TAB E

Arthur D Little

Escalator Step/Skirt Performance Standard Study

Final Report

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Report to
National Elevator Industry, Inc.

2 July, 1998

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Reference 34646

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Background

Recently, there has been public focus on minimizing escalator accidents, an issue the industry has worked on continuously. In particular, efforts have been centered on entrapments involving the gap produced by the skirt panel and the side of the step (referred to as step/skirt panel entrapment). Arthur D. Little, Inc. (ADL) was contracted by the National Elevator Industry, Inc. (NEII) to help generate a "performance standard" for future recommendation to the ASME A17.1 Main Committee as part of the industry's overall attempt to minimize the number of potential step/skirt panel entrapment accidents.[1]

Arthur D. Little's approach to generating a performance standard was to understand the parameters contributing to this accident type by performing the following four inter-related tasks:

- review accident data
- determine and document accident scenarios (with reference to human factors considerations)
- develop a first order mathematical model for the mechanics of this type of entrapment
- conduct laboratory experiments to validate the parameter relationships

Findings

Upon completing the above tasks, key findings are as follows:

1. The process of entrapment can be considered as a two part event:
    - the object in contact with the skirt panel no longer slides at the same rate as the moving step, or the object begins to chatter. [The premise is that potential for entrapment exists when this condition occurs; the object does not necessarily need to be wedged against the step for this potential to exist.]
    - an object in the gap produces loads perpendicular to the skirt panel and the side of the step; these load levels contribute to the depth of the entrapment.

2. The likelihood of entrapment is strongly influenced by the coefficient of friction.

3. Skirt panel stiffness, step lateral stiffness and step/skirt gap influence the likelihood of entrapment in varying degrees.

4. Step/skirt gap and step and skirt panel stiffness contribute to the maximum size of the entrapped object and the load levels produced on the entrapped object.

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[1] "Performance standard" is interpreted to mean escalator characteristics that the industry can achieve by design, manufacture, modification, and/or maintenance to minimize the potential for step/skirt entrapments.

Mathematical modeling identified coefficient of friction and step stiffness as key factors in the entrapment process. This finding was confirmed by conducting entrapment experiments involving a wedge-shaped Teflon test object. In general, the lower the coefficient of friction on the skirt panel, the less likely it was that wedge entrapment would occur. Similarly, wedge entrapment depth, when adjusted for gap size was reduced with the use of higher combined stiffness values for the skirt panel and the step.

Specifically, it was confirmed on a test escalator that the initiation of entrapment of a test wedge is strongly related to the coefficient of friction. It was observed that when the coefficient of friction between the skirt panel and the test object is approximately 0.6, initiation occurred in every case. However, when the coefficient of friction was 0.19, initiation occurred only 25% of the time (6 out of 24 tests). Moreover, at 0.6, the initiation probability was not dependent on the combined stiffness of the skirt panel and the step (over the ranges considered in the experiment). However, at the 0.19 friction level, the combined stiffness contributed to initiation in varying degrees. These results are depicted in Figure 6-1. This figure further implies that a family of curves exist for coefficients of friction between 0.19 and 0.6.

Similarly, wedge entrapment depth, when adjusted for gap size was influenced by combined stiffness and coefficient of friction. The coefficient of friction had the largest impact on the wedge entrapment depth. Furthermore, the gap-adjusted wedge depth was reduced when stiffness was increased. The only confirmed effect of gap size was simply that larger gaps admit larger objects into them.

Further experimentation (i.e., a larger number of tests) is recommended to confirm these findings, and to estimate a functional relationship between entrapment depth and coefficient of friction, combined stiffness, and gap size.

Conclusions & Recommendations

Based on the findings presented in this report, conclusions regarding escalator entrapment are listed below:

1. The A17.1 code is correct in requiring a lubricious skirt panel. However, it is very difficult to specify an actual coefficient of friction value between the skirt panel and various objects that may be susceptible to entrapment. Test data indicate that the lower the friction the less the entrapment likelihood. A coefficient of friction between the skirt panel and skin of no more than 0.2 may be adequate given the maximum loads an individual (adult or child) can impart. However, for objects such as shoes, it may be difficult to achieve a 0.2 or lower friction value. Nevertheless, manufacturers should set a goal of continuously striving to design a skirt panel with lower coefficients of friction.

2. The A17.1 code should specify measurement of the combined stiffness of the skirt panel and the step in the lateral direction, and establish a target for the combined stiffness of at least 4000 lbf/in. The interactive effects of combined stiffness and coefficient of friction need to be better understood, but test data clearly indicate that high combined stiffness lessens the likelihood of test wedge entrapment.

3. If the gap is within the current A17.1 code and the coefficient of friction is 0.2 or less, gap size does not seem to be a major contributor to entrapment probability or depth. Gap measurements should include step deadband. Thus, the A17.1 code recommendation of 0.19 inches should include the step deadband as well. If the coefficient of friction is 0.2 or lower, then a gap size of 0.19 inches appears adequate. Also, with higher friction gap size and combined stiffness both contribute to the possible size of entrapped objects and, consequently, the smaller the gap the better. In addition, monitoring the step deadband over time will serve as an indicator for worn step components.

In summary, reducing entrapment probability requires understanding and quantifying escalator step/skirt characteristics and their interdependencies. The findings of this study clearly indicate that the probability of entrapment can be reduced, by reducing COF and increasing combined stiffness. However, further testing is required to quantify this relationship with a sufficient level of precision. Furthermore, this study has (1) identified scientifically sound analytical techniques and (2) demonstrated how they can be applied to quantify and, subsequently reduce the likelihood of escalator step/skirt entrapment.

1. Introduction

1.1 Background Information

National Elevator Industry, Inc. (NEII) has contracted with Arthur D. Little, Inc. (ADL) to develop a performance standard for evaluating the potential for entrapment between the steps and the side (skirt) panels of moving escalators. This study was prompted by the occurrence of escalator accidents involving the step/skirt interface. Over the years the ASME A17 Committee has acknowledged this problem by making changes to part VIII of the ASME A17.1 code, which addresses escalator design and installation. Consequently, NEII has chosen to conduct a more comprehensive study to assist in developing proposed technical revisions that will be submitted to the ASME A17 Committee.

ASME A17.1-1996 [1] provides the following guidance 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

1.2 Program Objective

The objective of this study was to develop a quantitative performance standard which relates design parameters of escalators to the likelihood of an object being entrapped at the step/skirt interface. The characteristics recognized by NEII prior to this study as entrapment contributors were:

- The existence of a step/skirt gap
- The frictional force generated between an object and the skirt panel
- The mechanical stiffness of the skirt panel
- The manner in which the escalator is ridden

In developing a standard for NEII, ADL was charged with verifying the effect of these four factors on entrapment as well as investigating the possible existence of other contributing factors not previously recognized by the NEII members.

1.3 Program Approach

The approach to development of an escalator step/skirt performance standard followed the general path shown below.

- Research and documentation of likely step/skirt accident scenarios (including human factors considerations)
- Theoretical analysis of the mechanics of step/skirt entrapment
- Theoretical development of a link between design parameters and entrapment
- Performance of tests to validate the link between design parameters and entrapment
- Interpretation of test data and recommendations to NEII

Meetings were held with members of NEII in 1997 on April 3, August 18, October 30, and December 11, as well as March 19, 1998 to provide periodic updates on progress.

2. Accident Scenario Development

It is well understood that the manner in which a given escalator is ridden, as well as the condition of that escalator, affect the likelihood of a step/skirt entrapment. Therefore, it was important to first gain an understanding of how accidents occur from the perspective of human interaction. This was accomplished by gathering information from several sources, including data supplied by the NEII members, local and federal government reports, as well as conducting a literature search and assessing human factors considerations.

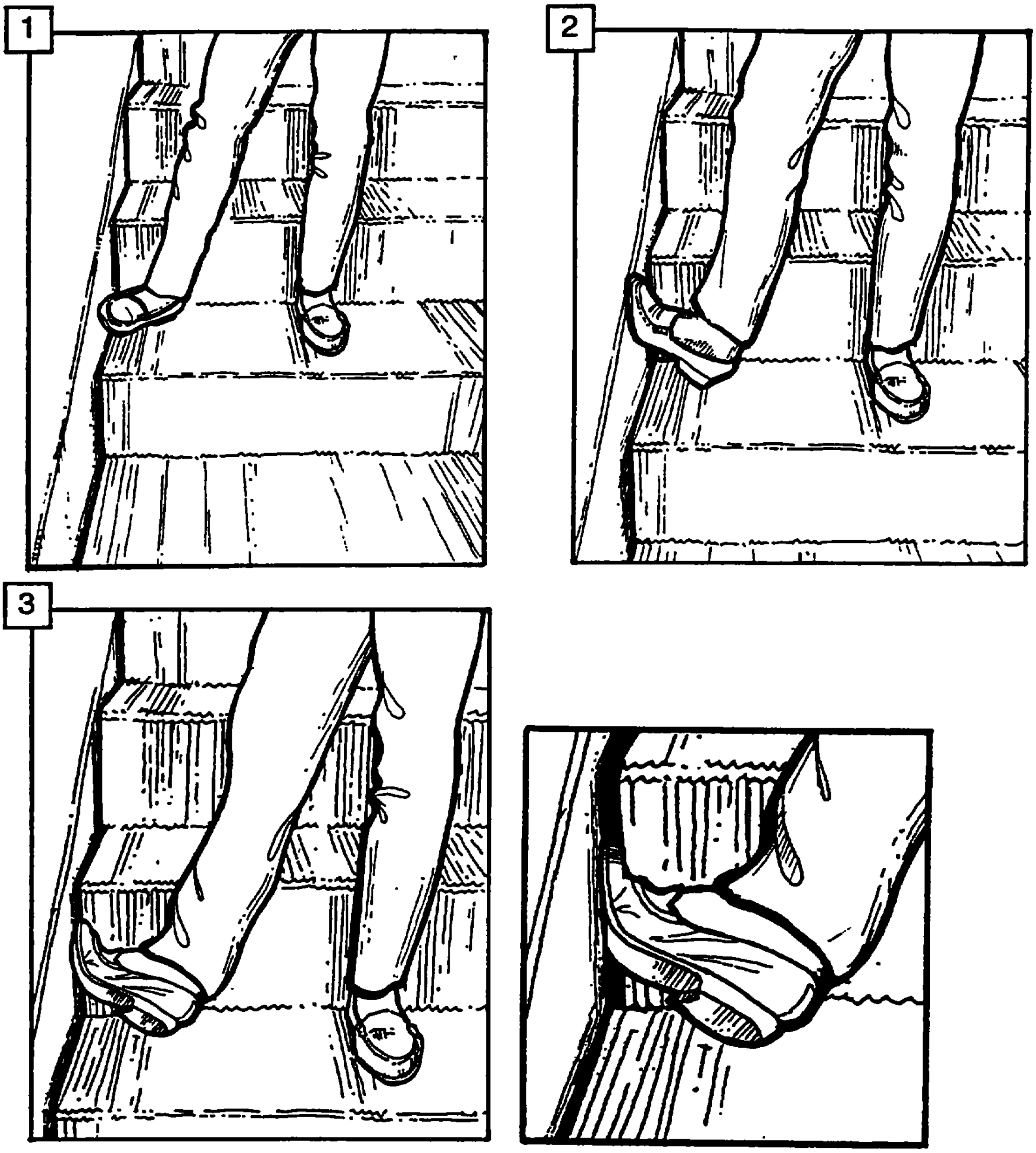
2.1 Past Accident Reports

The following documentation was examined for relevance to step/skirt entrapment:

- Information supplied by Otis, Schindler, and Montgomery-Kone
- Data supplied by the US Consumer Product Safety Commission (CPSC) [2]
  - 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 MA Department of Public Safety
- Literature search conducted by ADL

2.2 Human Factors Considerations

Building on previous discussions with the manufacturers, an escalator field investigation was conducted to define human interaction with the step/skirt interface during an accident. This investigation took place within the Boston, MA metro area subway system (MBTA). Several escalator units were visited at different stations within the MBTA. A stopped unit was found at Porter Square station (Cambridge, MA) where possible step/skirt accident scenarios were simulated and photographed using project participants as well as passersby as models. The photographs were used as a baseline to illustrate several accident scenarios. These illustrations are shown in Figures 2-1 through 2-4.

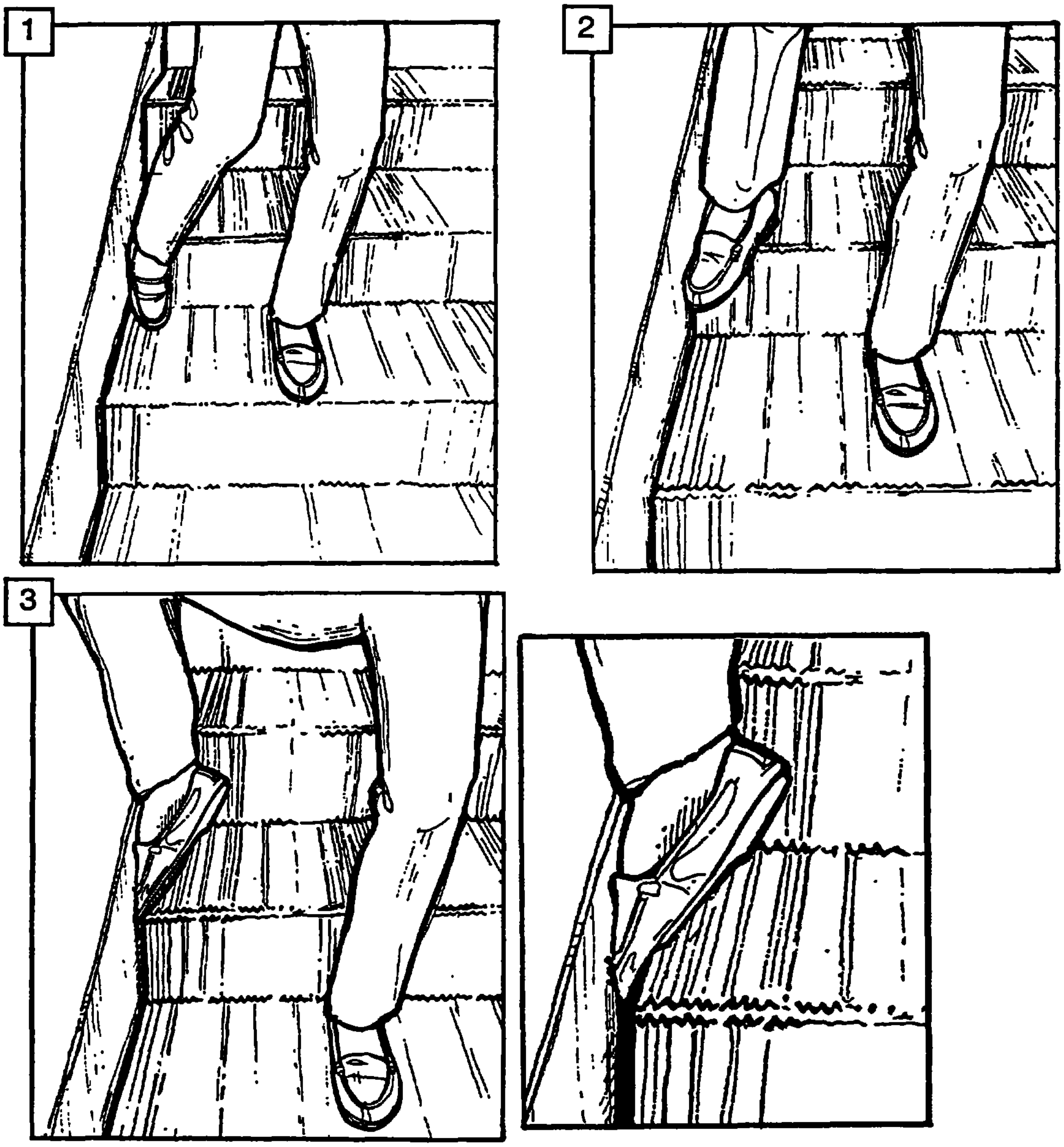


1. Toe section or foot is raised onto skirt panel

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

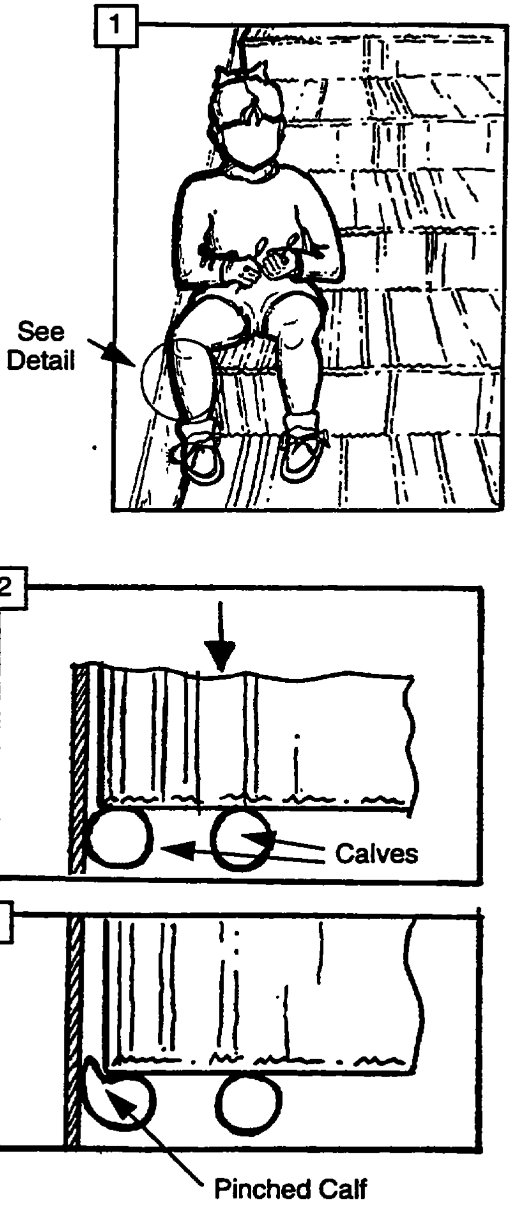
3. Friction between shoe and skirt panel is still sufficient to prevent foot from sliding
   Toe section becomes entrapped between panel and next higher step

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



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 2-2: Toe entrapment and release scenario for a down escalator.

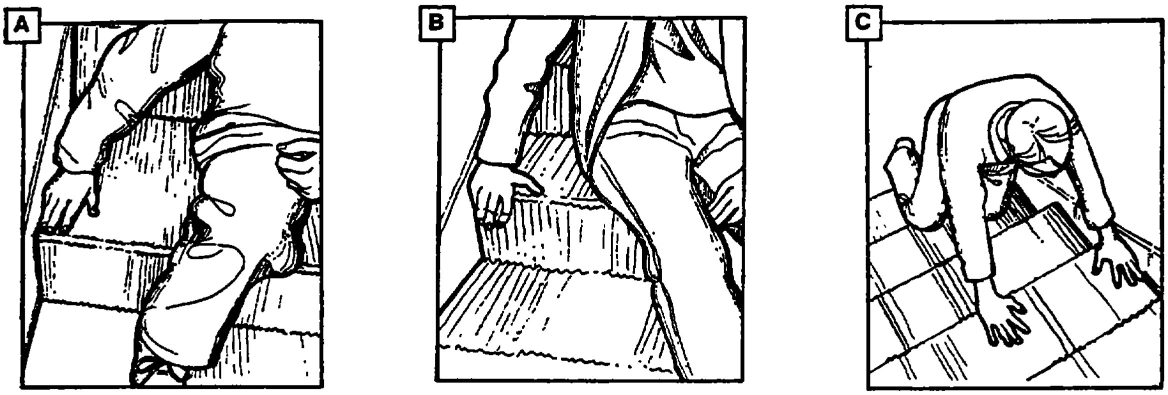


1. Child backs up and stands or sits too close to step immediately behind him/her such that calf is in contact with riser portion of that step

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 2-3: 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

- 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
- 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 2-4: Hand and finger entrapment scenarios for both escalator directions.

2.3 Accident Scenario Summary

The following possible accident scenarios at the step/skirt interface were documented and are summarized in Table 2-1.

Table 2-1: Summary of accident scenarios documented as a result of project sponsored human interaction investigation.

Accident Scenario	Direction	Entrapment Interface	See Figure
Foot/Toe Entrapment	Down	Riser/Skirt Panel	2-1
Toe Entrapment/Release	Down	Riser/Skirt Panel	2-2
Calf Entrapment	Down	Riser/Skirt Panel	2-3
Hand/Finger Entrapment (Both Directions)	Up	Tread/Skirt Panel	2-4
Hand/Finger Entrapment (Subject Sitting)	Down	Riser/Skirt Panel	2-4
Hand/Finger Entrapment (Subject Kneeling)	Up	Tread/Skirt Panel	2-4

(Note: The investigation focused on limb entrapment and did not consider the possible entrapment of shoe laces, clothing, or hair.)

3. Mechanics of Entrapment

The mechanics of step/skirt panel entrapment is a major factor in determining which escalator parameters contribute to the entrapment process. The assignment involved understanding the analytical requirements for each of the developed scenarios, understanding escalator designs, and performing the appropriate level mechanics analysis. The objective of the analysis was to focus on the first event of the entrapment process; namely the initiation of entrapment. The details of the entrapment process itself (when an object is already in the gap) was not germane to the objective of this assignment. The primary goal was to understand how to prevent the initiation. As a result, the following sections summarize the relevant analyses and are presented in the following order: escalator design considerations, entrapment scenario requirements, and entrapment analysis.

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 gap.

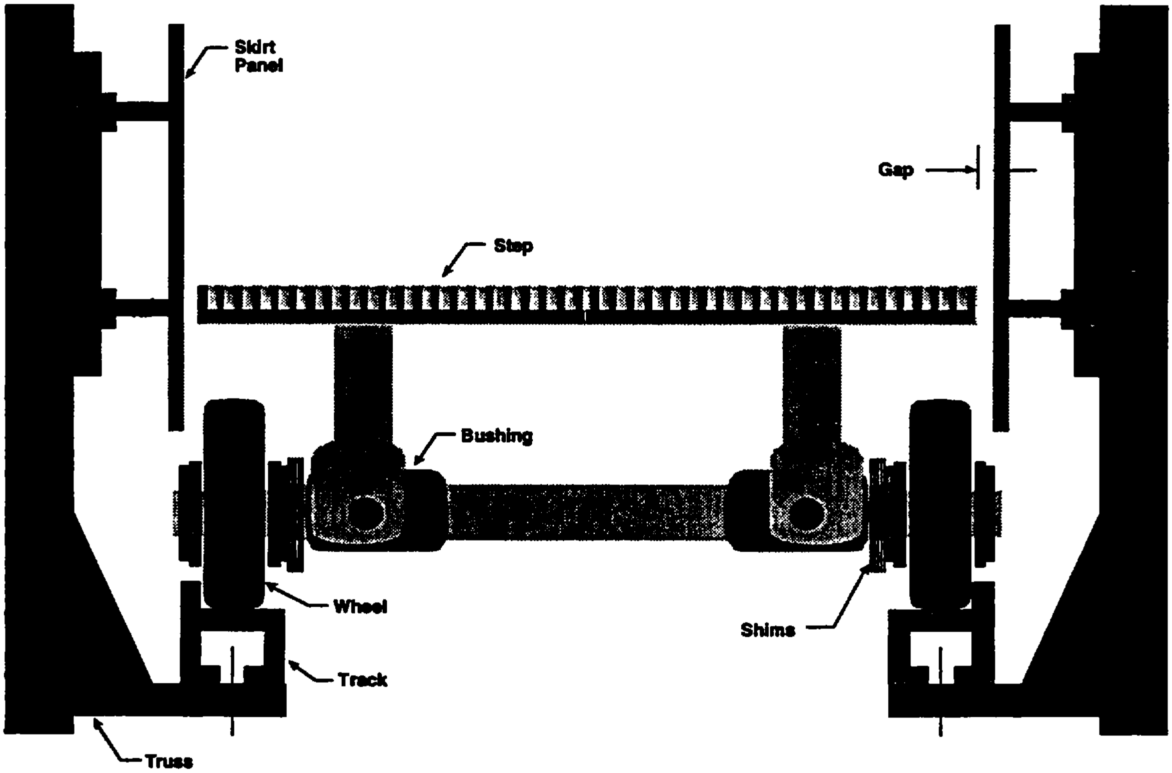


Figure 3-1: Escalator crossectional view.

Based on discussions with escalator manufacturers and a limited review of escalator designs, sources of gap variation were identified and illustrated in Figure 3-2.

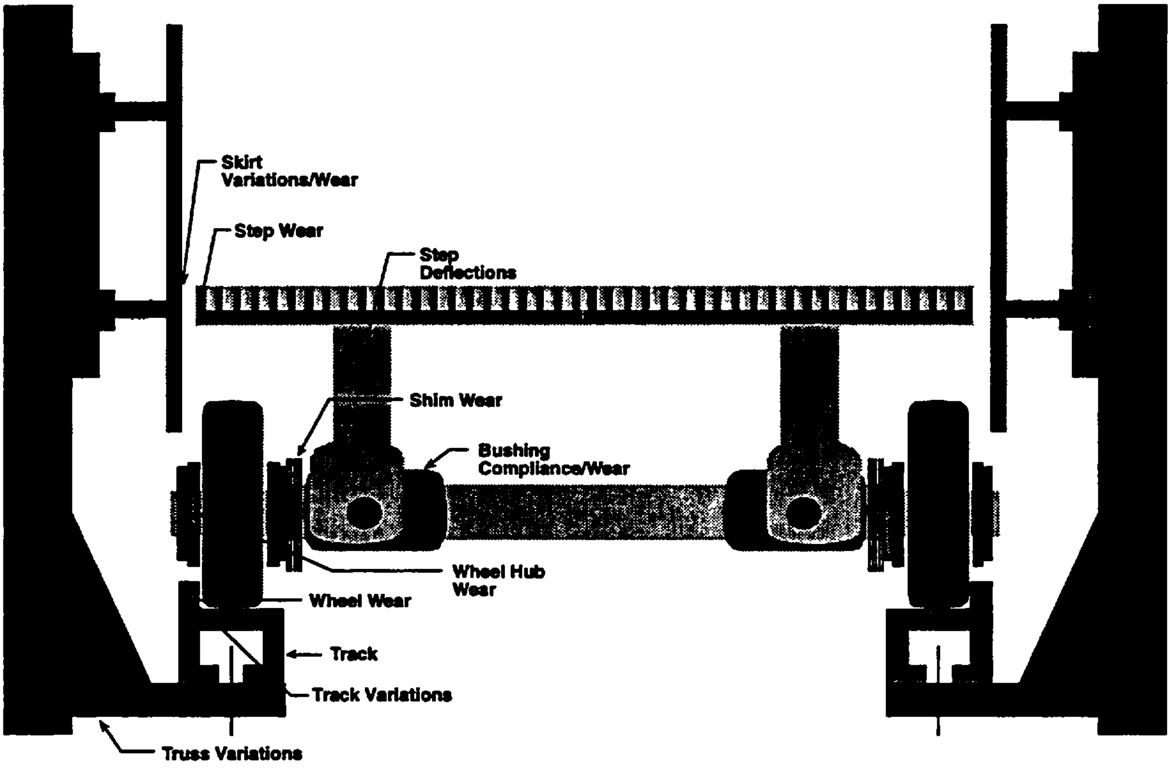


Figure 3-2: Step/skirt gap variation sources.

These gap variation sources can be grouped as side panel, step, or truss. The following options tree provides a road map of this grouping.

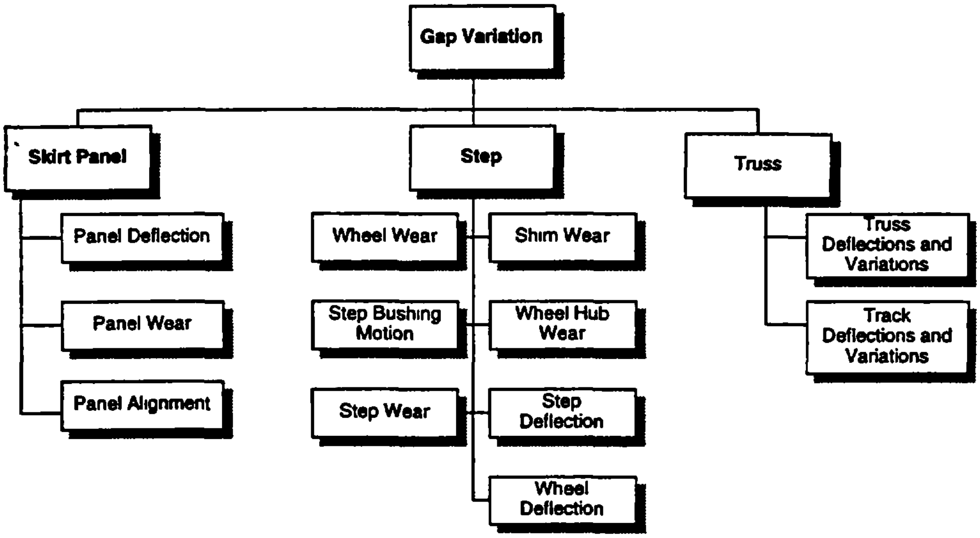


Figure 3-3: Gap variation source options tree.

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 analysis should include the following variables:

- *gap size* consisting of skirt panel variations, track variations, and worn components
- *skirt panel stiffness*
- *step stiffness* consisting of track, truss, and wheel/components

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.

3.2.1 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 3-4 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.

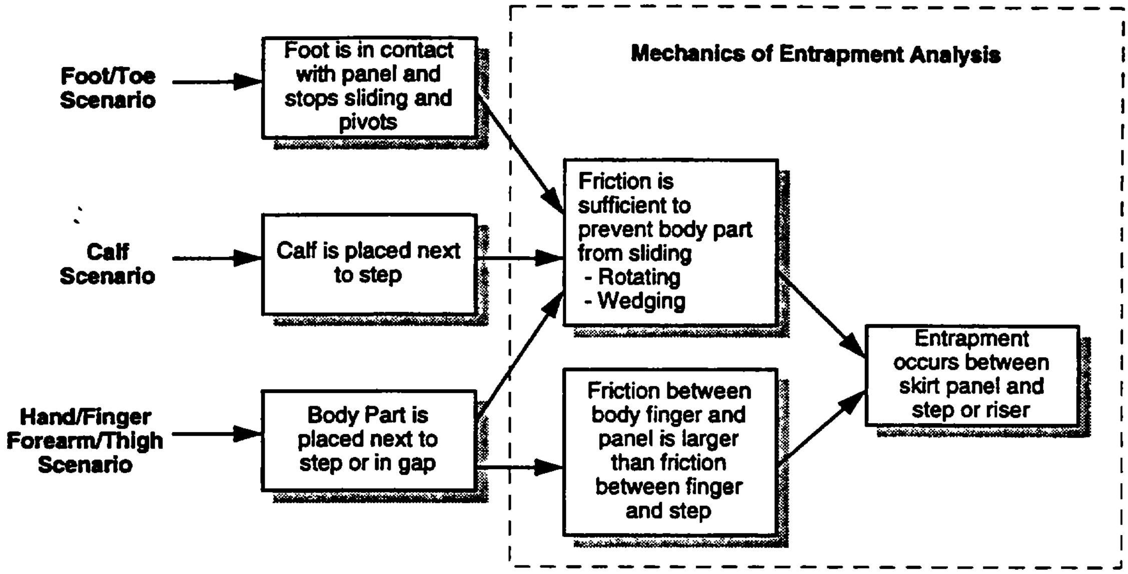


Figure 3-4: Entrapment Analysis definition.

The three resulting conditions are: object rotating into the gap; object wedging into the gap; or object spinning in the gap after entry. The latter is not considered relevant to the main objective of preventing entrapment initiation, and therefore will not be discussed here. The two conditions for further analysis are illustrated in Figure 3-5.

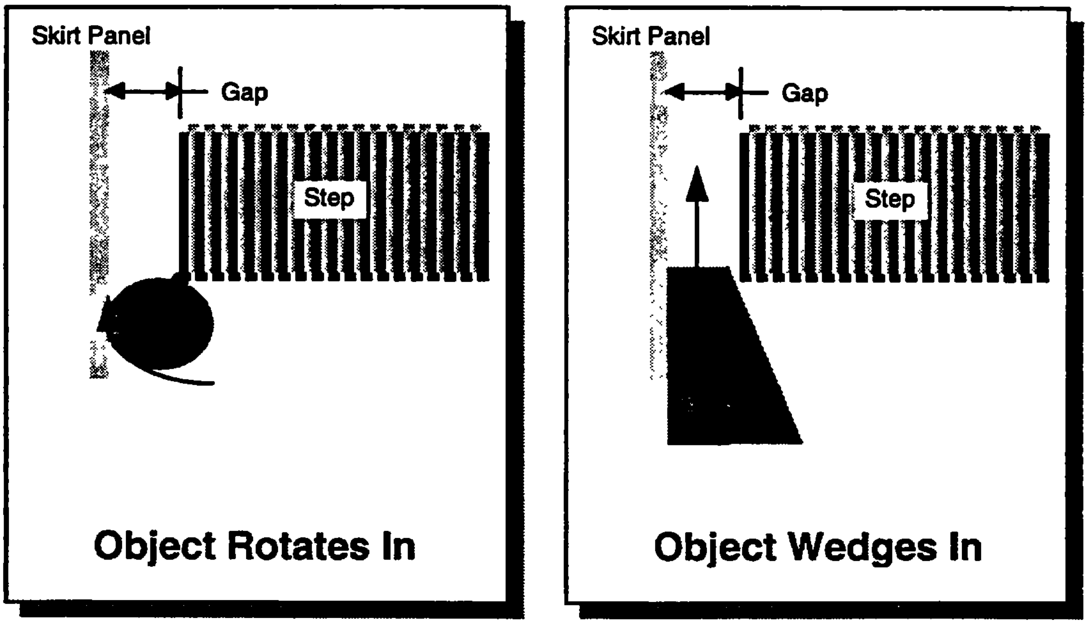
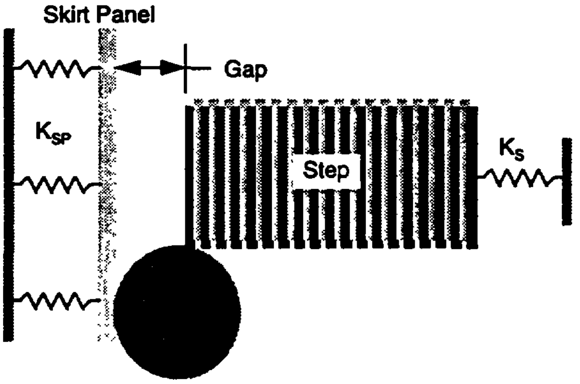


Figure 3-5: Entrapment diagrams (plan view).

3.2.2 Entrapment Analysis

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

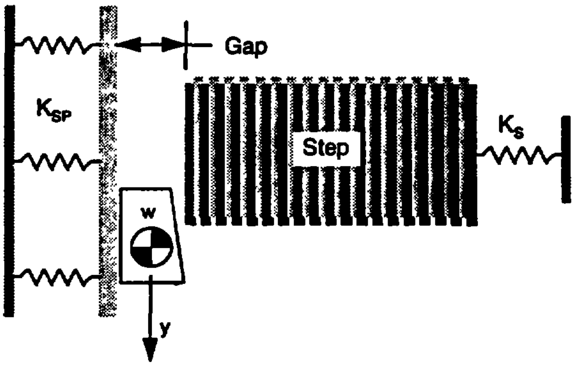
and,

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

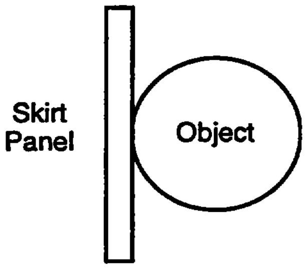
K_O = object stiffness

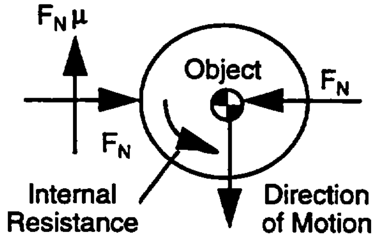
For an object wedging into the gap, a similar system diagram was generated.



3.2.2.1 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:

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

where: T_{internal} is the resisting torque
I is the inertia
θ'' is the angular acceleration

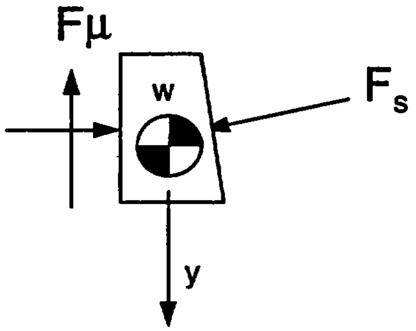
When the left side of this equation exceeds zero, then the object no longer slides -- it sticks or chatters on the skirt panel. Thus for the object to continue slipping,

$$F_N \mu \text{ (Radius)} < T_{\text{Internal}} \qquad (2)$$

or

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

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:

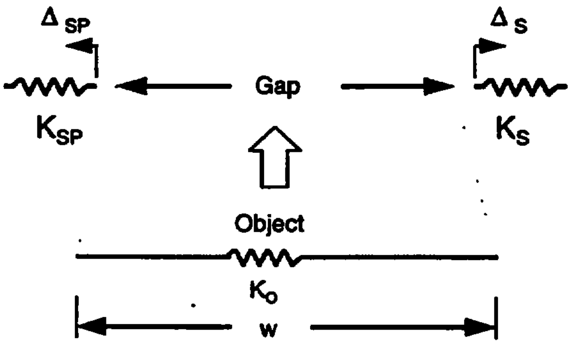
μ is the coefficient of friction
F_s is the normal force on the surface of the wedge
y'' is the wedge acceleration
θ is the angle of the wedge surface

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

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

3.2.2.2 Compliance Analysis

A compliance 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,

$$F_i = K_i \Delta_i \tag{8}$$

Combining these two equations leads to the following compliance relationship:

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

Thus, the generated force can be determined, given values for w, gap, and 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 becomes inherently non-linear
  - Very low stiffness or even deadband may be present followed by very high stiffness
  - Extremely low stiffness can exist due to "slop" in system
  - Step stiffness will change as chain 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.

3.2.2.3 Compliance Modeling

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

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

where the reciprocal of the combined system stiffness is

$$[1/K_{TOT}] = [1/K_o + 1/K_s + 1/K_{SP}] \tag{11}$$

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. Using the results of Burstein and Reilly [3] as a starting point, it was estimated that if the deflection δ of a human finger was limited to a maximum of 0.2 in., K_0 would be equal to approximately 40 lbf/in. and injury would be minimized.

A few key observations can be made regarding equation (10):

- The term $[1/K_{TOT}]$ can be minimized in order to minimize δ
- Minimizing $[1/K_{TOT}]$ is equivalent to maximizing the combined system stiffness
- The combined stiffness is dominated by the most compliant member in the system, in this case a "soft" object (human finger)
- The generated force F is difficult to control because w varies extensively
- The gap size G affects the size of objects that could be entrapped

Since the object compliance is difficult to control, the system must be analyzed for a wide range of object stiffness. As shown in Figure 3-6, step stiffness can be designed such that the combined stiffness deviation is minimal, given a skirt panel stiffness of 2500 lbf/in. At a step stiffness of 6500 lbf/in, a 2% deviation in total stiffness is achievable with an object stiffness as low as 40 lbf/in. This in turn implies a minimal amount of object deflection.

In general, it can be deduced from the above analysis that the combined stiffness of the skirt panel and step should be much larger than the object stiffness in order to minimize the amount of object deflection.

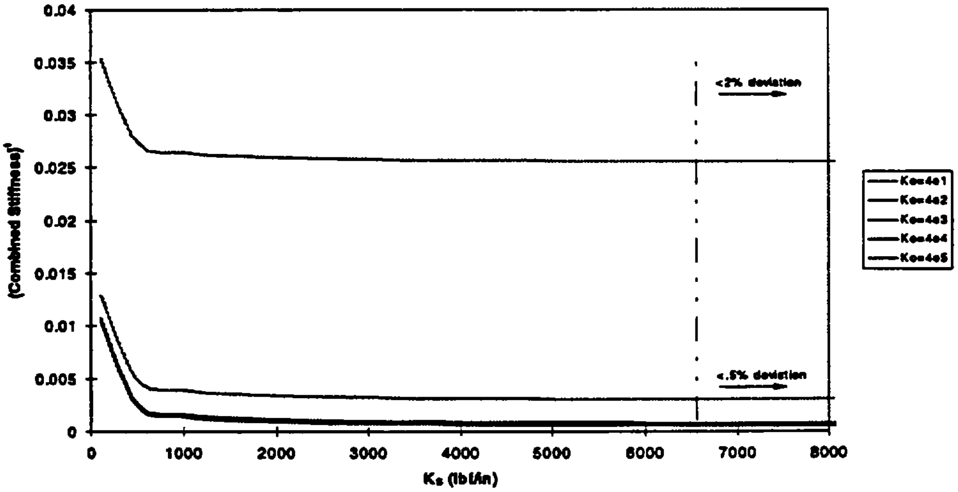


Figure 3-6: Combined Stiffness versus Ks for Various Object Stiffnesses (with Ksp = 2500)

4.1 Experimental Considerations

The analysis of the mechanics of entrapment identified which variables contribute to entrapment, namely step/skirt gap, skirt panel stiffness, coefficient of friction (object to skirt panel) and step lateral stiffness. Since the current ASME code discusses specific requirements for skirt panel stiffness and gap measurements, experiments focused initially on coefficient of friction and step lateral stiffness measurements. Later experimentation concentrated on entrapment simulation.

4.1.1 Key Experimental Assumptions

The key assumptions for these two variables as they relate to entrapment potential are as follows:

- Coefficient of Friction
  - Entrapment potential exists whenever an object in contact with the skirt panel ceases to slide.
  - The maximum allowable coefficient depends on a given accident scenario.

- Step Lateral Stiffness
  - A high value of step stiffness reduces entrapment depth.
  - Lateral step stiffness measurements should note any deadband in the step, take up that deadband distance, and then load the step.

4.1.2 Objectives of Experiments

The experiments were intended to confirm the key assumptions presented in the previous section. In particular, the experimental objectives were to:

- Determine the minimum coefficient of friction required to prevent the sliding of objects in various accident scenarios.
- Determine feasibility of measuring the step lateral stiffness of a test escalator.
- Determine how each variable, as presented in Section 3, affects entrapment initiation or depth.

The approach to conducting these tests used laboratory equipment at Arthur D. Little, as well as a test escalator and other equipment at Montgomery-Kone headquarters.

4.1.3 Coefficient of Friction Test Considerations

The potential for entrapment initiation occurs when the object in contact with the skirt panel no longer slides, and begins to resist motion (i.e. sticks to skirt panel). A thorough mechanical analysis considers the object in contact with the skirt panel and accounts for its internal object forces. Since these forces are difficult to determine, tests were performed using human hands and a typical athletic shoe as test samples.

The coefficient of friction test approach was as follows:

1. Determine suitable materials and their coefficient of friction against skin and a representative athletic shoe (e.g., 0.05, 0.1, 0.2, 0.3, 0.4, 0.5).
2. For each combination, determine the minimum normal force necessary such that the object begins to chatter or stop sliding.
3. Determine the normal force with which a person can push on the skirt panel in each accident scenario.
4. Determine the required coefficient of friction to prevent chatter for each accident scenario.

4.1.4 Step Lateral Stiffness Test Considerations

The step lateral stiffness measurement was made on a test escalator with the skirt panel removed. The measurement was made using an LVDT placed between the truss and the step, in conjunction with a load cell and pneumatic piston placed between the stiffest part of the truss member and the step. Measurements were taken in both skirt panel directions, noting any deadband in the step but not including the deadband distance in the measurement.

4.1.5 Entrapment Test Considerations

Entrapment was simulated using several wedge-shaped teflon test objects on the Montgomery-Kone test escalator. Two sets of tests were performed:

- Established frictional conditions necessary to cause entrapment of a test object and then reduced friction by controlled lubrication such that entrapment did not occur.
- Entrapped a test object and measured entrapment depth for both high and low values of step lateral and skirt panel stiffness.

4.2 Coefficient of Friction Tests

One of the contributing factors to escalator accidents is the coefficient of friction (COF) between the stationary skirt panel and the moving object. This is one of the most difficult aspects of escalator design to control. Factors such as skirt panel material, surface finish and condition, and applied material create a virtually endless number of combinations of COF values. Some escalator step/skirt accident scenarios involve entrapment of shoes and hands. Both offer very good adhesive properties, since they are used to grip floors and items respectively.

4.2.1 Objective

To understand what values of COF can be expected in a variety of escalator and rider combinations, a series of experiments was developed and conducted in the ADL

Physical Test Laboratory. These tests were run using a variety of materials, lubricants, shoe types, and human subjects. This resulted in a range of COF values which were used for chatter initiation tests.

4.2.2 Setup and Procedure

The COF setup utilized an Instron Test Machine and computer to record tangential load (F_T) data, and a laboratory scale to indicate the normal load (F_N). The setup is detailed in Figure 4-1. These two values are utilized to determine the COF using the equation:

$$\mu = F_T/F_N \tag{13}$$

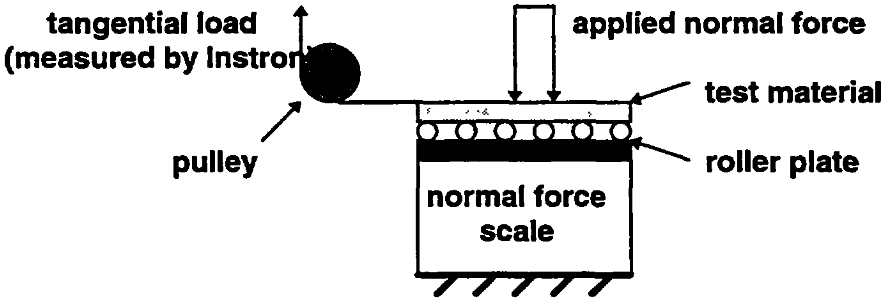


Figure 4-1: Coefficient of friction test setup.

This setup was used for both skin and shoe experiments. The normal load was maintained constant while the test material was displaced by the Instron machine. A computer program for tensile testing was utilized to control the movement of the test materials and record the tangential force and displacement. To minimize rolling friction in the test equipment a custom roller plate was built. This consisted of a rigid aluminum plate and two extrusions with low friction plastic wheels attached. The wheels were positioned every 2 inches along the 18 inch plate. Any rolling friction associated with this setup was consistent from one experiment to another.

For the skin friction experiments the side of the hand opposite the thumb was used. This orientation was found to be the most repeatable, controllable, and easiest to perform by the human subjects. To restrain the hands of human subjects from moving with the test material, an adjustable Velcro sling was used. The sling immobilized the arms and upper bodies of the subjects in the desired location and height.

The test for shoe friction allowed a simpler setup. Here each shoe was fitted with a small eye bolt at the back of the sole. The eye bolt was connected to a lab stand by a piece of music wire. The lab stand was weighted to prevent movement and the music wire was straightened to prevent any spring effects. This setup was consistent from one shoe to another, and repeatable from one experiment to another.

To apply the normal force to both the hand and shoes, #9 lead shot was used. The shot was put into small bags, each of which weighed approximately 2 pounds. This method allowed the bags to be placed on the subject's hand (or a shoe) and form to the features of each. This nearly eliminated the effect of the forearm muscles which could apply wrist rotation and influence the normal force.

For the COF testing several materials, shoe types, and skin types were used, as shown in Table 4-1.

Table 4-1: Materials used in COF testing.

Material	Shoe	Skin
High Density Polyethylene (HDPE)	Nike Running (new)	Two Subjects
Acrylonitrile-Butadiene-Styrene (ABS)	Brooks Cross-Trainer (used)	
Dupont Teflon	Sperry Boat Shoe (used)	
Dupont Delrin		
Acrylic*		
Anodized Aluminum*		
Stainless Steel		

* These materials were not used after the initial run. The COF values for skin and shoes approached 1. It was decided this value was excessive.

To conduct a test run, the test material was installed onto the roller plate and the normal force scale was set to zero. Either a shoe or hand was then placed in the center of the plate and the normal force was recorded. The first run was done with no additional weight besides that of the shoe or human subject. The following runs used the lead shot to increase the normal force, in order to prove that COF was independent of the normal force magnitude. The bags were placed directly on top of the shoe, and on the thumb/index finger of the hands. The positioning of weights on the hand was refined prior to beginning the experiments.

Once the setup was established for each run the Instron computer program was started. The program displaced the upper plate of the Instron at a rate of 50 inches/minute. The tangential force was transferred to the load cell in the upper plate and recorded by the computer program. The results of each run are plotted as force vs. displacement and the average tangential force is determined by the program. During the test the operator recorded the normal force on the digital scale. Figure 4-2 illustrates the test procedure. The chart includes steps for initiation of chatter testing which is covered in Section 5.3.

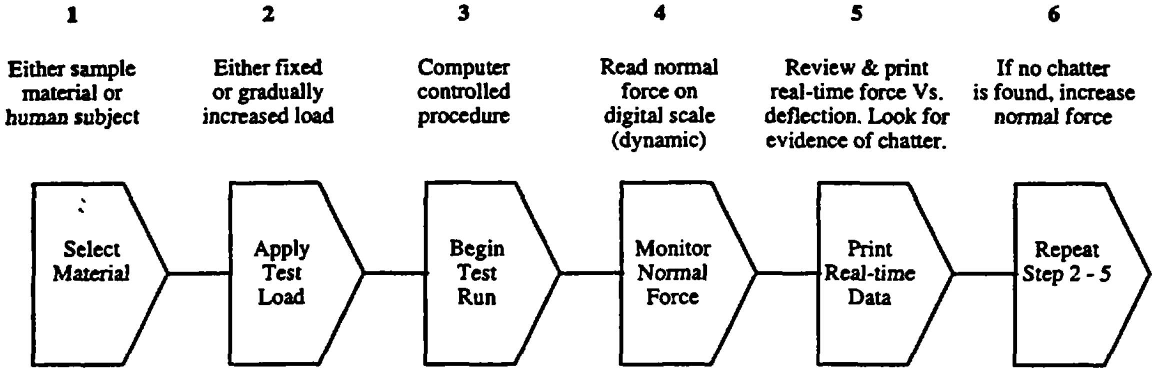


Figure 4-2: Friction test procedure flow.

4.2.3 Reduced Data and Results

A full range of COF values was obtained by testing several materials in contact with both skin and shoes using different lubrication media. Though this was not intended to represent actual conditions that exist on an escalator, lower COF values were required to evaluate the effects of COF on initiation of chatter. The first test was run with dry materials, the second with talcum powder, and the third with light spindle oil. Table 4-2 below summarizes the COF values that were observed under these specific test conditions; they are not intended to represent COF values that could result from testing other specimens. Several combinations were subsequently used to evaluate the initiation of chatter, and these entries are shaded.

Table 4-2: Coefficient of friction test measurements.

Test Material	Skin			Shoes		
	Dry	Talc	Oil	Dry	Talc	Oil
Stainless Steel	0.52	0.31	0.18	0.29	0.30	0.26
ABS	0.44	0.34	0.21	1.11	0.22	0.24
Delrin	0.35	0.34	0.18	0.80	0.27	0.23
HDPE	0.26	0.25	0.15	0.74	0.32	0.21
Teflon	0.50	0.28	0.12	0.34	0.22	0.19

Note: These values are not intended to represent actual conditions that exist on an escalator, but are only intended to establish a range of test conditions.

4.3 Initiation of Chatter Tests

4.3.1 Objective

The entrapment scenarios previously described occur when an object sliding along the skirt panel decelerates or stops. When the escalator step is moving, the relative velocity between the step and object is zero, and they are moving together. When the object begins to stick to the skirt panel it "chatters" and begins to move into the step/skirt gap.

To understand what loads will cause chatter to initiate, a series of experiments similar to the friction tests were conducted.

4.3.2 Setup and Procedure

In this experiment some of the COF values previously determined were selected to represent a broad range. The experiment utilized the same setup and basic procedure as the COF experiments. The difference in this experiment was a gradual increase of the normal load, in order to produce evidence of chatter. Chatter is graphically represented by cyclical steep positive and negative slopes in the force vs. deflection curve. The repetition is caused by the two test materials sticking to each other momentarily, then separating. Typically once chatter is initiated it will continue to occur until it is disrupted. The lack of chatter evidence is indicated by erratic or shallow slopes and lower peak-to-peak amplitudes. Figure 4-3 illustrates these two conditions. The plot is for shoe #1 @ $\mu = 0.33$, where chatter initiated at $F_N = 2.50$ lbf.

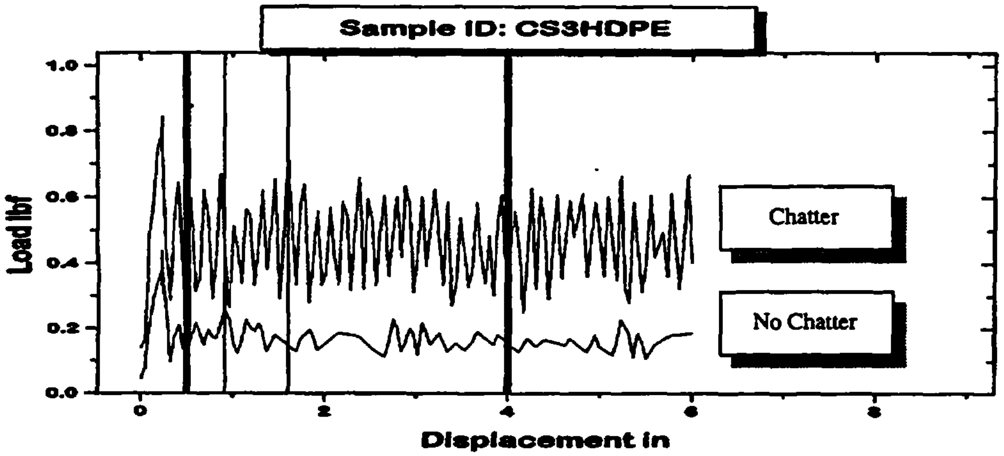


Figure 4-3: Typical chatter initiation plot.

4.3.3 Reduced Data and Results

Like the COF experiments, the two items sliding by each other represent the skirt panel and the rider. When chatter is initiated the contacting portion of the rider sticks to the skirt panel momentarily. This event may be sufficient to cause an entrapment.

Table 4-3: Initiation of Chatter Results.

COF	Chatter Initiation Results	Surface	Comment
0.19	No chatter at $F_n = 20$ lbf	Skin	
0.37	Chatter initiated at $F_n = 13.7$ lbf	Skin	
0.61	Chatter initiated at $F_n = 4.7$ lbf	Skin	
0.19	No chatter at $F_n = 14.9$ lbf	Shoe #1	(new running shoe)
0.33	Chatter initiated at $F_n = 2.5$ lbf	Shoe #1	
0.32	No chatter at $F_n = 10.3$ lbf	Shoe #3	(used boat shoe)

The initiation of chatter experimental results given in Table 4-3 show that low COF value for both skin and shoe friction will not promote the initiation of chatter.

4.4 Human Impart Tests

4.4.1 Objective

The objective of the human impart testing was to determine the normal force with which children and adults can push on the skirt panel in the various accident scenarios. This information in conjunction with the chatter initiation data could then be used to select loading for each material combination in the entrapment simulation experiments.

4.4.2 Setup and Procedure

Eight human test subjects were selected for these tests, with the intent of characterizing a cross-section of age/weight categories. Ten force application positions were tested, and each of these was replicated three times for each subject. The force positions were intended to characterize the possible skirt panel load applications for the previously described accident scenarios. A laboratory scale was used to register all forces.

4.4.3 Reduced Data and Results

The three replicate tests for each subject in each force application position were averaged. These averages are shown in Table 4-4.

Table 4-4: Human Impart Test Data

(All weights and forces in pounds)									
		Children					Adults		
	Age	11	7	8	9	5	28	37	36
	Weight	85	49	50	72	51	140	95	170
Position	Location								
Standing	Foot	9.9	3.4	4.9	11.7	5.3	12.1	6.6	19.0
	Calf	10.3	8.8	13.9	21.7	11.3	21.7	23.7	29.0
	Hand	13.9	11.9	7.3	11.3	6.0	16.7	10.3	18.0
	Toe	--	9.0	14.6	13.3	14.0	19.0	25.7	50.0
Leaning	Foot	9.2	6.0	5.8	8.7	4.3	9.5	21.3	--
	Calf	12.3	13.7	15.2	15.7	10.7	26.7	22.7	28.3
	Hand	8.0	12.0	16.3	7.3	11.3	22.7	18.0	30.6
Sitting	Foot	12.0	5.1	5.2	10.0	4.3	11.7	8.3	20.6
	Calf	13.3	7.8	6.5	18.3	9.7	21.0	15.6	25.0
	Hand	9.0	6.3	6.8	7.3	5.7	10.0	6.4	14.3

A probability model[4] was used to characterize the maximum forces observed over all ten scenarios, for children and adults. The model yielded one-percentile force estimates for children and adults, and results are shown in Table 4-5.

Table 4-5: Human Impart Test Results

Subject Type	1-Percentile Force Estimate (pounds)
Child	27
Adult	57

Table 4-5 is interpreted such that there is a 1% chance that a child would exert a force greater than 27 lb. on the skirt panel in these accident scenarios. Similarly, there is a 1% chance that an adult would exert a force greater than 57 lb. in these accident scenarios.

4.5 Step Lateral Stiffness

4.5.1 Objective

As detailed in the Mechanics of Entrapment section of this report, the step lateral stiffness (K_S) is a factor in the step/skirt/object lumped mass model. To determine the values of K_S an escalator was instrumented at the Montgomery-Kone facility in Moline, IL. Finite step stiffness results from the fact that steps of an escalator require some lateral movement to prevent system binding. If this was not permitted motion of the conveyor would be resisted by steps sliding against the skirt panels and associated structure, causing damage to one or both components.

4.5.2 Setup and Procedure

To gather K_S values, a portable test device built by Montgomery-Kone was used. The device consisted of a compressed nitrogen supply, two linear variable differential transformers (LVDT), a data acquisition system, and a pneumatic cylinder. The device was capable of being installed onto escalator steps and interfacing with a laptop computer to record data. This device was also instrumented with a double beam strain gauge to measure the coefficient of friction along the escalator.

Step lateral stiffness measurements were taken at three different locations on the test escalator, at the vertical skirt panel supports. These supports are substantial members in an orientation favorable to resisting deflection. To take the measurements, the test device was installed on the step to be measured. Next, the step was positioned so the pneumatic cylinder was in-line with the vertical support. Without deflecting the step the cylinder ram was placed on the skirt panel and the LVDT was placed on the opposite skirt panel. Figure 4-4 details the step stiffness setup and device.

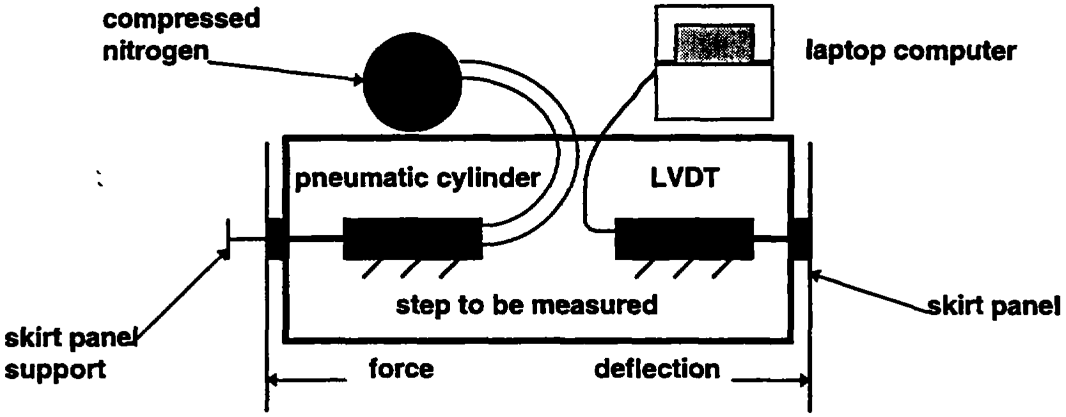


Figure 4-4: Step stiffness measurement setup.

The nitrogen pressure was increased from 0psi to 70psi in increments of 10psi. This yielded a maximum applied load of 220 lbf. At each of the load increments a deflection was read from the laptop computer. The total load and deflection were used to determine step stiffness. Each location was measured three times for a total of nine values.

4.5.3 Reduced Data and Results

After data collection and review the step stiffness values were calculated. Values ranged from 7860 lbf/inch to 11000 lbf/inch. When evaluating the data, the dead-band in the step was subtracted from the step deflection value prior to making the stiffness calculation. The dead-band is defined as the amount of lateral movement the step is capable of when minimally loaded. During the first of the three test runs the step was displaced to the side opposite the applied load. When the load was removed the step moved back to its original location, minus the dead-band displacement. This is evident in the no load LVDT readings at the beginning of each run. Dead-band values ranged from 0.011 inches to 0.023 inches.

4.6 Skirt Panel Stiffness

4.6.1 Objective

Similar to Step Lateral Stiffness (K_S), the Skirt Panel Stiffness (K_{SP}) is also a factor in the step/skirt/object lumped mass model. Though a recommended value for K_{SP} is detailed in ASME A17.1 code, it was also measured on the test escalator at Montgomery-Kone.

4.6.2 Setup and Procedure

To determine K_{SP} the Montgomery-Kone portable test device was used in similar manner to that described in section 5.3.2. The device was modified to utilize two LVDT's, one on each side of the step to measure skirt panel deflections. Each location was measured three times for a total of nine values. Figure 4-5 details the skirt panel stiffness setup and device.

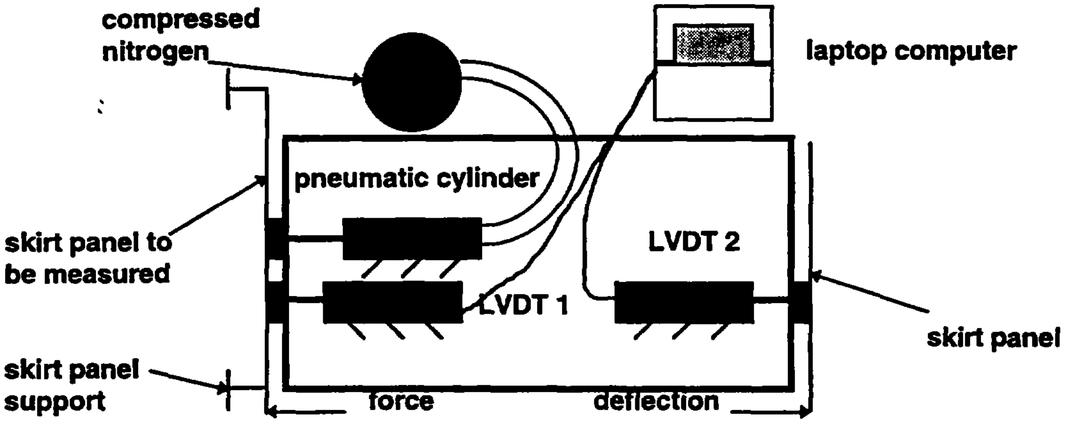


Figure 4-5: Skirt panel stiffness measurement setup.

The use of two LVDTs made it possible to separate the skirt panel deflection from the step deflection. To do this the same total load (220lbf) was applied and the same incremental steps were used as in the step stiffness tests. At each load level the two LVDT values were read. The two values were subtracted from each other to determine the amount of skirt panel deflection.

4.6.3 Reduced Data and Results

K_{SP} measurements were taken at three different locations along the escalator. The locations were chosen to account for variations in construction. Location #1 was a typical support mid point. The skirt panel and structure (behind skirt panel) were continuous. Location #2 was a joint location of both the skirt panel and structure. Location #3 was a modified structure section, where the structure was machined to reduce stiffness. This modification was done to provide a stiffness value lower than the existing design offered. Each of the three locations was tested three times. The skirt panel stiffness results are summarized in Table 4-6.

Table 4-6: Skirt panel stiffness results.

Location	Description	Stiffness (Ksp) Values
1	Typical mid support section, no joints	5500 lbf / inch 6111 lbf / inch 7097 lbf / inch
2	Joint of skirt panel and structure	3792 lbf / inch 3792 lbf / inch 4312 lbf / inch
3	Modified section for low K_{sp}	2471 lbf / inch 2417 lbf / inch 2557 lbf / inch

4.7 Entrapment Simulation

4.7.1 Objective

The ultimate goal of validation testing was to identify what factors influenced the likelihood of entrapment. Thus, it was decided that each of the factors from the lumped mass model needed to be evaluated for their individual and combined impact on entrapment. Knowing which factors have a dominant impact on entrapment will facilitate proper recommendations for minimizing entrapment in the field.

4.7.2 Setup and Procedure

A test matrix was designed to evaluate all of the lumped mass factors for a total of 16 unique conditions. Each condition was run three times totaling 48 observations in all. The same test device used in the step and skirt panel stiffness experiment was utilized for the entrapment simulations, although the LVDTs and laptop computer were not required. A teflon wedge test object was designed, where the geometry detailed in Figure 4-6 was chosen to allow the wedge to become entrapped but not destroyed. Oil lubricated teflon and silicone lubricated skirt panels yielded a COF value of 0.19. Adding a 40 durometer neoprene pad to the bottom of the wedge (indicated by dashed lines) increased the COF value to 0.6.

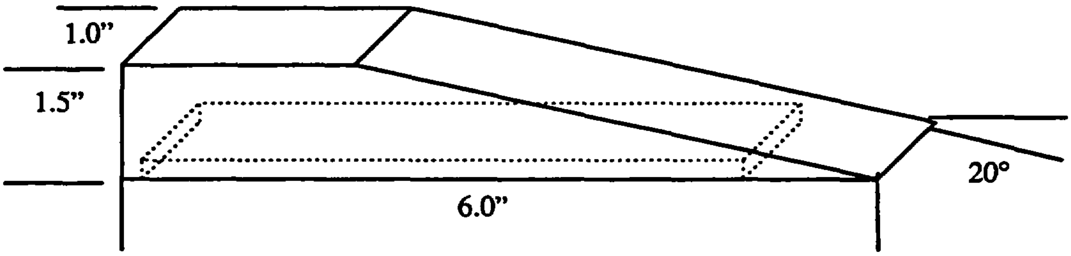


Figure 4-6: Teflon wedge object used for entrapment testing.

Table 4-7: Entrapment simulation test matrix.

CONDITION	COEFFICIENT OF FRICTION	SKIRT PANEL TO STEP GAP (in.)	STEP STIFFNESS (lbf/in)	SKIRT PANEL STIFFNESS (lbf/in)	COMBINED STIFFNESS (lbf/in)
1	0.19	0.1875	11000	2400	1970
2	0.19	0.1875	11000	6000	3880
3	0.19	0.1875	4000	2400	1500
4	0.19	0.1875	4000	6000	2400
5	0.19	0.0900	11000	2400	1970
6	0.19	0.0900	11000	6000	3880
7	0.19	0.0900	4000	2400	1500
8	0.19	0.0900	4000	6000	2400
9	0.6	0.1875	11000	2400	1970
10	0.6	0.1875	11000	6000	3880
11	0.6	0.1875	4000	2400	1500
12	0.6	0.1875	4000	6000	2400
13	0.6	0.0625	11000	2400	1970
14	0.6	0.0625	11000	6000	3880
15	0.6	0.0900	4000	2400	1500
16	0.6	0.0900	4000	6000	2400

Table 4-7 above presents the 16 unique conditions tested in the experiment. For each run the test device was positioned at the desired test location (compliant skirt panel, for example) and a Teflon wedge was placed between the skirt panel and the pneumatic ram, which was set approximately at 53 lbf for all runs. This value represents a force that is not likely to be exceeded by a human involved in any of the previously described accident scenarios, and was experimentally determined as part of the Human Impart testing described in Section 4[1]. The wedge was lubricated or fitted with a neoprene pad as required. All of the low and high COF tests were run independently so lubricants were not placed on dry surfaces accidentally. The stiffness of the step (K_S) was also preset prior to any test runs. The K_S value was varied by adding Bellville washers as required to the step axles. The K_S value was verified after any washers were added or removed.

After test preparation two observers rode on the moving step with the test device. One observer watched the Teflon wedge looking for movement towards the step/skirt gap or an entrapment. Movement toward the gap but no entrapment indicated the initiation of chatter (possibly leading to an entrapment). The other observer would determine the location along the skirt panel of the movement (or entrapment) when the observer indicated to do so. The escalator was immediately stopped upon the indication of either movement or an entrapment.

When an entrapment occurred, the teflon wedge was gouged by the edge of the step and a measurement was taken. The measurements were perpendicular to the skirt panel

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[1] The probability of exceeding a force of 53 lbf is estimated to be 2%.

surface on the wedge at the marked point on the 20° surface. This value represented the amount the step/skirt gap opened during the entrapment. If no entrapment occurred, the word “none” was used. In some cases the Teflon wedge slid until entrapment occurred at a particular point such as a skirt panel joint. This situation only occurred at two points. The first was at a joint between two skirt panels where there was a height shift. This caused the load to dramatically increase based on an increase in step deflection. The second location was at the intentionally modified skirt panel support to decrease stiffness. In two of the test runs an entrapment did occur, but so rapidly that the location and depth of entrapment was difficult to accurately determine.

4.7.3 Reduced Data and Results

Table 4-8 summarizes the results of the entrapment simulation experiments.

Table 4-8: Entrapment simulation test results.

CONDITION	COEFFICIENT OF FRICTION	SKIRT PANEL TO STEP GAP (in.)	COMBINED STIFFNESS OF STEP AND SKIRT PANEL (lbf/in)	GAP-ADJUSTED WEDGE DEPTH (in.) (average of three runs)
	1	2	3	
1	0.19	.187	1970	0.07
2	0.19	.187	3880	none
3	0.19	.187	1500	0.02
4	0.19	.187	2400	none
5	0.19	.090	1970	0.07
6	0.19	.090	3880	none
7	0.19	.090	1500	0.04
8	0.19	.090	2400	none
9	0.60	.187	1970	0.33
10	0.60	.187	3880	0.15
11	0.60	.187	1500	0.56[a]
12	0.60	.187	2400	0.22
13	0.60	.062	1970	0.19
14	0.60	.062	3880	0.25
15	0.60	.090	1500	0.29
16	0.60	.090	2400	0.29

The raw data for wedge depth dimensions were recorded in the laboratory as shown in Figure 4-7. The wedge depth data of Table 4-8 was reduced in the following manner. First, the results of three replicate runs at each unique condition were averaged. Second, the initial skirt panel to step gap setting was subtracted from the wedge depth averages. This quantity, referred to as the “Gap-Adjusted” wedge depth, represents a normalized depth value which accounts for the effect of initial gap setting on wedge entrapment depth.

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[a] Wedge depth was difficult to record in two of the three replicate test runs.

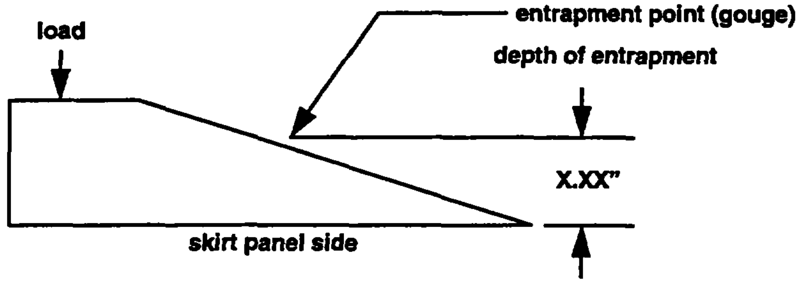

Figure 4-7: Basis for raw data recording of wedge entrapment depth.

5. Analysis of Test Results

Assumptions have been made regarding the initiation and depth of step/skirt entrapment based on mechanical modeling. Tests were performed to both prepare for and conduct entrapment tests on an escalator using plastic, wedge-shaped test objects. Statistical analysis was then used to interpret test data and validate key assumptions.

5.1 Analytical Objective

The objective of this analysis was to validate the following assumptions:

1. Coefficient of friction (COF) influences the initiation of entrapment.
2. Skirt panel stiffness (K_{SP}) and Step stiffness (K_S) both influence the depth of wedge entrapment.

A further objective was to understand and quantify any other interdependencies among the four variables previously defined; namely, COF, K_{SP}, K_S, and Gap regarding both entrapment initiation and depth.

5.2 Combined Stiffness

In parts of the following analysis, skirt panel stiffness and step stiffness were combined to form a "total" stiffness value expressed by

$$K_T = [1/K_{SP} + 1/K_S]^{-1} \tag{14}$$

The analysis was simplified by the fact that these two compliances act in series.

5.3 Review of Experimental Design

As mentioned in Section 4.7, the region of experimentation included four factors, each occurring at two test levels as shown in Table 5-1. These factors and levels were based on both theoretical considerations and laboratory test results. The variable levels were presumed to be sufficient to yield measurable differences in initiation and/or depth of entrapment.

Table 5-1: Region of experimentation for entrapment tests.

Factor	Symbol	Low Level	High Level	Units
COF	μ	0.19	0.60	–
Gap	G	0.09	0.19	in.
Step Stiffness	Ks	4000	11000	lbf/in.
Skirt Panel Stiffness	Ksp	2400	6000	lbf/in.

All 16 factor/level combinations were tested, and each combination was replicated three times. The response variable was the depth of wedge entrapment. If no entrapment occurred the depth was recorded as zero. Only the 16 extremes ("corner points") of the experimental region were tested; none of the factors were tested at intermediate levels.

5.4 Initiation of Entrapment Analysis

COF was the most critical factor influencing entrapment initiation. Wedge entrapment occurred in every test (24 trials) at $\mu = 0.6$. At $\mu = 0.19$ entrapment occurred in only 6 of 24 trials, and all 6 of these entrapments occurred at the lower K_{SP} level. This indicates a secondary influence of stiffness on entrapment initiation. In fact, there is evidence that the initiation of entrapment is related to the combined stiffness K_T.

A logistic regression model [5] was fit to the 24 test outcomes observed when $\mu = 0.19$. The regression yielded the following relationship:

$$\text{Probability of Entrapment Initiation} = 1 - [e^Y / (e^Y + 1)] \qquad (15)$$

where

$$Y = -1.98 + 1.41\,(K_T/1000) \qquad (16)$$

This model resulted in the probability estimates shown in Table 5-2. There is, however, a low degree of precision in these estimates due to the small number of tests performed at each K_T stiffness level.

Table 5-2: Wedge Entrapment probability vs. stiffness at $\mu = 0.19$.

K_S	K_{SP}	K_T	Y	Estimated Probability of Initiation of Wedge Entrapment
4000	2400	1500	0.14	0.47
11000	2400	1970	0.80	0.31
4000	6000	2400	1.40	0.20
11000	6000	3880	3.49	0.03

5.5 Depth of Wedge Entrapment Analysis

For the depth of wedge entrapment analysis, an average depth was computed from replicate tests at each of the 16 unique test conditions. The resultant 16 averages were then analyzed to determine which factors significantly influenced the depth of wedge entrapment. The technique of Analysis of Variance (ANOVA) was used to identify individual factors or combinations of factors (called interactions) that influenced entrapment depth. All 16 observations were used to estimate the effect of varying each factor.

Key findings are shown in Table 5-3. Varying COF from 0.60 to 0.19 clearly had the most significant effect on entrapment depth. Average entrapment depth was consistent with combined step/skirt stiffness values, although the differences in each case were only marginally significant. There is some indication of interactive effects, although further experimentation would be needed to confirm such findings.

Table 5-3: Key findings in depth of wedge entrapment experiments.

Factor	Level (units as indicated)	Average Gap-Adjusted Wedge Depth (in.)	Difference Between Levels
COF	0.60	0.26	0.24
	0.19	0.02	
Gap	0.19 in	0.13	0.01
	0.09 in	0.14	
K_T	1500 lbf/in	0.16	0.06
	1970 lbf/in	0.16	(Max.)
	2400 lbf/in	0.13	
	3880 lbf/in	0.10	

6. Conclusions and Recommendations

6.1 Key Findings

Upon completing the previously described tasks, key findings are as follows:

1. The process of entrapment can be considered as a two part event:
   - the object in contact with the skirt panel no longer slides at the same rate as the moving step, or the object begins to chatter. [The premise is that potential for entrapment exists when this condition occurs; the object does not necessarily need to be wedged against the step for this potential to exist.]
   - an object in the gap produces loads perpendicular to the skirt panel and the side of the step; these load levels contribute to the depth of the entrapment.

2. The likelihood of entrapment is strongly influenced by the coefficient of friction.

3. Skirt panel stiffness, step lateral stiffness and step/skirt gap influence the likelihood of entrapment in varying degrees.

4. Step/skirt gap and step and skirt panel stiffness contribute to the maximum size of the entrapped object and the load levels produced on the entrapped object.

Mathematical modeling identified coefficient of friction and step stiffness as key factors in the entrapment process. This finding was confirmed by conducting entrapment experiments involving a wedge-shaped Teflon test object. In general, the lower the coefficient of friction on the skirt panel, the less likely it is that initiation of wedge entrapment will occur. Similarly, wedge entrapment depth, when adjusted for gap size, was reduced with the use of higher combined stiffness values for the skirt panel and the step.

Specifically, it was confirmed on a test escalator that the initiation of test wedge entrapment was strongly related to the coefficient of friction. It was observed that when the coefficient of friction between the skirt panel and the test object is approximately 0.6, initiation of the test wedge entrapment occurred in every case. However, when the coefficient of friction was 0.19, initiation occurred only 25% of the time (6 out of 24 tests). Moreover, at 0.6, the initiation probability was not dependent on the combined stiffness of the skirt panel and the step (over the ranges considered in the experiment). However, at the 0.19 friction level, the combined stiffness contributed to initiation in varying degrees. These results are depicted in Figure 6-1. This figure further implies that a family of curves exists for coefficients of friction between 0.19 and 0.6.

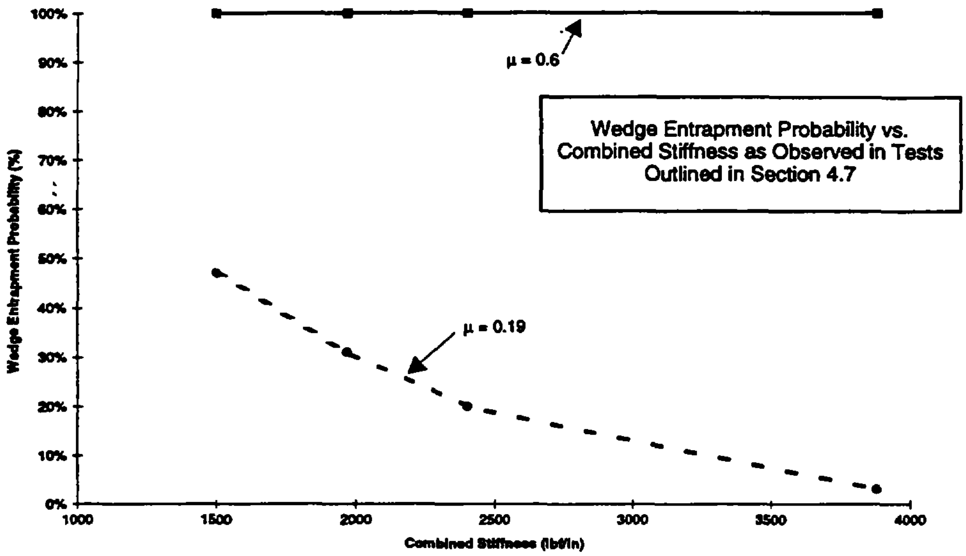

Figure 6-1: Wedge Entrapment Probability vs. Combined Stiffness

Similarly wedge entrapment depth, when adjusted for gap size, was influenced by combined stiffness and coefficient of friction. The coefficient of friction had the largest impact on the wedge entrapment depth. Raw data (i.e., the unadjusted wedge entrapment depths) simply suggest that larger gaps admit larger objects into them.

To reduce the data and examine the effect of gap size on wedge entrapment depth, the experimentally controlled gap sizes (given in Table 4-7) were subtracted from the observed wedge depths. As indicated in Figure 6-2, this adjustment accounted for the difference in the entrapment depth observed at the higher coefficient of friction. These results indicate that the initial gap setting had no measurable effect on wedge entrapment depth, for a given COF value.

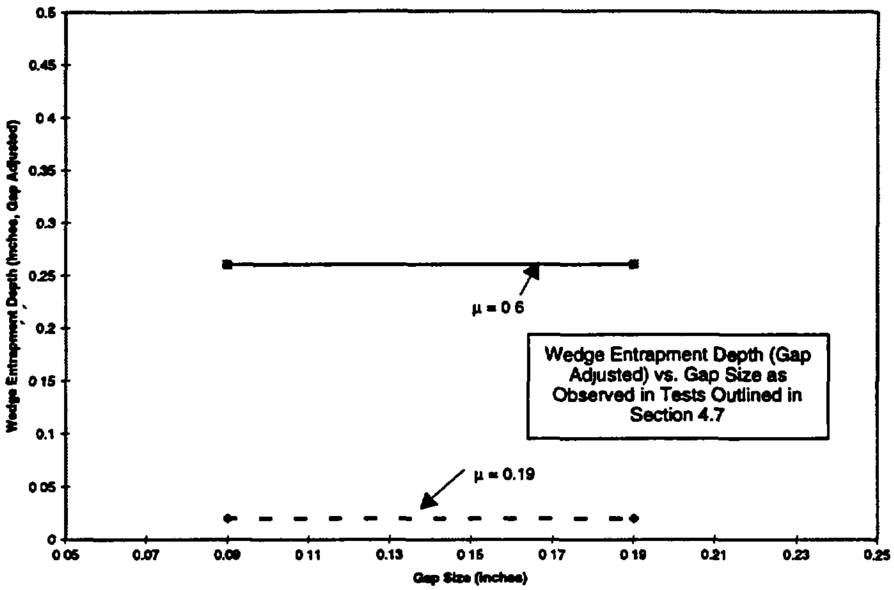

Figure 6-2: Gap-Adjusted Wedge Entrapment Depth vs. Gap Size

Furthermore, the gap-adjusted wedge depths suggest a reduction in entrapment depth when stiffness is increased. Test results are plotted in Figure 6-3; additional experiments are required to estimate this relationship for various intermediate coefficient of friction values.

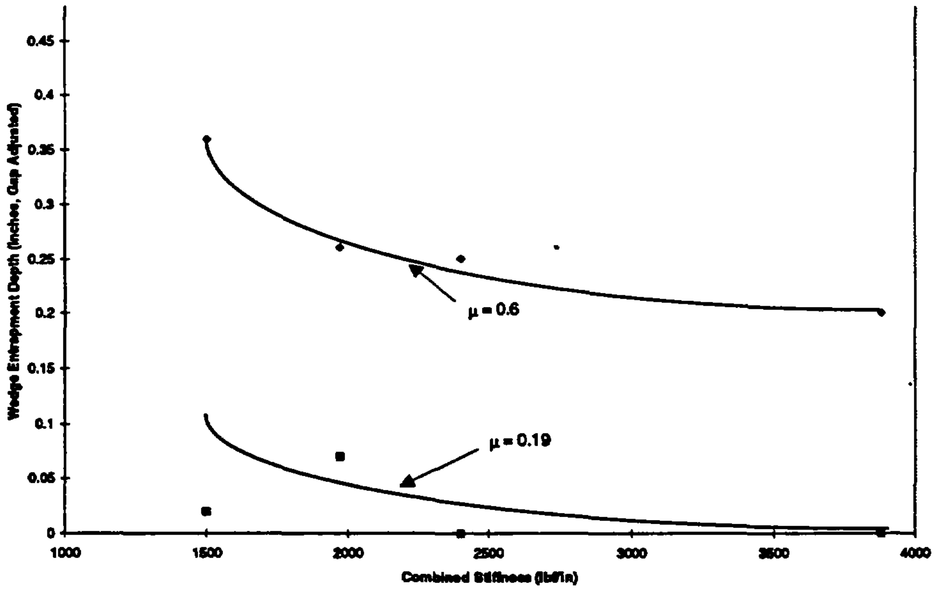

Figure 6-3: Gap-Adjusted Wedge Entrapment Depth vs. Combined Stiffness

Note: Curves shown are approximated from data observed in tests outlined in Section 4.7.

6.2 Conclusions and Recommendations

From the foregoing theory, experiments and statistical analysis, a qualitative estimate of the effect on entrapment can be made for each variable considered. These estimates are summarized in Table 6-1.

Table 6-1: Qualitative estimates of characteristic effect on wedge entrapment.

Entrapment Stage	Primary Effect	Marginal Effect	Negligible Effect
Initiation	COF	K_T	Gap
Gap-Adjusted Depth	COF	K_T	Gap

Many factors must be considered when recommending quantities and/or limits for the above variables. Among these are:

- Sound theoretical basis
- Sound engineering judgment
- Statistically significant experimental findings
- Practicality/Achievability

Conclusions regarding escalator entrapment are listed below:

1. The A17.1 code is correct in requiring a lubricious skirt panel. However, it is very difficult to specify an actual coefficient of friction value between the skirt panel and various objects that may be susceptible to entrapment. Test data indicate that the lower the friction the less the entrapment likelihood. A coefficient of friction between the skirt panel and skin of no more than 0.2 may be adequate given the maximum loads that an individual (adult or child) can impart. However, for objects such as shoes, it may be difficult to achieve a 0.2 or lower friction value. Nevertheless, manufacturers should set a goal of continuously striving to design a skirt panel with lower coefficients of friction.

2. The A17.1 code should specify measurement of the combined stiffness of the skirt panel and the step in the lateral direction, and establish a target for the combined stiffness of at least 4000 lbf/in. The interactive effects of combined stiffness and coefficient of friction need to be better understood, but test data clearly indicate that high combined stiffness lessens the likelihood of test wedge entrapment.

3. If the gap size is within the current A17.1 code and the coefficient of friction is 0.2 or less, gap size does not seem to be a major contributor to entrapment probability or depth. Gap measurements should include step deadband. Thus, the A17.1 code recommendation of 0.19 inches should include the step deadband as well. If the coefficient of friction is 0.2 or lower, then a gap size of 0.19 inches appears adequate.

4. In the case of high friction, gap size and combined stiffness both contribute to the possible size of entrapped objects and, consequently, the smaller the gap the better. In

addition, monitoring the step deadband over time will serve as an indicator for worn step components.

Reducing entrapment probability requires understanding and quantifying escalator step/skirt characteristics and their interdependencies. The foregoing findings clearly indicate that the probability of entrapment can be reduced. This study has identified scientifically sound analytical techniques, and demonstrated how they can be applied, in order to reduce the likelihood of escalator step/skirt entrapment. However, further testing is required in order to accomplish the following two objectives:

- Create a sufficiently precise statistical model ("entrapment index") which relates coefficient of friction, combined stiffness and step/skirt gap to the probability and depth of an escalator step/skirt entrapment
- Make recommendations to the ASME A17 committee including
  - Specification of parameters to be measured in the field
  - Evaluation and interpretation of field data using an "entrapment index".

7. References

1. American Society of Mechanical Engineers. "ASME Code A17.1, Part VIII Escalators", (1996).

2. Data supplied by the U.S. Consumer Product Safety Commission
   - National Electronic Injury Surveillance System (NEISS)
   - Injury or Potential Injury Incident File (IPII)
   - Death Certificate File (DCRT)
   - In-Depth Investigation File (INDP)

3. Burstein, A.H. and Reilly, D.T. "The Elastic Properties of Compact Bone Tissue", *J. Biomechanics*, **8**, pp. 393-405, (1975).

4. Nelson, W. "Applied Life Data Analysis", Wiley, (1982).

5. Hosmer, D.W. and Lemeshow, S. "Applied Logistic Regression", Wiley, (1989).

TAB F

Arthur D Little

Escalator Step/Skirt Performance Standard

Final Report

Disclaimer

This report was commissioned by The National Elevator Industry, Inc. on terms specifically limiting Arthur D. Little's liability. This report represents Arthur D. Little's best judgment in light of information made available to us. This report must be read in its entirety and does not constitute a legal opinion. Use of this report by any party other than an employee of The National Elevator Industry, Inc., subjects that party to the terms of the Agreement between The National Elevator Industry, Inc. and Arthur D. Little, including the limitation of liability. Any use the reader makes of this report, or any reliance upon or decisions to be made based upon this report are the responsibility of the reader and the reader hereby releases and agrees to indemnify Arthur D. Little from any claims based upon the reader's use of this report.

Report to:
National Elevator Industry, Inc.

September 16, 1999

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Reference 39813-00

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Background

The escalator industry has continuously focused on reducing escalator accidents. Recently, these efforts centered on reducing entrapments at the step/skirt panel interface (referred to as step/skirt panel entrapment). However, 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.

Arthur D. Little, Inc. (ADL) was contracted by the National Elevator Industry Inc., (NEII) to help develop a Step/Skirt Index for use with a performance standard for future recommendation to the ASME A17 committee as part of the industry's overall attempt to reduce the potential for step/skirt panel entrapments.

Arthur D. Little's program approach involved identifying accident scenarios, conducting tests to formulate an index, and generating concepts for measuring the Step/Skirt Index. The approach to this assignment is illustrated in Figure E-1.

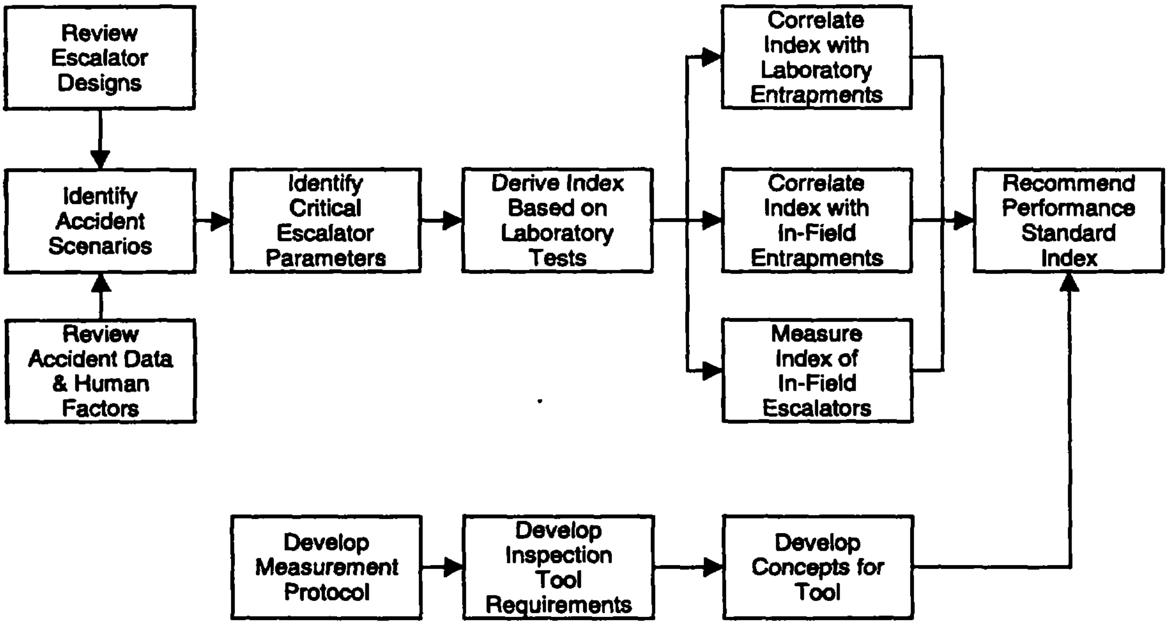

Figure E-1: ADL's program approach

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

Results

Key findings, which are based on a foundation of analytical review and both laboratory and in-field tests, include the following:

- The basic escalator design parameters contributing to entrapment potential include:
  - Skirt panel stiffness
  - Step lateral stiffness
  - Step deadband (free side-to-side motion)
  - Initial gap size
  - Coefficient of friction (COF or μ)
- A "loaded gap" (gap dimension under load) term was introduced as a single term for skirt panel stiffness, step lateral stiffness, step deadband, and initial gap size.
- A Step/Skirt Index was developed to assess the potential for step/skirt entrapment. The Index can be determined with only two measurements; i.e., the loaded gap and the coefficient of friction.
- The Index was demonstrated to correlate with laboratory and in-field test results.

The Step/Skirt Index was formulated through a set of experiments that were planned under guidance of statistical considerations. The resulting Index accounted for both "small" and "large" object entrapments. Following discussions with NEII and the CPSC, the decision was made to focus the Index on "small," child-sized objects only, since this outcome would be more conservative.

The Index developed for "small" objects is summarized below:

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

where: COF = coefficient of friction between the skirt panel and a polycarbonate test sample
and e = the base for natural (Naperian) logarithm = 2.718

The Index represents a relative measure, with values ranging from zero to one. The lower the Index, the lower the potential for a step/skirt entrapment to occur.

As depicted in Figure E-2, the Index can also be represented graphically.

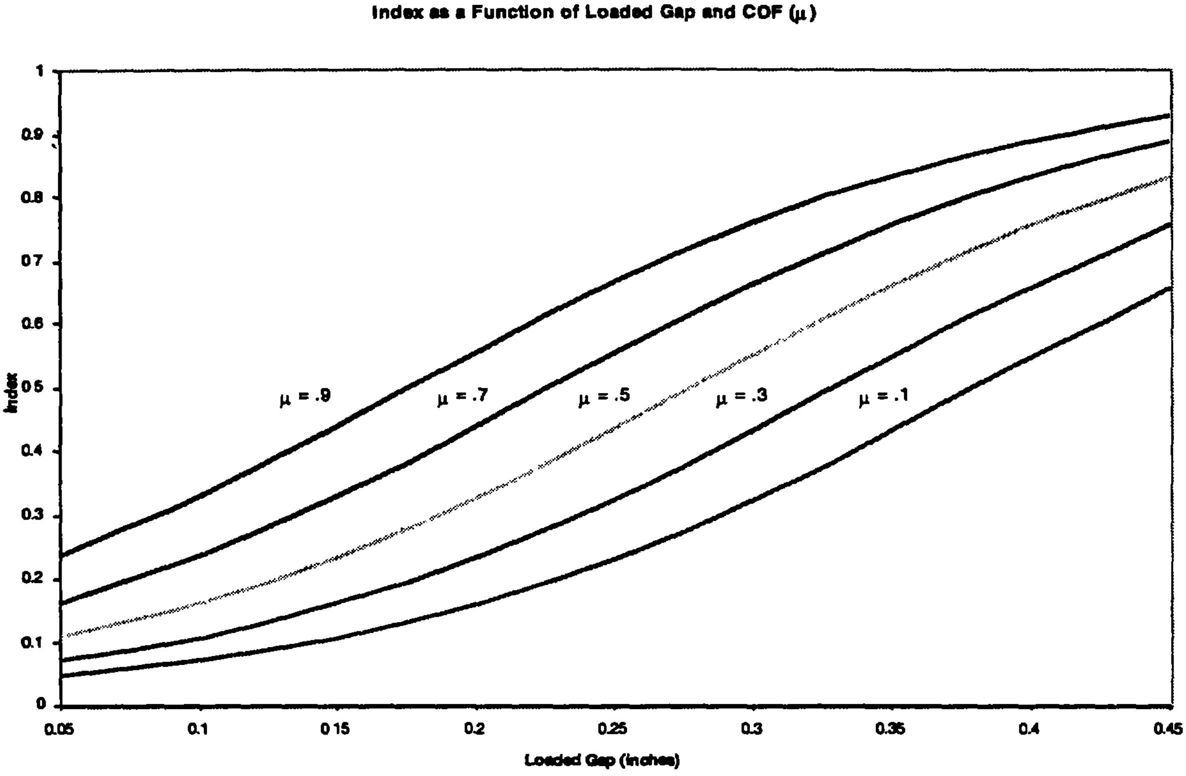

Figure E-2: Step/Skirt Index

This Index was tested both in the laboratory and in the field. Test objects included athletic shoes and artificial hands, feet, and calves. The test results correlated with the Index prediction. In general, under severe (i.e., entrapment inducing) test conditions, the lower the Index the fewer observed entrapments, and the higher the Index, the more observed entrapments.

Shoe entrapments were observed only at a relatively high Index value. Child hand entrapments did not occur at low Index values. Although calf entrapments were observed at low Index values, the number of calf entrapments was probably due to the high coefficient of friction of the artificial skin (relative to human skin), the severe test conditions, and the difficulty in classification of the test outcome. (Some of the recorded calf entrapments were more representative of pinches rather than entrapments.)

In-field escalator measurements to evaluate the Step/Skirt Index proved feasible. These tests were conducted with the same equipment used for the laboratory tests. An in-field test procedure was developed and confirmed with actual tests following discussions with escalator maintenance, service, and inspection personnel.

The Step/Skirt Index was evaluated on four in-field escalators. (Current ASME A17.1 code does not specify coefficient of friction or loaded gap, but code values suggest Step/Skirt Index values between 0.2 and 0.7.)[1] Their Step/Skirt Index values ranged from 0.46 to 0.67. These measurements yielded two important outcomes:

- Step/Skirt Index values varied along the length of the escalator based on the size of the loaded gap and the coefficient of friction.
- Visual inspection alone can be misleading. Although an escalator may have uniform gaps and skirt panels, there may be one or many regions with a higher Index value.

In addition, Step/Skirt Index gauge requirements and concepts were generated to ensure that a gauge is feasible to measure the Step/Skirt Index. A focus group confirmed the requirements and revealed that safety and gauge performance were key requirements, followed by ease of use and cost. Developed gauge concepts indicated that numerous design approaches are possible. These approaches ranged from electromechanical devices with limited data acquisition requirements, to very sophisticated devices with "high-end" data acquisition systems that can both track the Index as a function of escalator position, and maintain data over time. A preliminary engineering layout of one gauge embodiment was created. This concept primarily used off-the-shelf components and appears feasible.

Recommendations

Recommendations for a threshold Index value for the step/skirt performance standard depend on several considerations. Some of these factors are listed below, and a discussion of these points is required prior to making final recommendations.

1. The threshold Index value should correspond to a low likelihood of entrapment expected to occur under laboratory (severe) test conditions.
2. The threshold Index value should be achievable and maintainable in field installations (based on current escalator designs and code requirements).
3. The threshold Index value should be capable of discriminating the entrapment potential of escalators:
   - Reasonably reliable predictive capability must be demonstrated under test environments
   - Predictive errors must be recognized.
4. Sound theoretical analyses and engineering judgement should be combined with practical concerns, (i.e., what can be achieved in escalator design and maintenance).

Based on the review of escalator designs, analytical results, and findings obtained throughout this assignment, Arthur D. Little recommends the following:

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[1] This is based on step/skirt gaps between 0.19" and 0.38", and observed coefficients of friction with a polycarbonate test specimen ranging from 0.2 to 0.44.

1. The ASME A17.1 code should require a threshold Step/Skirt Index value. Selection of this threshold value should be based on the results of this assignment for reducing entrapments and, conjointly, with what can be achieved in the field.
2. The ASME A17.1 requirement for minimum skirt panel stiffness and a lubricious skirt panel are superceded with this Index requirement. However, these requirements may still be treated as minimum or good practice.
3. The ASME A17.1 requirement for a maximum step/skirt gap should be superceded by this Index requirement. If the escalator industry desires to specify a maximum gap, then a maximum loaded gap value should be specified.
4. Monitoring the Index (especially the loaded gap component) over time may serve as an indicator for worn escalator components.
5. As with any continuous improvement effort, the goal is to reduce the potential for incidents and identify opportunities for further reduction of the potential for these incidents through a plan to lower the allowable threshold Index value until these incidents are significantly reduced. This plan should consider the results achieved in reducing the potential for these incidents as a consequence of the initial standard and determine the desirability of more stringent requests, taking into account additional state-of-the-art improvements.