and average COF values. The frictional and normal forces on the test specimen were recorded every hundredth of a second. To filter out some of the noise in the measurement, a moving average of five COF values were used in this analysis.

Initial Gap, Stationary Step. Using the test apparatus, a 25 lbf load was applied from the step to the skirt panel, and then removed. This process removed any deadband from the step. The unloaded gap was then measured with a tapered feeler gauge. Measurements of initial gap near the comb plates were taken manually due to the size of the laboratory test apparatus. The step deadband was removed by manually pushing the step away from the skirt panel then allowing it to spring back into position. The gap was then measured with a tapered feeler gauge.

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[3] Twenty five pounds was selected as the applied load because human impart testing of the various accident scenarios indicated children can impart a maximum of 25 lbf to the skirt panel. See ADL report to NEII dated July 2, 1998 for more detail.

Loaded Gap, Stationary Step. Two steps were selected for this test based on their apparent condition. One step was selected as a representative step on the escalator, and the other was selected from steps that appeared to be unusual. A 25 lbf load was applied from the step to the skirt panel and the gap was measured with a tapered feeler gauge. This measurement was repeated for a 75 lbf load to allow calculation of combined step/skirt stiffness. The measurement was replicated for the opposite side skirt panel. Then the procedure was repeated for the remaining test step.

Loaded Gap, Moving Step. This test allowed an assessment of loaded gap variability along the length of the straight inclined portion of the escalator (see Figure 3-2). Two steps also were selected for this test. The same steps that were selected for the loaded gap stationary step tests were used in these tests. A 25 lbf load was applied from the step to the skirt panel, and a load cell measured the applied load. The loaded gap was measured with an LVDT referenced to the edge of the step. The escalator was started and gap and normal force measurements were taken every hundredth of a second during the test runs along the length of the inclined portion of the escalator. These measurements were repeated at 75 lbf normal load to allow the combined stiffness to be calculated. These measurements were replicated for the opposite side skirt panel. This procedure was then repeated for the other test step.

		Gap while Stationary			Gap while Moving	
Step No.	Side	Initial	@ 25 lbf	@ 75 lbf	@ 25 lbf	@ 75 lbf
1	Right					
1	Left					
2	Right					
2	Left					

Table 3-2: Gap measurement test matrix

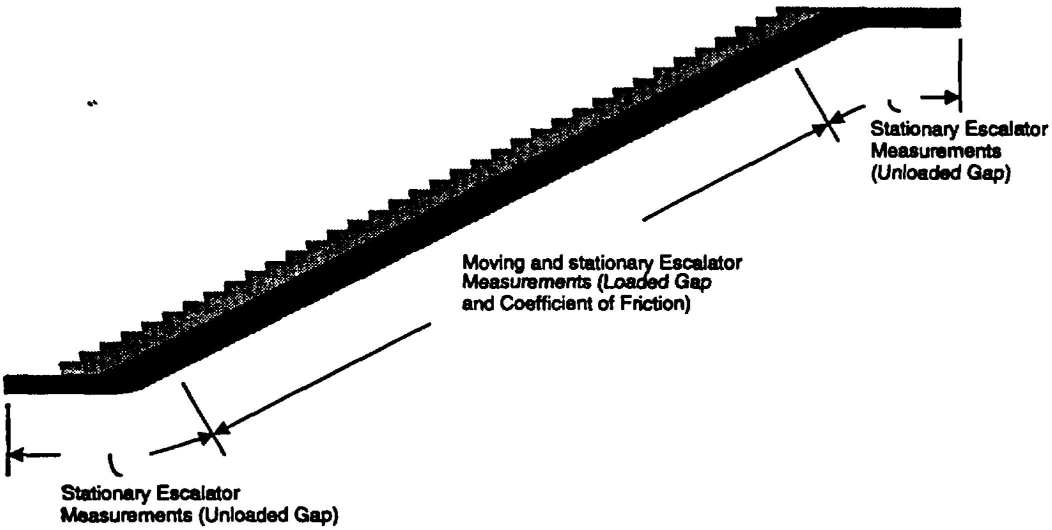

Figure 3-1: Moving and stationary escalator conditions

3.3 Results

Measurements on escalators in the field characterized the relative condition of the step/skirt interface on these escalators. The Index for the in-field escalators ranged from 0.46 to 0.67 based on the 99 percentile level[4] of the recorded continuous Index measurements. Results are summarized in Table 3-3 below.

Escalator ID	Location	Skirt Panel Condition	Installation Date	Measured Index*
1	Department Store	Dry Stainless Steel	Late 1994	0.54
2	Shopping Mall	Lubricated Bronze	February 1989	0.60+
3	Mass transit system	Dry Stainless Steel	Pre 1975	0.67
4	Department Store	Dry Stainless Steel	1950's	0.46

* These measurements are for polycarbonate test samples on a continuous running escalator based on a 99 percentile level.

+ Index will be reduced to .31 level if the loaded gap is reduced at one location from .4" to .23".

Table 3-3: Index for in-field escalators

These results indicate that Index measurements are capable of distinguishing between escalators in the field.

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[4] One percent of recorded index measurements were higher than the reported value, and 99% of the recorded index measurements were lower than the reported value.

Results from moving tests were used for three principle reasons. One, variability in the step/skirt interface on installed escalators requires measurements to be taken at a large number of locations along the escalator in order to capture a representative sample of an escalator's condition. Two, the coefficient of friction is most easily measured while the escalator is moving and the loaded gap measurements can easily be taken at the same time under the same conditions. Three, step/skirt entrapments occur while the escalator is moving and testing under similar conditions is desirable.

Coefficient of friction tests were repeatable, but measurements contained high frequency noise that was filtered. Of the three sample materials evaluated, polycarbonate has the most desirable coefficient of friction properties. Neoprene left a sticky residue and had a high COF that resulted in forces on the step high enough to potentially cause damage to the escalator. Delrin and polycarbonate both left no residue on the skirt and generated acceptable force levels. Polycarbonate was selected as the test sample because its coefficient of friction on stainless steel was closest to that of human skin. Coefficient of friction test results are summarized below in Table 3-4.

Material	Human Skin	Delrin AF	Polycarbonate	Neoprene
Stainless Steel	0.18 to 0.52*	0.10 to 0.25	0.19 to 0.44	0.8 to 1
* From laboratory testing described in ADL report dated July 2, 1998 [2]				

Table 3-4: Coefficient of Friction Comparison

Values presented in Table 3-4 are based on average COF values measured on escalators in the laboratory and in the field.

3.3.1 Proposed Test Protocol

The in-field Index measurements resulted in the following measurement protocol.

ESCALATOR
FIELD TEST MEASUREMENT
PROTOCOL

Initial Inspection

The first step is to inspect the escalator. This inspection should be performed without making any alterations to the escalator including, but not limited to, cleaning or lubricating the skirt panel.

1. *Visually inspect the condition of step/skirt panel gap while the escalator is stationary. Mark a step and operate the escalator to bring other steps into view as required until every step on the escalator has been examined. Document any*

outstanding conditions, such as step/skirt gaps larger than code, damaged steps, damaged step treads, damaged skirt panels, mismatched skirt panel joints, or sharp edges on the edge of the step or skirt panel. Pay particular attention to the gaps between the riser portion of the step and the skirt panel.

2. *Run the escalator in its typical direction of travel for at least two cycles of steps. If the escalator is operated in both directions, run the escalator for at least 2 cycles of steps in both the up and down directions. Visually examine the step/skirt gaps along the entire length of the escalator. Pay particular attention to the gaps at the transitions. Document if there is any abnormal operation of the escalator such as jumping steps, irregular step movement, step/skirt panel interference, or skirt panel misalignments.*

Coefficient of Friction and Loaded Gap, Moving Step

Select two steps to conduct this test. One step should be selected as a representative step. It should appear similar to the majority of the other steps on the escalator. A second step should be chosen to represent any unusual step or group of steps. Steps that appear to have been replaced, exhibit excessive wear, show signs of damage, or move in irregular ways are candidates for the second test step. If all the steps appear similar, then the steps should be randomly selected. In any case the test steps should be separated by at least 8 steps.

If the escalator is a "down" escalator, or the escalator is operated in both directions, the test step should be moved to the top of the escalator before the curved skirt panels prior to each test run, and run down during the test. If the escalator is normally operated as an "up" escalator, then the test step should be moved to the bottom of the escalator just before the curved skirt panels prior to each test run, and run up during the test.

1. *Install the test apparatus on the step to be tested. Install a polycarbonate frictional test sample (see appendix for frictional test sample specifications) on the test apparatus.*
2. *Orient the frictional force transducer to match the angle of the skirt panel (See Figure 3-3).*
3. *Using the test apparatus apply a 25 lbf load between the step and the skirt. The load should be maintained throughout the test.*
4. *Start a new test and begin acquiring data. A coefficient of friction and a loaded gap measurement should be recorded every 8 inches at a minimum.*
5. *Run the escalator continuously until the test step and apparatus reach the curved skirt panel at the opposite end of the escalator. Stop collecting data.*
6. *Process the collected data (see the appendix for instructions for data processing)*
7. *View and record the collected Index.*

8. *Repeat steps 1 through 7 for both sides of both test steps. Use a new friction pad for each run.*
9. *The Index values calculated in this way should not exceed the values specified by ASME A17.1 and/or ASME A17.3 code.*

Loaded Gap, Stationary Step

This test will be conducted in the curved and horizontal portions of the escalator where moving step testing was not conducted. See Figure 3-2 below. The steps selected for this test can be the same as those used for the COF and moving step tests. The escalator should be stationary while these measurements are taken.

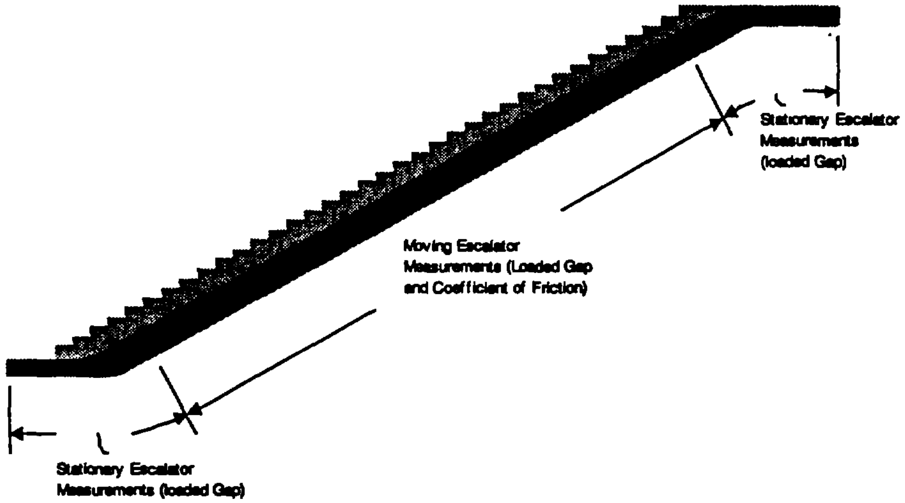


Figure 3-2: Escalator Index test regions

1. *Move the step to be tested to the flat portion of the escalator at the bottom of the escalator. The edge of the comb plate should be approximately 6 inches from the edge of the test step.*
2. *Install the test apparatus on the step to be tested. Install a plastic pad on the portion of the apparatus, which touches the skirt panel to avoid damage to the skirt panels.*
3. *Using the test apparatus apply a 25 lbf load between the step and the skirt.*
4. *Measure and record the loaded gap (see appendix for details on measuring the loaded gap).*
5. *Remove the 25 lbf load and advance escalator so that the device moves approximately 12 inches further away from the comb plate.*
6. *Repeat steps 3-5 until the test apparatus has reached the start point of the dynamic runs.*
7. *Repeat steps 1 through 6 for the other side of the skirt panel.*

8. *Repeat the previous 7 steps, but this time start at the top of the escalator and gradually move the escalator down until the apparatus has reached the area where moving step measurements were made.*
9. *The recorded loaded gap measurements should not exceed the values specified by ASME A17.1 and/or ASME A17.3 code.*

Appendix – Test Specifications

Calculation of the sliding coefficient of friction (COF).

The friction test sample should conform to the following specifications:

[illegible] Type	*[illegible] Color*	*[illegible] Finish*	*Area in contact with skirt panel (in^2)*	*[illegible] Specification*
Polycarbonate w/o fillers	*Natural no Pigments*	*Smooth or Glossy (less than 32µ in. or .8 µm)*	*4.5 ± 0.5 and at least .03" thick*	*GE Lexan 100 series or equivalent*

Sliding coefficient of friction measurements should measure the coefficient of friction for the sample sliding in the direction of the step motion under 25 pounds of normal force at the speed of the steps. The COF should be calculated as the frictional force divided by the normal load and should be accurate to ± 0.03.

Calculation of the loaded gap

The loaded gap is defined as the gap at the front of the step between the step and the skirt panel when a 25 lbf is applied laterally to the step from the skirt. A 25 ± 2.5 lbf should be applied from the step to the skirt panel. The center of the applied load should be no less than 1 inch below the line formed by the front corners of the steps and no more than 4 inches from that same line. Furthermore, the load should be within 10 inches of the front of the step. The load should be distributed over an area no less than 3 square inches and no more than 6 square inches. (See Figure 3-3)

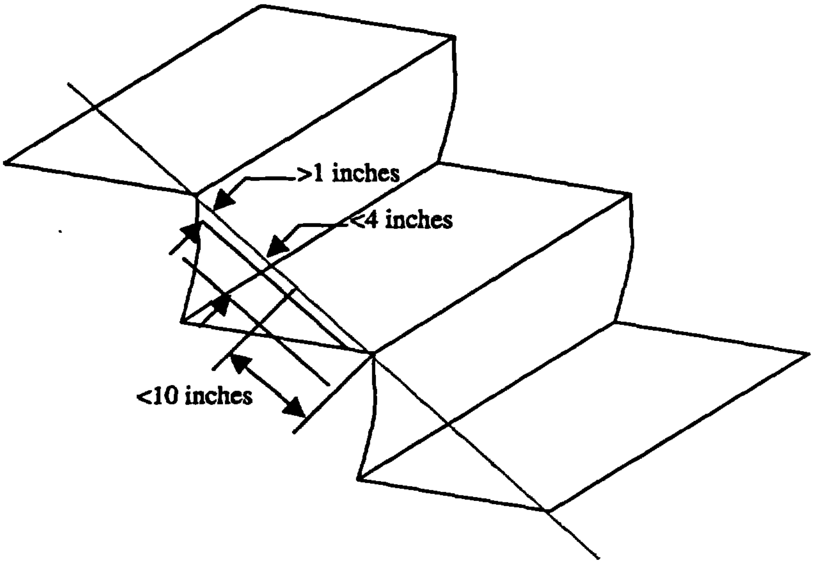


Figure 3-3: Location of coefficient of friction tests

The loaded gap is defined as the maximum distance from the edge of the step to the skirt panel under load.

Index calculations

At each measurement point on the escalator the Index value is calculated from the value of the sliding coefficient of friction (COF) and loaded gap information at that point on the escalator as follows:

$$\boxed{y = -3.77 + 2.37(COF) + 9.30(loaded\ gap)} \qquad \boxed{Index = \frac{e^{y}}{e^{y}+1}}$$

The Index can also be determined by referring to the curves in Figure 3-4. These calculations generate an Index value at a single point on the escalator. The overall performance Index for the escalator is the maximum value of the recorded Index values.

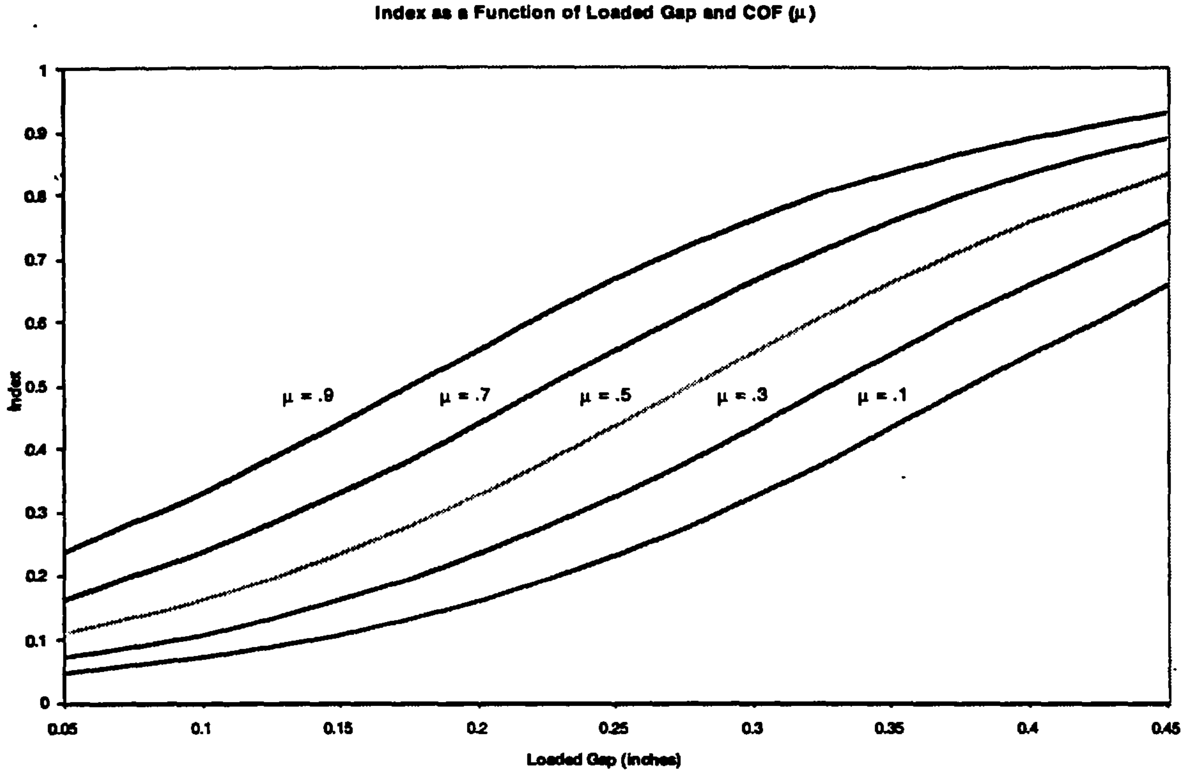


Figure 3-4: Graphical representation of the Step/Skirt Index

4. Measurement Tools and Concepts

4.1 Approach

In order for the Step/Skirt Index to become a useful tool to evaluate installed escalators, inspectors and service personnel must be able to measure the Index on a field escalator quickly and easily. Hardware requirements for an Index measurement gauge design were generated by analyzing the technical requirements for an Index measurement device and the needs of gauge stakeholders according to the following methodology.

1. Gauge stakeholders were identified and their relative importance established.
2. A focus group meeting was held to gather customer needs information from escalator service personnel, maintenance personnel, and inspectors.
3. High level needs of the stakeholder groups were identified and qualitatively rated.
4. Technical requirements for the Index gauge were developed through an analysis of the Index and an understanding of the physical requirements of the Index measurements.
5. Gauge concepts were generated through group and individual brainstorming sessions.
6. Concepts were evaluated according to the requirements.
7. The most promising concepts were further developed to establish technical feasibility.

4.2 Hardware Requirements

Several industry stakeholders were identified, including

- Escalator owner/operator
- Escalator manufacturers
- Escalator maintenance
- Device manufacturer
- Inspectors

Other non-industry stakeholders-passengers and regulatory groups, one of which, the CPSC, participated in the interview process for this report. The needs of the stakeholders, and the relative importance of these needs, were identified and confirmed in a focus group (7/12/99) and through discussions with representatives of NEII and the CPSC. The resulting rank ordering of stakeholder needs is shown in Figure 4-1. The relative importance score gives an approximate measure for prioritizing needs to aid in trade-off analyses, concept selection, and development of the Index measurement gauge.

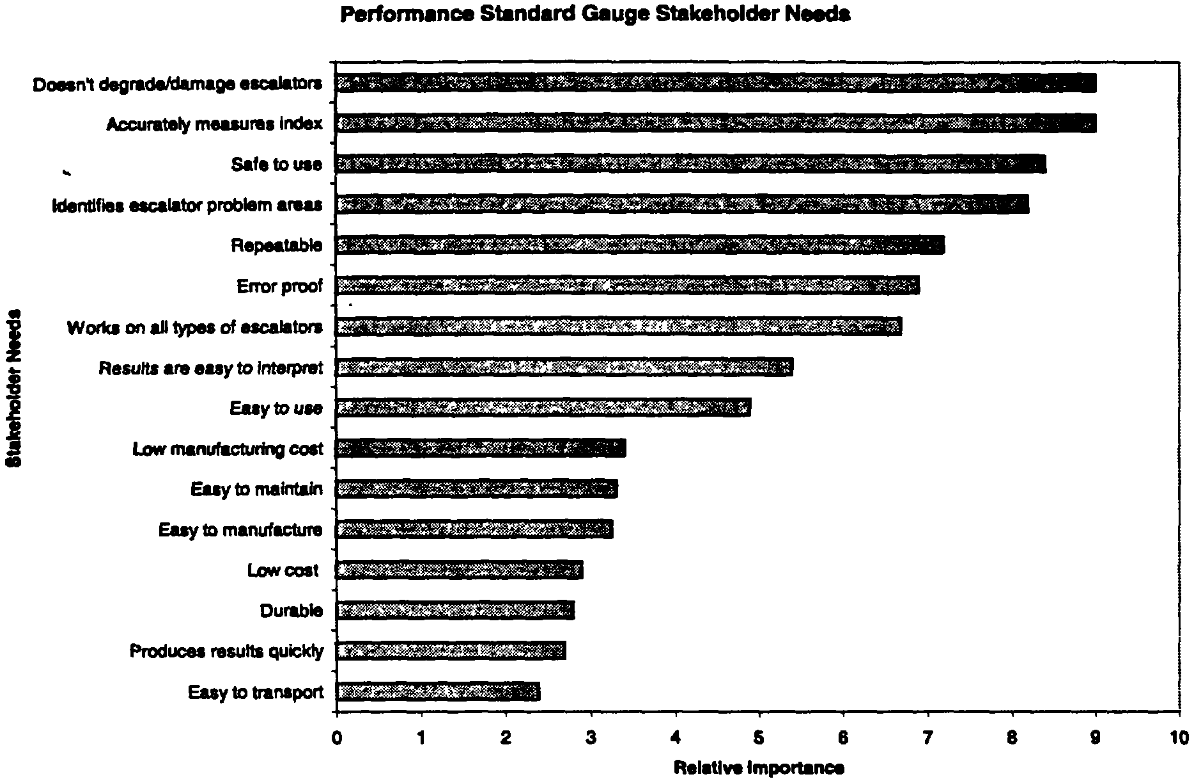


Figure 4-1: Stakeholders' needs

The top level needs generally relate to the technical performance and safety of the device. Ease of use, cost, and maintainability scored lower in importance for most users.

To translate these needs into technical requirements for the device, a Quality Function Deployment (QFD) based technique was used. Measurable engineering metrics were then developed to quantify each of the customer needs. See Table 4-1 below.

Engineering Metrics

	Preferred	dwn	nom	dwn	dwn	nom	up	nom	dwn	dwn	dwn	dwn	up	up	dwn	dwn	dwn	dwn	dwn	dwn	up
Customer Requirements	Weight	Damage to escalator after impact with comb plate	Indicates problem locations on escalator	Variation in index measurements	% deviation from true index	Displays components of index	Damage to device after improper use on escalator	External power required	Likelihood device will be set up such that results will be inaccurate	Time to set up device	Time to record measurements	Time to perform calculations	Percentage of escalators in the US on which device will function	Percentage of units that survive a 5 ft. drop	Number of measurements required	Unit sent back under warranty	Cost	Hrs of initial Training	Time required for routine maintenance	Mass	Expected life
Easy to transport	2 4							3												9	
Produces results quickly	2 7	1	3			1		3	1	9	9	9			3			1			
Durable	2 8						9							9		9					9
Low cost	2 9		3			3	3		3	9	3	3	3	1	1		3	3	3		
Easy to manufacture	3 3															3	3				
Easy to maintain	3 3						3							3		3		3	9		
Low manufacturing cost	3 4															3	9				
Easy to use	4 9	3	1			1	1	3	3	9	9	9	1	1	9			3		1	
Results are easy to interpret	5 4		9			9															
Works on all types of escalators	6 7												9								
Error proof	6 9	9	1				9	3	9					3	1			1			
Repeatable	7.2			9	9				1												
Identifies escalator problem areas	8 2		9			9															
Safe to use	8 4	9					3	9													
Accurately measures index	9 0			9	9				3												
Doesn't degrade/damage escalators	9 0	9																			
Technical Targets		No	Yes	3%	5%	Yes	75%	None	5%	5 min/location	60 Sec	5 minutes	99%	75%	1	0.5%	$1,000	<1 hour	3 hours/year	10 kg	5 Years
	Raw Score	236	151	146	146	139	136	126	122	94 5	77 1	77 1	73 9	63 6	62	55 1	49 1	42.9	38 4	26 5	25.2
	Relative Weight	0 13	0 08	0 08	0 08	0 07	0 07	0 07	0 06	0 05	0 04	0 04	0 04	0 03	0 03	0 03	0 03	0 02	0 02	0 01	0 01

Table 4-1: Technical Requirements

4.3 Concept Generation

The concept generation methodology was developed at ADL and has been proven on numerous development projects. The concept generation process consists of the following steps.

- A briefing package was developed and distributed to all participants.
- Two sessions were held consisting of participants with backgrounds in the following areas.
  - mechanical engineering
  - electrical engineering
  - sensor development
  - physics
  - industrial design
  - human factors
- Concepts were documented, discussed and evaluated.
- Concepts were ranked against the requirements to identify the "best" approaches.

In order to facilitate the free flow of ideas, the design problem was broken into four principle brainstorming areas: gap measurement, COF measurement, normal load application, and attachment method. Ideas were generated and documented in each of the areas. A summary of concepts generated during the brainstorming follows. (See Figure 4-2)

- **Gap**
  - Wedge
  - Stepped Wedge
  - Dial Indicator
  - Cam Measures Rotation
  - [redacted]
  - [redacted]
  - CCD Camera
  - Air Gauge
  - Laser
  - Ultrasonic
  - Mechanical Linkage
  - Gauge Blocks
  - Capacitive
  - Inductive
  - Rotary Wedge

- **COF**
  - Spin Disk Measure Torque
  - Measure Time for Spinning Disk to Slow
  - [redacted]
  - [redacted]
  - [redacted]
  - Measure Temperature Rise
  - Measure Braking Force to Slow Rotation of Wheel
  - Multiple Measurements to Further Characterize COF
  - Viscous Force Measurement
  - Break Away Devices
  - Add on to Cordless Drill
  - Sheet Between 2 Coils

- **Normal Load**
  - [redacted]
  - [redacted]
  - Magnets
  - Linear Motor
  - Pneumatic Piston
  - [redacted]
  - Air Bladder
  - Lead Screw & Motor
  - Torque Motor
  - Pneumatic Spring
  - Leaf Spring
  - Rack and Pinion

- **Attachment Method**
  - [redacted]
  - Wedge
  - Sticky Tape
  - [redacted]
  - Wedge Clamps
  - [redacted]
  - Inflatable Bladder
  - Cam Locks
  - Pin in Plates
  - Velcro
  - Piezo Clamps
  - Solidifying Gel Fill Treads

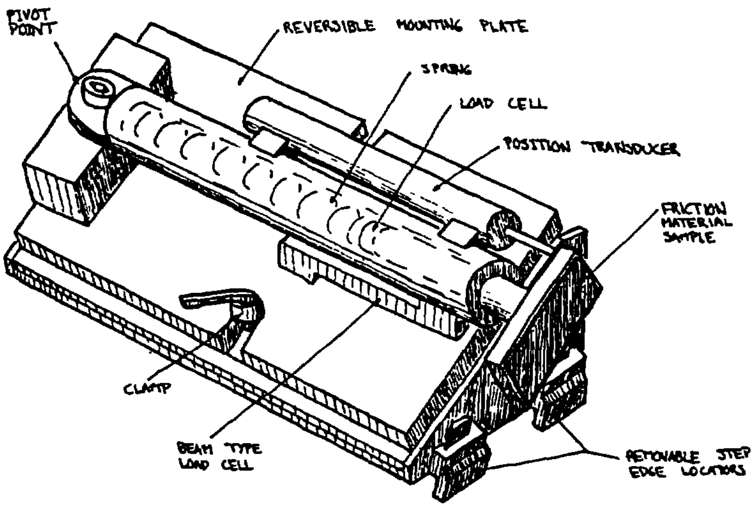
Figure 4-2: Concept summary

These ideas were then ranked to identify the preferred ideas in each area. Preferred ideas are shaded in Figure 4-2. The "best" concepts were assembled from the preferred ideas in each concept area. A brief description for the three complete concepts is presented below.

Pivoting Piston

- Normal force created by a spring
- Load cell measures drag force
- LVDT or encoder to measure loaded gap

Concept Description:



Comments:

+ Uses many off the shelf components with minimal modification
+ Rugged
+ Step edge locators eliminate need for additional gap measurements

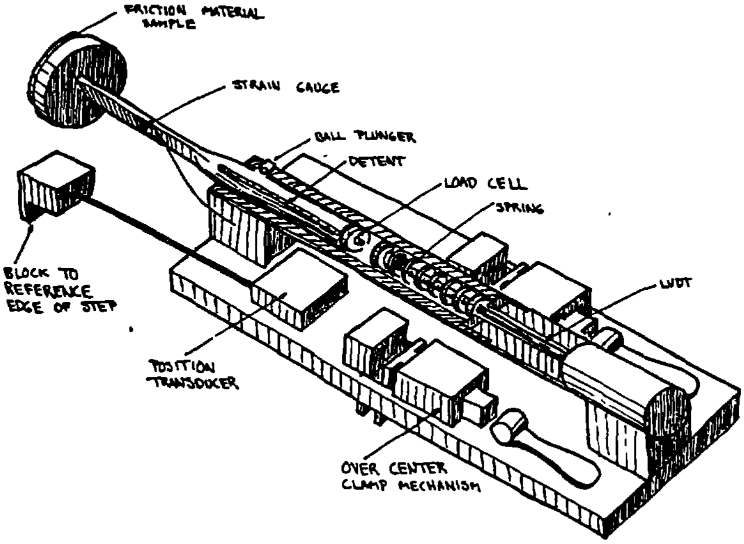
- Clamps must be able to move freely relative to device when unclamped then hold device to step with no movement
- Must control thickness of the friction sample
- Friction may build up at the pivot
- Step edge locators must be removed prior to use

Figure 4-3: Gauge concept – Pivoting piston

“Flexi-Stick”

- Similar to spring piston with integral LVDT
- Strain gauge on flexible membrane measures drag force

Concept Description:



Comments:

+ Toggle clamps will attach device to step quickly
+ Integral LVDT directly on center
+ Can reference edge of step quickly
+ Small, light package

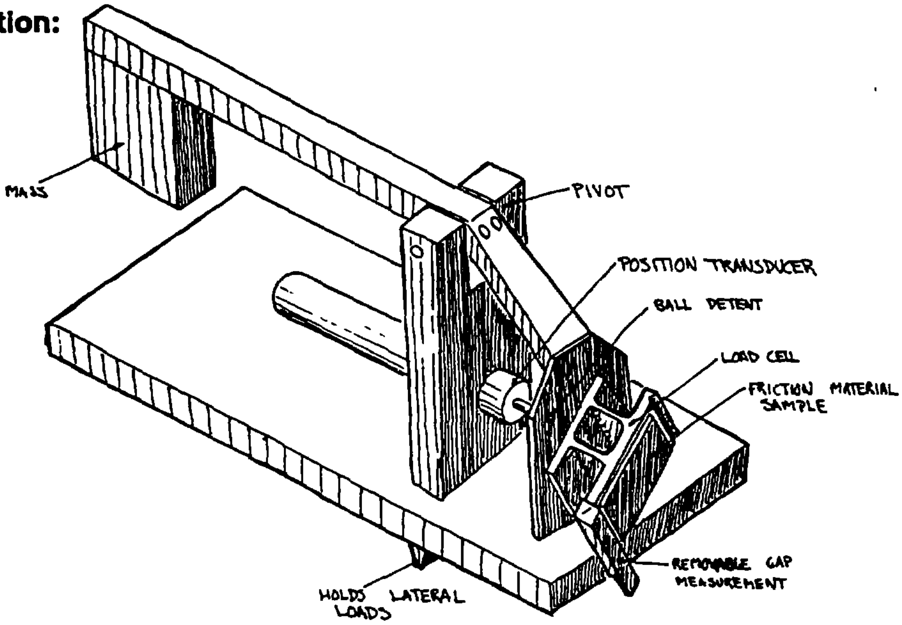
- Strain gauge and load cells will need signal conditioning and are susceptible to noise
- Rotary to linear transducer is fragile and expensive
- Must control thickness of the friction sample
- Strain gauge must be calibrated

Figure 4-4: Gauge concept – Flexi stick

Pivoting Mass

- Mass and a linkage provide normal force
- Load cell measures drag force

Concept Description:



Comments:

+ Eliminates one load cell
+ Can rapidly change sides
+ Device only loosely fixed to step, may not damage comb upon impact

- Problems maintaining alignment of friction sample
- Friction may build up at the pivot
- Gap measurement device must be removed prior to use
- Mass may not be enough to hold device in position

Figure 4-5: Gauge concept – Pivoting mass

4.4 Concept Feasibility Layout

To minimize developmental time and cost for the gauge, a preferred concept, the Flexi Stick incorporating a large number of purchased components was selected. A CAD layout was developed to more completely explore the space constraints of the concept. Several changes were made to reduce the cost of the device and accommodate the size constraints of off-the-shelf components. A brief description of some of the selected components and design changes follows.

The load cell was used to measure the normal force in the Flexi-Stick concept sketch was eliminated to reduce the cost of the device. The LVDT used to measure the gap was used in conjunction with a spring of a known rate to calculate the normal load on the friction test sample. Because the device will only operate in a small range of spring extensions and normal forces centered around 25 lbf, the spring and LVDT system can be calibrated to achieve the necessary accuracy.

A preliminary analysis indicated that linear ball bushings would be required to generate acceptable internal frictional forces. Ceramic linear bushings have coefficients of friction in the range of 0.04-0.08, which would result in a frictional load due to the ball bushing of approximately 3 lbf. Since frictional loads are inherently unpredictable, the friction due to the bushings alone would prevent the device from meeting the target accuracy. Ball bushings have COF on the order of 0.004 that will generate frictional loads of approximately 0.15 lbf well within the required accuracy.

A stock, data logging system that is capable of accepting and storing data from a range of sensors was selected. The data logging system also generates a regulated excitation voltage for the load cell and cable extension transducer. A rechargeable battery was selected to reduce operating costs and eliminate the need to change batteries frequently. An LVDT with internal electronic conditioning circuit that run directly off battery power was selected to reduce the current requirements for the data logging system. Collected data would be downloaded to a computer spreadsheet that could be programmed to automatically calculate and display the Index and other escalator parameters. Custom electronics can be developed to track and display escalator parameters in real time, but will require a larger, up-front design effort.