5.1 Results and Conclusions

Reducing entrapment potential requires understanding and quantifying escalator step/skirt characteristics and interdependencies. The foregoing findings clearly indicate that the potential for entrapment can be reduced. This study has implemented scientifically sound analytical techniques, and has demonstrated how they can be applied, in order to reduce the likelihood of escalator step/skirt entrapment. Also, this assignment resulted in several observations and conclusions. These findings are based on a foundation of analytical review, and both laboratory and in-field tests.

- 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 to enable a single measurement 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 from two measurements: the loaded gap and the coefficient of friction.
- The Index was shown to correlate with laboratory and in-field test results.

The Step/Skirt Index was formulated through experiments that were planned under guidance of statistical considerations. Initially, various test objects representing child-sized and adult-sized fingers and shoes were used. These included flat sheets of various thicknesses and rounds of various diameters. In addition, these test specimens had various durometers (or stiffness values). The resulting Index accounted for "small" and "large" objects. Later, during 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 on "small" objects is summarized below:

$$y = -3.77 + 2.37(COF) + 9.30(\textit{loaded gap})$$

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

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

Also, this Index can be represented graphically (see Figure 5-1).

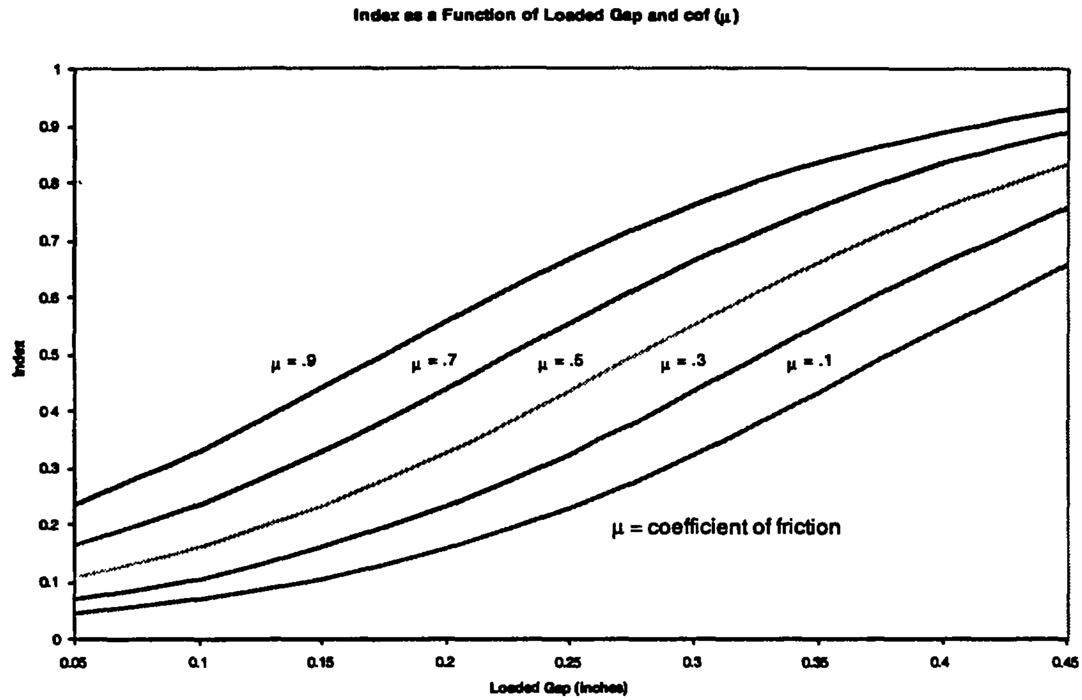


Figure 5-1: Step/Skirt Index as a function of loaded gap and COF (μ)

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 test conditions, the lower the Index the fewer observed entrapments, and vice versa.

Shoe entrapments required a relatively high Index value. Child hand entrapments did not occur at low Index values; however, calf entrapments were observed at low Index values. The calf entrapments were probably due to the high coefficient of friction of the artificial skin, relative to human skin, the severe test conditions, and the difficult 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 to be feasible. These tests were conducted with the same equipment used for the laboratory tests. An in-field test procedure [Section 3.3.1] was developed and confirmed with actual tests and through discussions with escalator maintenance, service, and inspection personnel.

Four in-field escalators were evaluated for their Step/Skirt Index. (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.)[5] Their Step/Skirt Index values ranged from 0.46 to 0.67. These measurements revealed two important observations:

- 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 was misleading. Although an escalator may have uniform gaps and skirt panels, there may be one region with a higher Index value.

A review of the laboratory entrapment test results indicated that when Index values were low enough to reduce hand and calf entrapments, then shoe entrapments would also be reduced. Thus, the focus needed to be on hand and calf entrapments. A top-level summary of the observed hand and calf entrapments indicated that hand entrapments are highly unlikely at low Index values, whereas calf entrapments were still observed. The following table summarizes this data (Table 5-1):

Polycarbonate-based Index Level[5]	Observed Entrapments (%)	
	Child's Hand[6]	Child's Calf[6]
0.2 to 0.3	67%	100%
0.1 to 0.2	7%	33%
0 to 0.1	0%	44%

Table 5-1: Summary of observed hand and calf entrapment

Table 5-1 Index level was based on coefficient of friction for polycarbonate test specimens.

Based on these test results, a reasonable threshold Step/Skirt Index value should be based, predominantly, on the hand data. Furthermore, the observed entrapment percentages were plotted and indicated that a significant reduction in hand entrapments occurred when the Index was less than or equal to 0.2, as shown in Figure 5-2.

[5] 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.
[6] Sawbones artificial hand and calf

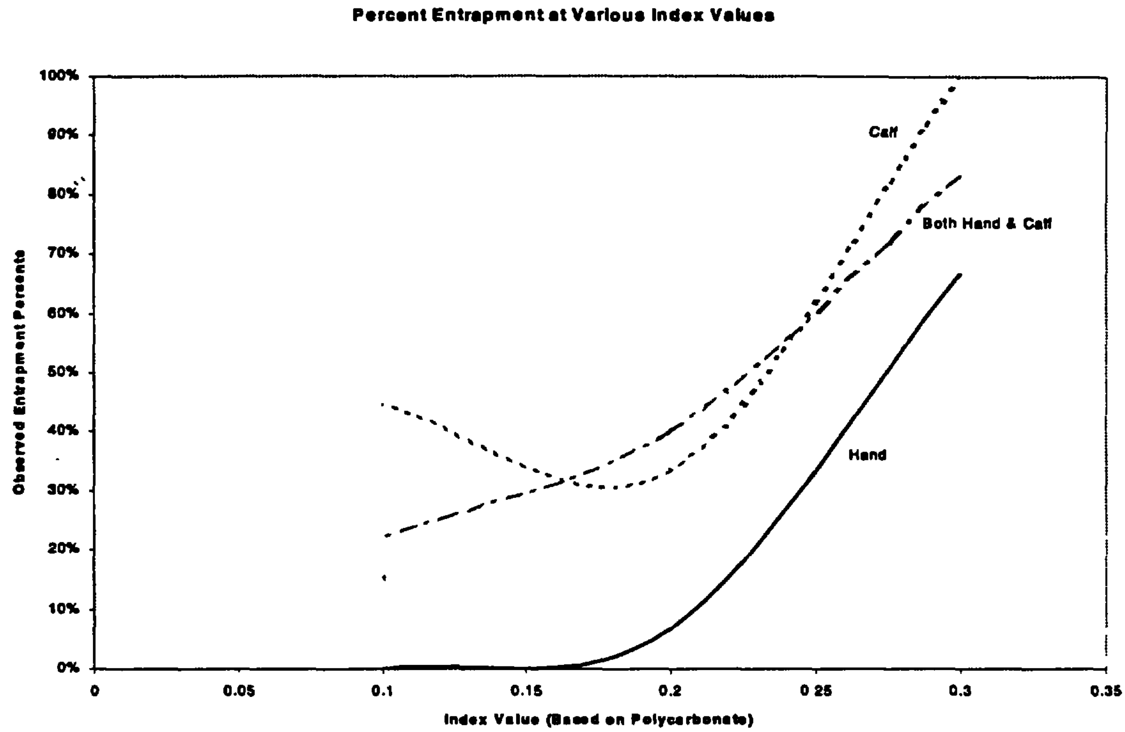


Figure 5-2: Percent entrapment at various index values

A few factors may have contributed to the observed calf entrapments. These include the following:

- The test environment was severe; the intent was to increase the likelihood of entrapment by imposing high-stress conditions (e.g., object position, forces, etc.).

- The coefficient of friction for Sawbones skin is higher than that of human skin (based on limited laboratory tests). This higher coefficient of friction contributed to the number of observed entrapments. The following table summarizes the coefficient of friction for human skin, Sawbones skin, and polycarbonate when tested on a stainless steel skirt panels. (These coefficient of friction ranges were obtained for lubricated and dry conditions).

Human Skin	0.18 to 0.52
Sawbones Skin	0.3 to 0.8
Polycarbonate	0.19 to 0.44

- Classification of test outcomes was difficult; some of the recorded calf entrapments were more representative of pinches rather 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.

In addition, a statistical analysis of the hand and calf test data yielded a model that estimated the conditional probability of test object entrapment at any specified Index value. The probability was conditional in the sense that it was relative to the test environment in which high-stress conditions were imposed to induce entrapment. Computational details and underlying theory are well documented in statistical literature [6]. Also, analytical output included a Classification Table that related probability model predictions to outcomes observed in the laboratory. The table below illustrates the trade-offs between the two types of prediction errors at an Index value of 0.2 for hand entrapments. This table can be generated for any Index value.

	Observed (in lab tests)	
Predicted (by model)	**Entrapment**	**No Entrapment**
Entrapment (I > 0.2)	5	1
No Entrapment (I < 0.2)	1	23

The upper right cell represents "false positive" outcomes (e.g., the Index model predicted an entrapment, but none occurred). The lower left cell represents "false negative" outcomes. False negative conditions are undesirable since the model predicted no entrapment, but one entrapment was observed in the laboratory. This Classification Table further indicates that 93% (28/30) of the model predictions are correct. Table entries depend on the Index value selected – for example, lowering the selected Index value (i.e., lower than 0.2) increases the number of false positives while reducing the number of false negatives.

Furthermore, it was evident that prediction error decreased significantly for Index values below 0.2 when false negatives were plotted for both the artificial hand and calf model and the hand only model (reference Figure 5-3).

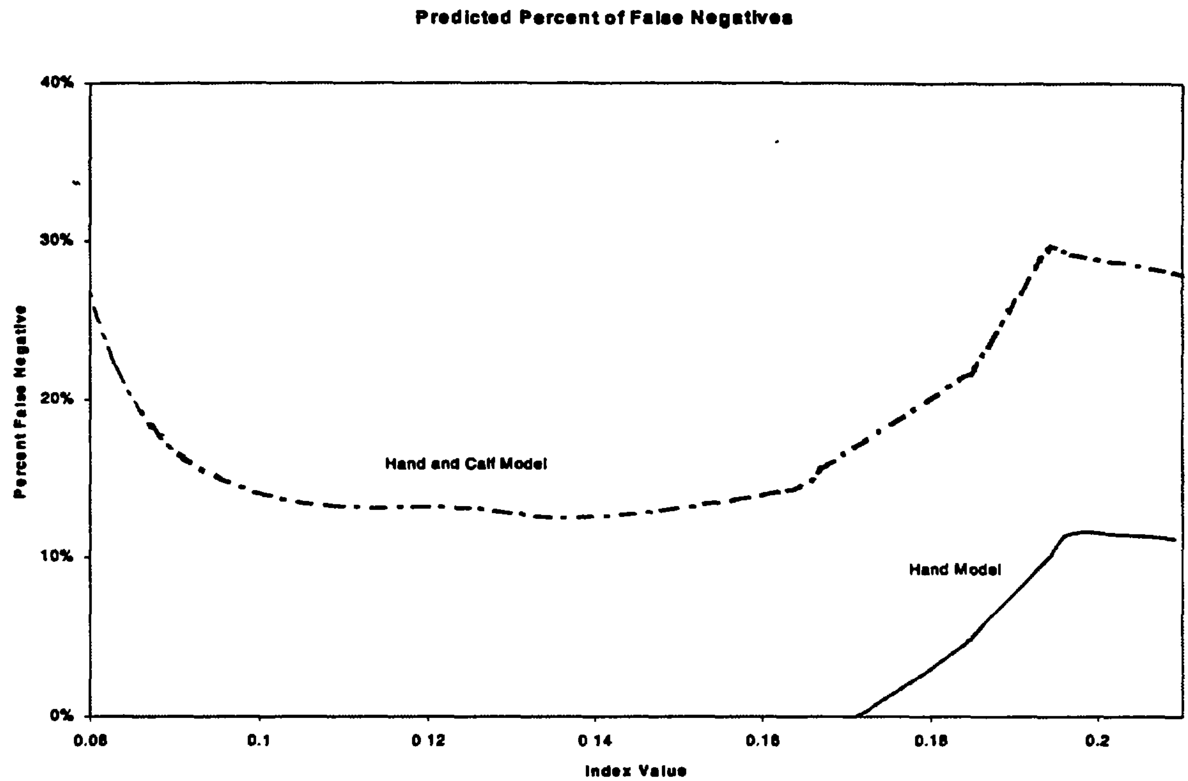


Figure 5-3: Predicted percent of false negatives

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 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 track both Index as a function of escalator position and maintain historical data. A preliminary engineering layout of one gauge embodiment was created. This concept primarily used off-the-shelf components and appears feasible.

5.2 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.

- The threshold Index value should correspond to a low likelihood of entrapment expected to occur under laboratory (high-stress) test conditions.
- The threshold Index value should be achievable and maintainable in field installations (based on current escalator designs and code requirements).
- 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.
- Sound theory, analysis and engineering judgement should be combined with practical concerns (i.e.,what can be achieved in escalator design and maintenance).

Based on the above discussion, the review of escalator designs, analytical results and findings obtained throughout this assignment, the following recommendations are presented:

1. The ASME A17.1 code should require a step/skirt threshold 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 a 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 with this Index requirement. If the escalator industry desires to specify a maximum gap, then a maximum loaded gap value should be referenced.
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.

6. References

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

[2] Escalator Step/Skirt Performance Standard Study, ADL report to NEII, July 2, 1998.

[3] 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)

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

[5] Gunst, R.F. and R. L. Mason. "How to Construct Fractional Factorial Experiments," ASQC Statistics Division, Vol. 14 (1991).

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

[7] SAS Institute Inc., SAS/STAT User's Guide, Version 6, Vol. 2 (1989).

[8] Gunter, B. "Second-Class Citizens and Experimental Design," Quality Progress, Oct. 1996.

Appendix

Laboratory Index Formulation Experiment

Analytical Data Set

Laboratory Index Formulation Experiment

Analytical Output
(SAS PROC LOGISTIC)

Polycarbonate-Based Index vs. Object-Based Index

Regression Analysis

Step/Skirt Index Validation Test

Statistical Analysis

Appendix

Laboratory Index Formulation Experiment

Analytical Data Set

test	test ID	step	skirt	gap	cof	objects	no. trial	no. entrap	sizedumy	loadgapc
1	1	2000	2300	12	0.2	100	.	.	1	0.39
1	2	4000	2300	6	0.8	1000	2	2	1	0.20
1	3	11000	5000	6	0.5	12000	2	0	1	0.19
1	4	4000	5000	2	0.6	1000	2	0	1	0.07
1	5	4000	2300	6	0.6	1000	2	2	1	0.20
1	6	2000	2300	2	0.6	100	2	0	1	0.08
1	7	4000	5000	12	0.8	1000	2	2	1	0.38
1	8	11000	5000	6	0.3	12000	2	0	1	0.19
1	9	11000	2400	2	0.8	12000	1	0	1	0.07
1	9	11000	2400	2	0.8	100	2	0	1	0.07
1	10	3700	2400	6	0.3	12000	1	1	1	0.20
1	10	3700	2400	6	0.3	1000	1	1	1	0.20
1	11	2000	5000	6	0.6	12000	1	1	1	0.20
1	11	2000	5000	6	0.6	100	1	0	1	0.20
1	12	3700	5000	12	0.6	12000	2	2	1	0.38
1	12	3700	5000	12	0.6	1000	2	2	1	0.38
1	13	3700	2400	6	0.6	100	1	0	1	0.20
1	13	3700	2400	6	0.6	1000	1	0	1	0.20
1	14	11000	2400	12	0.6	1000	2	2	1	0.38
1	14	11000	2400	12	0.6	12000	2	2	1	0.38
1	15	3700	5000	2	0.3	12000	1	0	1	0.07
1	15	3700	5000	2	0.3	100	1	0	1	0.07
1	16	2000	5000	6	0.8	1000	1	0	1	0.20
1	16	2000	5000	6	0.8	12000	1	1	1	0.20
1	1	2000	2300	12	0.2	100	2	2	0	0.39
1	2	4000	2300	6	0.8	1000	2	0	0	0.20
1	3	11000	5000	6	0.5	12000	2	0	0	0.19
1	4	4000	5000	2	0.6	1000	2	0	0	0.07
1	5	4000	2300	6	0.6	1000	2	0	0	0.20
1	6	2000	2300	2	0.6	100	2	2	0	0.08
1	7	4000	5000	12	0.8	1000	2	2	0	0.38
1	8	11000	5000	6	0.3	12000	2	0	0	0.19
1	9	11000	2400	2	0.8	12000	1	0	0	0.07
1	9	11000	2400	2	0.8	100	2	0	0	0.07

1	10	3700	2400	6	0.3	12000	1	0	0	0.20
1	10	3700	2400	6	0.3	1000	1	0	0	0.20
1	11	2000	5000	6	0.6	12000	1	0	0	0.20
1	11	2000	5000	6	0.6	100	1	0	0	0.20
1	12	3700	5000	12	0.6	12000	2	2	0	0.38
1	12	3700	5000	12	0.6	1000	2	0	0	0.38
1	13	3700	2400	6	0.6	100	1	0	0	0.20
1	13	3700	2400	6	0.6	1000	1	0	0	0.20
1	14	11000	2400	12	0.6	1000	2	0	0	0.39
1	14	11000	2400	12	0.6	12000	2	0	0	0.39
1	15	3700	5000	2	0.3	12000	1	0	0	0.07
1	15	3700	5000	2	0.3	100	1	0	0	0.07
1	16	2000	5000	6	0.8	1000	1	0	0	0.20
1	16	2000	5000	6	0.8	12000	1	0	0	0.20

1	1	2000	2300	12	0.2	100	2	0	0	0.40
1	2	4000	2300	6	0.8	1000	2	0	0	0.20
1	3	11000	5000	6	0.5	12000	2	0	0	0.19
1	4	4000	5000	2	0.6	1000	2	0	0	0.07
1	5	4000	2300	6	0.6	1000	2	2	0	0.20
1	6	2000	2300	2	0.6	100	2	1	0	0.09
1	7	4000	5000	12	0.8	1000	2	2	0	0.39
1	8	11000	5000	6	0.3	12000	2	0	0	0.19
1	9	11000	2400	2	0.8	12000	1	0	0	0.08
1	9	11000	2400	2	0.8	100	2	0	0	0.08
1	10	3700	2400	6	0.3	12000	1	0	0	0.20
1	10	3700	2400	6	0.3	1000	1	0	0	0.20
1	11	2000	5000	6	0.6	12000	1	0	0	0.21
1	11	2000	5000	6	0.6	100	1	0	0	0.21
1	12	3700	5000	12	0.6	12000	2	0	0	0.39
1	12	3700	5000	12	0.6	1000	2	0	0	0.39
1	13	3700	2400	6	0.6	100	1	0	0	0.20
1	13	3700	2400	6	0.6	1000	1	0	0	0.20
1	14	11000	2400	12	0.6	1000	2	0	0	0.39
1	14	11000	2400	12	0.6	12000	2	0	0	0.39
1	15	3700	5000	2	0.3	12000	1	0	0	0.07
1	15	3700	5000	2	0.3	100	1	0	0	0.07

1	16	2000	5000	6	0.8	1000	1	0	0	0.21
1	16	2000	5000	6	0.8	12000	1	0	0	0.21
1	1	2000	2300	12	0.2	100	.	.	1	0.39
1	2	4000	2300	6	0.8	1000	2	0	1	0.20
1	3	11000	5000	6	0.5	12000	2	0	1	0.19
1	4	4000	5000	2	0.6	1000	2	0	1	0.07
1	5	4000	2300	6	0.6	1000	2	0	1	0.20
1	6	2000	2300	2	0.6	100	2	0	1	0.08
1	7	4000	5000	12	0.8	1000	2	2	1	0.38
1	8	11000	5000	6	0.3	12000	2	0	1	0.19
1	9	11000	2400	2	0.8	12000	1	0	1	0.07
1	9	11000	2400	2	0.8	100	2	0	1	0.07
1	10	3700	2400	6	0.3	12000	1	0	1	0.20
1	10	3700	2400	6	0.3	1000	1	0	1	0.20
1	11	2000	5000	6	0.6	12000	1	0	1	0.20
1	11	2000	5000	6	0.6	100	1	0	1	0.20
1	12	3700	5000	12	0.6	12000	2	2	1	0.38
1	12	3700	5000	12	0.6	1000	2	2	1	0.38
1	13	3700	2400	6	0.6	100	1	1	1	0.20
1	13	3700	2400	6	0.6	1000	1	0	1	0.20
1	14	11000	2400	12	0.6	1000	2	2	1	0.39
1	14	11000	2400	12	0.6	12000	2	2	1	0.39
1	15	3700	5000	2	0.3	12000	1	0	1	0.07
1	15	3700	5000	2	0.3	100	1	0	1	0.07
1	16	2000	5000	6	0.8	1000	1	1	1	0.20
1	16	2000	5000	6	0.8	12000	1	0	1	0.20
1	1	2000	2300	12	0.2	100	2	0	0	0.44
1	2	4000	2300	6	0.8	1000	2	0	0	0.24
1	3	11000	5000	6	0.5	12000	2	0	0	0.21
1	4	4000	5000	2	0.6	1000	2	0	0	0.09
1	5	4000	2300	6	0.6	1000	2	0	0	0.24
1	6	2000	2300	2	0.6	100	2	2	0	0.13
1	7	4000	5000	12	0.8	1000	2	0	0	0.41
1	8	11000	5000	6	0.3	12000	2	0	0	0.21
1	9	11000	2400	2	0.8	12000	1	0	0	0.10

1	9	11000	2400	2	0.8	100	2	0	0	0.10
1	10	3700	2400	6	0.3	12000	1	0	0	0.24
1	10	3700	2400	6	0.3	1000	1	0	0	0.24
1	11	2000	5000	6	0.6	12000	1	0	0	0.24
1	11	2000	5000	6	0.6	100	1	0	0	0.24
1	12	3700	5000	12	0.6	12000	2	0	0	0.41
1	12	3700	5000	12	0.6	1000	2	0	0	0.41
1	13	3700	2400	6	0.6	100	1	0	0	0.24
1	13	3700	2400	6	0.6	1000	1	0	0	0.24
1	14	11000	2400	12	0.6	1000	2	0	0	0.41
1	14	11000	2400	12	0.6	12000	2	0	0	0.41
1	15	3700	5000	2	0.3	12000	1	0	0	0.10
1	15	3700	5000	2	0.3	100	1	1	0	0.10
1	16	2000	5000	6	0.8	1000	1	0	0	0.24
1	16	2000	5000	6	0.8	12000	1	0	0	0.24

1	1	2000	2300	12	0.2	100	2	0	0	0.44
1	2	4000	2300	6	0.8	1000	2	0	0	0.24
1	3	11000	5000	6	0.5	12000	2	0	0	0.21
1	4	4000	5000	2	0.6	1000	2	0	0	0.09
1	5	4000	2300	6	0.6	1000	2	0	0	0.24
1	6	2000	2300	2	0.6	100	2	0	0	0.13
1	7	4000	5000	12	0.8	1000	2	0	0	0.41
1	8	11000	5000	6	0.3	12000	2	0	0	0.21
1	9	11000	2400	2	0.8	12000	1	0	0	0.10
1	9	11000	2400	2	0.8	100	2	0	0	0.10
1	10	3700	2400	6	0.3	12000	1	0	0	0.24
1	10	3700	2400	6	0.3	1000	1	0	0	0.24
1	11	2000	5000	6	0.6	12000	1	0	0	0.24
1	11	2000	5000	6	0.6	100	1	0	0	0.24
1	12	3700	5000	12	0.6	12000	2	0	0	0.41
1	12	3700	5000	12	0.6	1000	2	0	0	0.41
1	13	3700	2400	6	0.6	100	1	0	0	0.24
1	13	3700	2400	6	0.6	1000	1	0	0	0.24
1	14	11000	2400	12	0.6	1000	2	0	0	0.41
1	14	11000	2400	12	0.6	12000	2	0	0	0.41
1	15	3700	5000	2	0.3	12000	1	0	0	0.10

1	15	3700	5000	2	0.3	100	1	0	0	0.10
1	16	2000	5000	6	0.8	1000	1	0	0	0.24
1	16	2000	5000	6	0.8	12000	1	0	0	0.24
1	1	2000	2300	12	0.2	100	.	.	1	0.42
1	2	4000	2300	6	0.8	1000	2	2	1	0.22
1	3	11000	5000	6	0.5	12000	2	0	1	0.20
1	4	4000	5000	2	0.6	1000	2	0	1	0.09
1	5	4000	2300	6	0.6	1000	2	0	1	0.22
1	6	2000	2300	2	0.6	100	.	.	1	0.11
1	7	4000	5000	12	0.8	1000	2	2	1	0.40
1	8	11000	5000	6	0.3	12000	2	0	1	0.20
1	9	11000	2400	2	0.8	12000	.	.	1	0.09
1	9	11000	2400	2	0.8	100	.	.	1	0.09
1	10	3700	2400	6	0.3	12000	1	0	1	0.22
1	10	3700	2400	6	0.3	1000	1	0	1	0.22
1	11	2000	5000	6	0.6	12000	1	1	1	0.22
1	11	2000	5000	6	0.6	100	1	1	1	0.22
1	12	3700	5000	12	0.6	12000	.	.	1	0.40
1	12	3700	5000	12	0.6	1000	.	.	1	0.40
1	13	3700	2400	6	0.6	100	1	1	1	0.22
1	13	3700	2400	6	0.6	1000	1	0	1	0.22
1	14	11000	2400	12	0.6	1000	2	2	1	0.40
1	14	11000	2400	12	0.6	12000	2	2	1	0.40
1	15	3700	5000	2	0.3	12000	.	.	1	0.09
1	15	3700	5000	2	0.3	100	.	.	1	0.09
1	16	2000	5000	6	0.8	1000	1	1	1	0.22
1	16	2000	5000	6	0.8	12000	1	0	1	0.22

Laboratory Index Formulation Experiment

Analytical Output
(SAS PROC LOGISTIC)

The LOGISTIC Procedure

000200

Data Set: WORK.TEST1ALL
Response Variable (Events): ENTRAP
Response Variable (Trials): TRIAL
Number of Observations: 158
Link Function: Logit

Response Profile

Ordered Value	Binary Outcome	Count
1	EVENT	58
2	NO EVENT	184

WARNING: 10 observation(s) were deleted due to missing values for the response or explanatory variables.

Model Fitting Information and Testing Global Null Hypothesis BETA=0

Criterion	Intercept Only	Intercept and Covariates	Chi-Square for Covariates
AIC	268.538	199.370	.
SC	272.027	213.326	.
-2 LOG L	266.538	191.370	75.168 with 3 DF (p=0.0001)
Score	.	.	66.875 with 3 DF (p=0.0001)

Analysis of Maximum Likelihood Estimates

Variable	DF	Parameter Estimate	Standard Error	Wald Chi-Square	Pr > Chi-Square	Standardized Estimate	Odds Ratio
INTERCPT	1	-6.2554	0.9867	40.1915	0.0001	.	.
COF	1	2.3702	1.1513	4.2384	0.0395	0.227935	10.69
LOADGAPC	1	9.3006	1.8122	26.3399	0.0001	0.602989	999.00
S_DUMMY	1	2.4927	0.4175	35.6485	0.0001	0.671215	12.09

Association of Predicted Probabilities and Observed Responses

Concordant	= 82.0%	Somers' D	= 0.650
Discordant	= 17.0%	Gamma	= 0.657
Tied	= 1.0%	Tau-a	= 0.238
(10672 pairs)		c	= 0.825

Arthur D Little

The LOGISTIC Procedure

Classification Table

	Correct		Incorrect		Percentages				
Prob Level	Event	Non-Event	Event	Non-Event	Correct	Sensi-tivity	Speci-ficity	False POS	False NEG
0.000	58	0	184	0	24.0	100.0	0.0	76.0	.
0.020	54	16	168	4	28.9	93.1	8.7	75.7	20.0
0.040	52	50	134	6	42.1	89.7	27.2	72.0	10.7
0.060	50	64	120	8	47.1	86.2	34.8	70.6	11.1
0.080	50	82	102	8	54.5	86.2	44.6	67.1	8.9
0.100	48	88	96	10	56.2	82.8	47.8	66.7	10.2
0.120	48	98	86	10	60.3	82.8	53.3	64.2	9.3
0.140	48	98	86	10	60.3	82.8	53.3	64.2	9.3
0.160	48	102	82	10	62.0	82.8	55.4	63.1	8.9
0.180	48	110	74	10	65.3	82.8	59.8	60.7	8.3
0.200	48	112	72	10	66.1	82.8	60.9	60.0	8.2
0.220	44	114	70	14	65.3	75.9	62.0	61.4	10.9
0.240	44	136	48	14	74.4	75.9	73.9	52.2	9.3
0.260	44	140	44	14	76.0	75.9	76.1	50.0	9.1
0.280	44	158	26	14	83.5	75.9	85.9	37.1	8.1
0.300	42	158	26	16	82.6	72.4	85.9	38.2	9.2
0.320	40	162	22	18	83.5	69.0	88.0	35.5	10.0
0.340	40	164	20	18	84.3	69.0	89.1	33.3	9.9
0.360	40	164	20	18	84.3	69.0	89.1	33.3	9.9
0.380	36	168	16	22	84.3	62.1	91.3	30.8	11.6
0.400	36	176	8	22	87.6	62.1	95.7	18.2	11.1
0.420	33	176	8	25	86.4	56.9	95.7	19.5	12.4
0.440	33	179	5	25	87.[illegible]	56.9	97.3	13.2	12.3
0.460	33	179	5	25	87.6	56.9	97.3	13.2	12.3
0.480	33	179	5	25	87.6	56.9	97.3	13.2	12.3
0.500	29	179	5	29	86.0	50.0	97.3	14.7	13.9
0.520	29	183	1	29	87.6	50.0	99.5	3.3	13.7
0.540	26	183	1	32	86.4	44.8	99.5	3.7	14.9
0.560	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.580	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.600	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.620	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.640	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.660	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.680	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.700	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.720	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.740	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.760	26	184	0	32	86.8	44.8	100.0	0.0	14.8
0.780	10	184	0	48	80.2	17.2	100.0	0.0	20.7
0.800	6	184	0	52	78.5	10.3	100.0	0.0	22.0
0.820	6	184	0	52	78.5	10.3	100.0	0.0	22.0

The LOGISTIC Procedure

000202

Classification Table

	Correct		Incorrect		Percentages				
Prob Level	Event	Non-Event	Event	Non-Event	Correct	Sensi-tivity	Speci-ficity	False POS	False NEG
0.840	2	184	0	56	76.9	3.4	100.0	0.0	23.3
0.860	2	184	0	56	76.9	3.4	100.0	0.0	23.3
0.880	0	184	0	58	76.0	0.0	100.0	.	24.0

Polycarbonate-Based Index vs. Object-Based Index

Regression Analysis

Model: MODEL1
Dependent Variable: O_INDEX

000204

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	1.33855	1.33855	180.420	0.0001
Error	18	0.13354	0.00742		
C Total	19	1.47209			

Root MSE	0.08613	R-square	0.9093
Dep Mean	0.41050	Adj R-sq	0.9042
C.V.	20.98271		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > |T|
INTERCEP	1	0.959343	0.04517243	21.237	0.0001
LP_INDEX	1	0.733172	0.05458373	13.432	0.0001

Step/Skirt Index Validation Test

Statistical Analysis

DATA

EXPERIMENTAL RESULTS

000206

OBS	X	TRIALS	EVENTS
1	0.59	6	6
2	0.20	6	5
3	0.19	6	4
4	0.16	12	2
5	0.12	12	0
6	0.07	18	4

The LOGISTIC Procedure

000207

Data Set: WORK.C
Response Variable (Events): EVENTS
Response Variable (Trials): TRIALS
Number of Observations: 6
Link Function: Logit

Response Profile

Ordered Value	Binary Outcome	Count
1	EVENT	21
2	NO EVENT	39

Model Fitting Information and Testing Global Null Hypothesis BETA=0

Criterion	Intercept Only	Intercept and Covariates	Chi-Square for Covariates
AIC	79.694	60.344	.
SC	81.788	64.532	.
-2 LOG L	77.694	56.344	21.350 with 1 DF (p=0.0001)
Score	.	.	17.055 with 1 DF (p=0.0001)

PREDICTIVE MODEL

Analysis of Maximum Likelihood Estimates

Variable	DF	Parameter Estimate	Standard Error	Wald Chi-Square	Pr > Chi-Square	Standardized Estimate	Odds Ratio
INTERCPT	1	-3.5337	1.1209	9.9393	0.0016	.	.
X	1	18.6321	7.2687	6.5708	0.0104	1.510619	999.000

Association of Predicted Probabilities and Observed Responses

Concordant	= 75.7%	Somers' D	= 0.623
Discordant	= 13.4%	Gamma	= 0.699
Tied	= 10.9%	Tau-a	= 0.288
319 pairs)		c	= 0.811

000208

The LOGISTIC Procedure

Classification Table

	Correct		Incorrect		Percentages				
Prob Level	Event	Non-Event	Event	Non-Event	Correct	Sensi-tivity	Speci-ficity	False POS	False NEG
0.060	21	0	39	0	35.0	100.0	0.0	65.0	.
0.080	17	0	39	4	28.3	81.0	0.0	69.6	100.0
0.100	17	0	39	4	28.3	81.0	0.0	69.6	100.0
0.120	17	14	25	4	51.7	81.0	35.9	59.5	22.2
0.140	17	14	25	4	51.7	81.0	35.9	59.5	22.2
0.160	17	14	25	4	51.7	81.0	35.9	59.5	22.2
0.180	17	14	25	4	51.7	81.0	35.9	59.5	22.2
0.200	17	14	25	4	51.7	81.0	35.9	59.5	22.2
0.220	17	14	25	4	51.7	81.0	35.9	59.5	22.2
0.240	17	26	13	4	71.7	81.0	66.7	43.3	13.3
0.260	17	26	13	4	71.7	81.0	66.7	43.3	13.3
0.280	17	26	13	4	71.7	81.0	66.7	43.3	13.3
0.300	17	26	13	4	71.7	81.0	66.7	43.3	13.3
0.320	17	26	13	4	71.7	81.0	66.7	43.3	13.3
0.340	17	26	13	4	71.7	81.0	66.7	43.3	13.3
0.360	15	26	13	6	68.3	71.4	66.7	46.4	18.8
0.380	15	36	3	6	85.0	71.4	92.3	16.7	14.3
0.400	15	36	3	6	85.0	71.4	92.3	16.7	14.3
0.420	15	36	3	6	85.0	71.4	92.3	16.7	14.3
0.440	15	36	3	6	85.0	71.4	92.3	16.7	14.3
0.460	15	36	3	6	85.0	71.4	92.3	16.7	14.3
0.480	11	36	3	10	78.3	52.4	92.3	21.4	21.7
0.500	11	36	3	10	78.3	52.4	92.3	21.4	21.7
0.520	6	36	3	15	70.0	28.6	92.3	33.3	29.4
0.540	6	38	1	15	73.3	28.6	97.4	14.3	28.3
0.560	6	38	1	15	73.3	28.6	97.4	14.3	28.3
0.580	6	38	1	15	73.3	28.6	97.4	14.3	28.3
0.600	6	39	0	15	75.0	28.6	100.0	0.0	27.8

CLASSIFICATION TABLE

TAB G

Arthur D Little

Arthur D. Little International, Inc.
Acorn Park
Cambridge, Massachusetts
02140-2390 U S A

Telephone (1) 617.498 5000
Fax (1) 617 498.7200

January 19, 2000

000210

Mr. Edward A. Donoghue
President
Edward A. Donoghue Associates, Inc.
1677 County Route 64
P.O. Box 201
Salem, New York
12865-0201

Re: Revised Escalator Factory and CPSC Index and Friction Test Results

Dear Ed:

Please find attached a revised test report correcting the error in the December 13, 1999 report. The data reported included an error in the results. The index level of 0.11 (goal = 0.10) with a loaded gap of 0.140 inches and COF of 0.15 should have the following results.

Hand Entrapments 0 of 6

Calf Entrapments 0 of 6

Toe Entrapments 0 of 6

Toe Entrapment and Release 0 of 6

If you have any questions regarding these tests, please call me at 617.498.6483

Sincerely,

[signature]

Raymond Avitable
Consultant
Technology and Innovation

Cc: R. Farra

January 19, 2000 **REVISED – SUPERSEEDS REPORT DATED DECEMBER 13, 1999**

NEII Factory Index Measurement and Evaluation
Test Plan

Test Objective: The objective of the factory tests was to measure the index of standard production escalators, then conduct entrapment scenario tests to determine the condition of escalators currently being installed. The escalators were not modified or conditioned in any way prior to performing the tests.

Test Plan: The test plan for the NEII factory tests is detailed in the October 6, 1999 proposal to NEII (ADL Ref. 39813 R5). Four entrapment scenarios were tested.

- 6 toe entrapment scenarios @ 20 lbf normal force
- 6 toe entrapment and release scenarios @ 20 lbf normal force
- 6 hand entrapment scenarios @ 15 lbf normal force
- 6 calf entrapment scenarios @ 25 lbf normal force

Test Procedure: The procedure used for the factory index measurement tests is detailed in the ADL report "Escalator Step/Skirt Performance Standard, Final Report", dated September 16, 1999, in section 2, pages 2.3 to 2.7

Test Equipment: The equipment used for the factory index measurement tests is the same that has been used for all NEII tests, including those conducted at NEII member facilities and customer installations. The equipment is detailed in the ADL report "Escalator Step/Skirt Performance Standard, Final Report", dated September 16, 1999, in section 2, pages 2.3 to 2.7

Test Results: Tests were conducted at two NEII member factories. Both escalators tested were the companies' most common currently produced design. Generally the two shoe entrapment scenarios did not show evidence of any entrapments. The calf scenarios were the most likely to cause entrapments. The hand scenarios were less likely to cause entrapments. The data are summarized below.

Location "E"

Index Values:	**0.09**	**0.09**	**0.10**
Friction:	0.23	0.23	0.30
Loaded Gap:	0.101	0.101	0.091

Entrapment Results

Hand entrapment:	0 entrapments out of 6 attempts
Calf entrapment:	4 entrapments out of 6 attempts
Toe entrapment & release:	0 entrapments out of 6 attempts
Toe entrapment:	0 entrapments out of 6 attempts

Location "C"

Index Values:	**0.21**	**0.22**
Friction:	0.46	0.46
Loaded Gap:	0.147	0.154

Entrapment Results

Hand entrapment:	1 entrapments out of 6 attempts
Calf entrapment:	3 entrapments out of 6 attempts
Toe entrapment & release:	0 entrapments out of 6 attempts
Toe entrapment:	0 entrapments out of 6 attempts

CPSC Index Variation Evaluation
Test Plan

Test Objective: The objective of the CPSC index tests was to determine the effects, if any, on entrapments by generating a given index with various COF and loaded gap values.

Test Plan: The test plan for the CPSC tests is detailed in the October 6, 1999 proposal to NEII (ADL Ref. 39813 R5), Four entrapment scenarios were tested. Four index levels; 0.10. 0.15, 0.20, 0.40, were set up using two different values for both COF and loaded gap. The values for COF and loaded gap were varied over relatively "high" and "low" levels. The index values and entrapment scenarios are listed below.

Index	Test Conditions
0.10	a) low loaded gap and high COF b) high loaded gap and low COF
0.15	a) low loaded gap and high COF b) high loaded gap and low COF
0.20	a) low loaded gap and high COF b) high loaded gap and low COF
0.40	a) low loaded gap and high COF b) high loaded gap and low COF

- 6 toe entrapment scenarios @ 20 lbf normal force
- 6 toe entrapment and release scenarios @ 20 lbf normal force
- 6 hand entrapment scenarios @ 15 lbf normal force
- 6 calf entrapment scenarios @ 25 lbf normal force

Test Procedure: The procedure used for the factory index measurement tests is detailed in the ADL report "Escalator Step/Skirt Performance Standard. Final Report", dated September 16. 1999, in section 2, pages 2.3 to 2.7

Test Equipment: The equipment used for the CPSC index variation tests is the same that has been used for all NEII tests, including those conducted at NEII member facilities and customer installations. The equipment is detailed in the ADL report "Escalator Step/Skirt Performance Standard. Final Report", dated September 16, 1999, in section 2, pages 2.3 to 2.7

Test Results:

Index Target = 0.10

Index Values:	**0.11**		
Friction:	low	=	0.15
Loaded Gap:	high	=	0.140

Entrapment Results

Hand entrapment:	0 entrapments out of 6 attempts
Calf entrapment:	0 entrapments out of 6 attempts
Toe entrapment & release:	0 entrapments out of 6 attempts
Toe entrapment:	0 entrapments out of 6 attempts

Index Values: **0.11**
Friction: high = 0.34
Loaded Gap: low = 0.094

Entrapment Results

Hand entrapment:	0 entrapments out of 6 attempts
Calf entrapment:	6 entrapments out of 6 attempts
Toe entrapment & release:	0 entrapments out of 6 attempts
Toe entrapment:	0 entrapments out of 6 attempts

Index Target = 0.15

Index Values: **0.15**
Friction: low = 0.12
Loaded Gap: high = 0.193

Entrapment Results

Hand entrapment:	0 entrapments out of 6 attempts
Calf entrapment:	0 entrapments out of 6 attempts
Toe entrapment & release:	0 entrapments out of 6 attempts
Toe entrapment:	0 entrapments out of 6 attempts

Index Values: **0.16**
Friction: high = 0.39
Loaded Gap: low = 0.128

Entrapment Results

Hand entrapment:	0 entrapments out of 6 attempts
Calf entrapment:	6 entrapments out of 6 attempts
Toe entrapment & release:	0 entrapments out of 6 attempts
Toe entrapment:	0 entrapments out of 6 attempts

Index Target = 0.20

Index Values: **0.19**
Friction: low = 0.22
Loaded Gap: high = 0.193

Entrapment Results

Hand entrapment:	0 entrapments out of 6 attempts
Calf entrapment:	6 entrapments out of 6 attempts
Toe entrapment & release:	0 entrapments out of 6 attempts
Toe entrapment:	0 entrapments out of 6 attempts

Index Values: **0.20**
Friction: high = 0.48
Loaded Gap: low = 0.132

Entrapment Results

Hand entrapment:	0 entrapments out of 6 attempts
Calf entrapment:	5 entrapments out of 6 attempts
Toe entrapment & release:	0 entrapments out of 6 attempts
Toe entrapment:	0 entrapments out of 6 attempts

Index Target = 0.40

Index Values:	**0.40**	
Friction:	low =	0.21
Loaded Gap:	high =	0.320

Entrapment Results

Hand entrapment:	3 entrapments out of 6 attempts
Calf entrapment:	6 entrapments out of 6 attempts
Toe entrapment & release:	0 entrapments out of 6 attempts
Toe entrapment:	0 entrapments out of 6 attempts

Index Values:	**0.41**	
Friction:	high =	0.48
Loaded Gap:	low =	0.245

Entrapment Results

Hand entrapment:	1 entrapments out of 6 attempts
Calf entrapment:	6 entrapments out of 6 attempts
Toe entrapment & release:	0 entrapments out of 6 attempts
Toe entrapment:	0 entrapments out of 6 attempts

The following table contains previous data (Table 2-14) incorporating new data from this test, and indicates that the results are very consistent with the previous data.

Index Level	Child's Shoe		Child's Hand	Child's Calf	Total No. of Entrapments	Percent Entrapment
	Toe Entrapment	Entrapment and Release				
.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	0/12	0/12	4/12	12/12	16/48	33%
.3-4	--	--	--	--	--	--
.2-.3	0/9	0/9	2/9	8/9	10/36	28%
.1-.2	0/30	0/30	1/45	23/45	24/150	16%
.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						

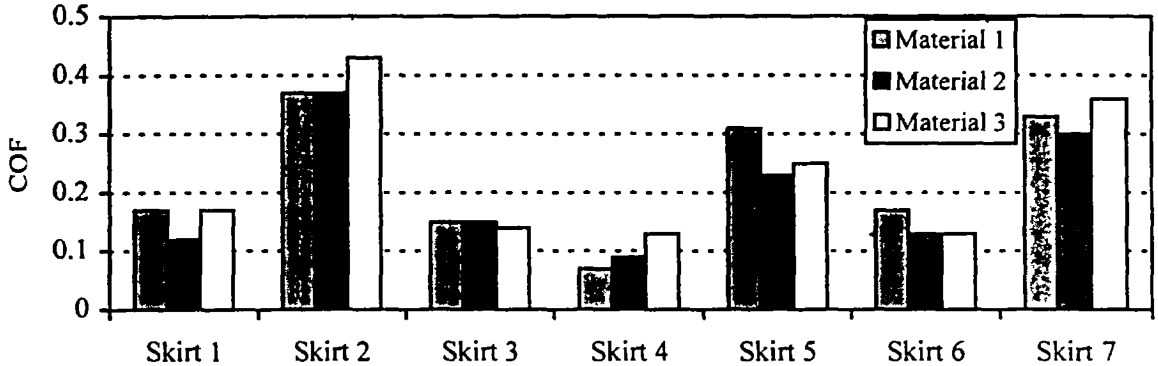
Table 0-1: Index based on polycarbonate test specimen COF

NEII
Polycarbonate Friction Tests
And
Statistical Evaluation

Test Results:
Average Coefficient of Friction values (3 observations per material / skirt panel combination)

	Skirt 1	Skirt 2	Skirt 3	Skirt 4	Skirt 5	Skirt 6	Skirt 7
Material 1	0.17	0.37	0.15	0.07	0.31	0.17	0.33
Material 2	0.12	0.37	0.15	0.09	0.23	0.13	0.30
Material 3	0.17	0.43	0.14	0.13	0.25	0.13	0.36

Average Coefficient of Friction



Statistical Results:

Objective: Test to determine if different Polycarbonate materials yield significantly different COF values.

Data: 3 Polycarbonate materials
7 Skirt panels
3 Replicate COF measurements at each of the 21 material / skirt panel combinations

Analysis: First we tested the assumption of additivity; i.e., the difference among the 3 Polycarbonate materials does not depend on the skirt panel. Theory and application are described in the statistical literature (e.g. Snedecor & Cochran); results indicate an additive model is applicable (i.e., there is no evidence of a material / skirt panel interaction).

Then we applied another statistical tool (analysis of variance) to test for differences among the 3 Polycarbonate materials. Results were as follows:

- Materials were not significantly different; COF averages were 0.23, 0.22 and 0.20 over all 7 test skirt panels.
- Skirt panels were very different; COF averages ranged from 0.10 to 0.39.
- Experimental error (normal variation from one measurement to the next) was small: the standard error of the mean COF over 7 different skirt panel samples was $\pm$ 0.010.
- The experiment was quite sensitive in that a relatively small difference between materials (as small as 0.038) would have been declared statistically significant; even had a difference that small been observed, it may be too small to be of practical significance.

Conclusion: The three Polycarbonate materials did not yield problematic differences in coefficient of friction measurements when tested over a wide range of skirt panel specimens. Observed differences were within normal variation expected to occur over replicate measurements.

Equipment:

Normal Force Scale:	Electroscale 401, 0 – 50 lbf
Tangential Force Scale:	Instron Universal Test Machine, model 1122
Load Cell:	Instron Reversible, model 2511-301, 0 – 1000 lbf (20-lbf scale used)
Software:	Instron Series IX Automated Materials Tester version 7.26.00

Polycarbonate Samples:
26 companies were identified as manufacturers of Polycarbonate. Four companies manufactured virgin Polycarbonate, with three capable of providing molded samples. Several other companies were identified as compounders of Polycarbonate (the addition of Titanium fibers for example). General-purpose material was selected for its availability. 4-inch diameter or 3 x 4-inch rectangles were used. All samples were nominally 1/8 inch thick. The sample sources and grades are listed below. Material data sheets are attached.

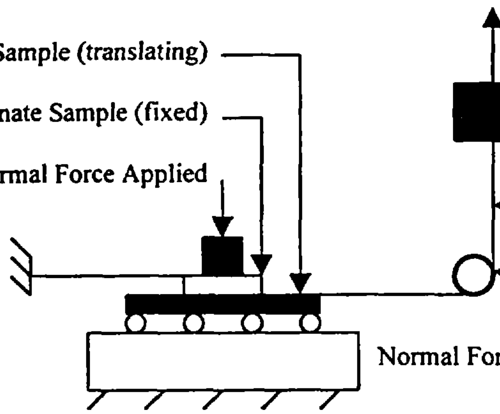
- Dow Plastics, Calibre® 201-22, 4-inch diameter disc
- G.E. Plastics, Lexan® 121, 3 x 4 inch rectangle
- Bayer Plastics, Makrolon® 2205, 3 x 4 inch rectangle (via Sheffield Plastics) *

* Industrial suppliers AIM Plastics and McMaster-Carr use Sheffield Plastics for their supplier of Polycarbonate sheets. The grade is the same as the one provided directly from Sheffield.

Skirt Panel Samples:
3 NEII member companies provided skirt panel samples. The only portion of the skirt panels tested was the surface facing the escalator steps. Each section was approximately 6-inches wide and 12-inches long. Listed below is a description of the various skirt panels tested. The test results detailed in this report do not correlate to the list in any way.

Manufacturer #1:	Black painted Clear painted
Manufacturer #2:	Black painted Clear painted Polished steel
Manufacturer #3:	Black painted Polished steel

Setup:
The test setup used for this series of friction tests is the same as that used for all previous NEII friction tests, including those conducted for human skin, artificial skin, and shoes. The Instron machine was used in a tensile mode using a pulley to change the direction of travel to apply a load tangential to the normal load. This change in direction allowed the skirt panel sample to be translated over rollers to remove the friction between the sample and the normal force scale. The Polycarbonate sample was held in place while a dead weight applied the normal force. Each Polycarbonate sample was fixed with two-sided tape to an aluminum plate, which was restrained from moving. The dead weight was placed on top of the aluminum plate. Each skirt panel section was also taped to the translation table.



Procedure:

1. Using two-sided tape install the skirt panel section to the center of the translation table. Clean the surface of the sample with a clean, lint free towel. Do not use any solvent-based cleaning solutions, as it may damage any coated surfaces.

2. Using two-sided tape install the Polycarbonate samples in the center of the aluminum plate. Clean the surface of the sample with a clean, lint free towel. Do not use any solvent-based cleaning solutions.

3. Check to see if both sample material surfaces are dry prior to beginning the test.

4. Using the position of the crosshead on the Instron machine, orient the translation table so the Polycarbonate sample is at the front of the skirt panel section. Set the displacement of the crosshead to no less than 6 inches. The travel of the translation table should not allow the Polycarbonate sample to come off the skirt panel section.

5. Calibrate the load cell and software and set the full range reading to 20 lbf.

6. Apply a dead weight to the top of the aluminum plate holding the Polycarbonate sample. The weight should be approximately 5 lbf. The normal force scale will measure the total normal force.

7. Using the Instron software, and the Instron machine, set the crosshead speed to 20 inches per minute.

8. Start a new test with the Instron software. While the test is running, monitor the normal force as read digitally by the normal force scale. Record the average force.

9. Repeat the test three times for each sample.

10. To determine the coefficient of friction, divide the average tangential force as determined by the Instron software by the average normal force. COF = F_t/F_n.

TAB H

United States
CONSUMER PRODUCT SAFETY COMMISSION
Washington, D.C. 20207

1

MEMORANDUM

DRAFT

DATE: February 7, 2000

TO: Patricia L. Hackett, Project Manager
Directorate for Engineering Sciences

THROUGH: Susan W. Ahmed, Ph.D.
Associate Executive Director
Directorate for Epidemiology

Russell H. Roegner, Ph.D.
Director
Division of Hazard Analysis

FROM: Michael A. Greene, Ph. D.
Mathematical Statistician
Division of Hazard Analysis

SUBJECT: Analysis of the Escalator Step/Skirt Performance Standard

The attached report provides an assessment of the statistical analysis leading to the step/skirt performance standard.

Analysis of NEII Escalator Proposals
Revisions to ASME A17

Executive Summary

As a result of theoretical and laboratory research on escalators, the National Elevator Industry, Inc. has proposed revisions to the escalator safety codes to the American Society of Mechanical Engineers. These revisions are intended to improve the safety requirements in the standard related to the risk of entrapment between the step and skirt. The recommendations are based on a Step/Skirt Performance Index (Index). The Index is a mathematical model that is related to the chance that a human limb will be entrapped between the step and skirt of the escalator. Components of the Index include the distance between the step and the skirt, the resistance of the skirt and step to deflection and the coefficient of friction of the skirt.

The proposed revisions to the escalator safety codes will specify a maximum allowable value for the Index. The revised code, based on the Index, will usually result in a smaller distance between the step and the skirt than the current code. Escalators with high values of the Index will be out of compliance and will require modification. For escalators with Index values somewhat above the standard, installing deflectors along the skirt will allow compliance without further modification to the escalator.

The Index was developed by Arthur D. Little, Inc. in a two-year research program. In this program, entrapment scenarios were developed from research on hazard patterns in the National Electronic Injury Surveillance System (NEISS) and other data sources. Then entrapment tests were conducted using actual escalators. During the tests, it was possible to vary the skirt-step distance, coefficient of friction and other variables, to determine the effect of these variables on entrapment.

The escalator entrapment experiments used in developing the Index, involved generic shapes serving as prototypes for human objects. The Index was then validated with other objects representing simulated children's hands, calves and shoes. The simulated objects had the same shape as human objects and were covered with a material that had a coefficient of friction similar to human skin. The objects were intended to simulate scenarios where children were entrapped.

During the validation research, the Index was shown to predict the likelihood of entrapment of the simulated child's hand very accurately. It did not predict children's calf entrapment nor children's shoe entrapment as accurately. Calf entrapment occurred at almost every level of the Index. Shoe entrapments occurred only at very high values of the Index.

In addition to those problems in predicting calf and shoe entrapments, the Index did not accurately predict the entrapment of "large" objects. Large objects were intended to simulate adult entrapment scenarios. Only generic large shapes were used,

that is, there was no validation study with simulated large objects representing objects like adult hands, shoes or calves. Probably more research is required to explain the mechanism of large object entrapment and to create a useful predictive model for these objects.

The Step/Skirt Performance Index improves on the current code. The present code requires a maximum of 3/16 inch gap, and specifies that the skirt panel shall be "smooth and made from a low friction material or treated with a friction reducing material." The proposed standard specifies a tradeoff between gap and coefficient of friction. Also, the present code does not require deflectors and is not specific about how to measure the gap. The proposed standard requires deflectors for some escalators that would not otherwise meet the code. Additionally, the proposed standard is very specific about how the Index will be measured. In this regard, the proposed standards and the supporting research represent progress in improving the safety of escalators.

1.0 Introduction

The National Elevator Industry, Inc., representing manufacturers of escalators, has proposed changes to the American Society of Mechanical Engineers (ASME). The proposed standards include the following:

- A17.1d-2000 and A17.3 covers already installed escalators. Such escalators with a Step/Skirt Performance Index (Index) of more than 0.4 will not be in compliance with the standard. Escalators with Index values between 0.15 and 0.4 will require a deflector and escalators under 0.15 will not require a deflector.

- A17.1-2000 covers new escalators. These escalators with an Index value of more than 0.25 will not be in compliance. Escalators with Index values between 0.15 and 0.25 will require a skirt deflector and escalators with Index values below 0.15 will be in compliance without a deflector.

- In addition, new escalators will not be allowed to have a loaded gap of more than 5mm (0.2").

The basis for these standards were laboratory and field studies of escalator entrapments conducted on behalf of the National Elevator Industry, Inc. by Arthur D. Little, Inc (ADL). In these studies, ADL developed the Index as a single measure of how likely an entrapment would be to occur when an object was placed against the skirt panel next to the gap between the step and the skirt. This Index is intended to serve as a measure of the entrapment hazard for an escalator.

The purpose of this analysis is to review the research leading to the proposed standards. The central issue is to determine if the research provides evidence that the proposed standards will reduce the entrapment hazard of escalators, especially to young children.

Section 2 of this analysis briefly discusses hazard patterns obtained from CPSC's National Electronic Injury Surveillance System (NEISS) and reported by ADL. Section 3 reviews the development of the Index. This section covers some of the theory and the initial testing that led to a mathematical model for the probability of entrapment. Section 4 covers the validation of the Index. This part of the research used simulated body parts. The last section evaluates the research program.

2.0 Hazard Patterns

In research conducted between April and June 1998 (see ADL, 1999a), using data from the CPSC's National Electronic Injury Surveillance System (NEISS) and the State of Massachusetts, ADL studied the interaction between humans and escalators that led to escalator entrapments. Several scenarios were developed. Two involved foot/shoe/toe entrapment where (1) the shoe is caught in the gap between the side skirt and the step or (2) the shoe is caught between the side skirt and the riser behind the step where the subject is standing. A third scenario involves calf entrapment when a child is sitting on a step and the calf is positioned against the skirt. The fourth scenario describes hand or finger entrapments. This occurs with a person sitting and then resting a hand on the side of the step near the gap. The scenario may also occur when a person falls on the escalator, then grasps the side of the step with his hands.

These scenarios are consistent with CPSC data (see memo from D.K. Tinsworth and J. McDonald, 1999). NEISS data show an average of 5,800 escalator emergency department treated injuries between 1994 and 1998. These authors conducted a more detailed examination of 1998 data. They showed that about 15 percent of the injuries or 1,200 involved entrapments (body part, clothing or shoes caught). Of these 1,200 entrapments, an estimated 800 occurred to children 14 years of age and younger.

ADL's hazard analysis continued by considering the forces involved in entrapments (ADL, 1999a, page 1-12). The entrapment event begins with a body part placed against the skirt panel. A friction force then decelerates the body part or stops the body part from sliding along the skirt. The body part then either rotates or wedges into the gap between the step and the skirt or the riser and the step. The physics involved require the force exerted by the object to overcome the combined lateral stiffness of the step and skirt panel in order to become entrapped.

3.0 Development of The Step/Skirt Performance Index

This section reviews the development of the Index. Section 3.1 discusses the basis for ADL's selection of variables. Section 3.2 describes the experimental design. Section 3.3 describes CPSC's concerns about the test plan, primarily focusing on the absence of sufficient variability in the experimental design. Section 3.4 discusses ADL's subsequent modification of the experimental design and study objectives. Section 3.5 presents ADL's Index that emerged from the experimental design. CPSC's reanalysis of the experimental data is found in Section 3.6. This is separated into reanalysis of the large object data in section 3.61 and the small object data in section 3.62. Section 3.7 describes ADL's revision to the Index so that it would only consider small objects. Finally, section 3.8 presents ADL's final modification to the Index that substituted the coefficient of friction for a standard test object for the test object's coefficient of friction.

3.1 Selection of variables

On the basis of the hazard pattern research and the physical models of entrapments, ADL began an experimental program to determine the effect of the different factors on the probability of entrapment. Initially they identified six factors. These were as follows:

Location: One of two escalators used in the test
Step Stiffness: 2,000, 4,000 or 11,000 lbf/in.
Skirt Panel Stiffness: 2,400 lbf/in and 5,000 lbf/in
Gap: 1/16, 3/16 or 3/8 inch
Coefficient of Friction: 0.2, 0.5 or 0.8
Object Characteristics: shape, size, force exerted against the skirt and stiffness.

ADL provided a rationale for the range of values for these different variables, as the extremes or plausible values that would be encountered in real escalators (ADL, 1999a, page 2-2). Escalator manufacturers provided two new escalators for testing. The step stiffness values of 2000 lbf/in and 11,000 lbf/in were chosen as practical lower and upper limits. The skirt panel stiffness of 2,400 was the present A17 code minimum, while 5,000 lbf/in was a value found in the test escalator. The gap measurement of 1/16 inch was chosen as a practical lower limit for the test escalator. The other two values represent the current A17.1 code (3/16 inch) and the A17.1 and A17.3 historical maximums (3/8 inch). The values for the coefficient of friction were chosen to identify the test escalator lower limit, a mid-range and a practical upper limit representing dry skin against the escalator skirt.

ADL also identified seven generic test objects that would be used in the entrapment experiments. The characteristics of these objects are shown in table 1 below.

Table 1
Generic Test Object Characteristics, Shape, Size and Force

Simulated Scenario (Part Entrapped)	Object Shape	Object Size (in)	Size Category	Object Force (lbf)
Child Sitting (Finger)	Circular	¼ d x 3	Small	10
Child Sitting (Calf)	Circular	1¼ d x 3	Small	25
Child Standing (Foot)	Rectangular	¼ x 3 x 3	Small	20
Adult Sitting (Finger)	Circular	¾ d x 3	Large	20
Adult Standing (Foot)	Rectangular	½ x 3 x 3	Large	70
Adult Standing (Foot)	Rectangular	1 x 3 x 3	Large	70
Wedge	Wedge	1 x 20° taper	Large	53

Source: ADL (1999a, page 2-3). "d" means diameter.

Table 1 shows a collection of items intended to represent foot or shoe, finger and calf objects, with large (adult) and small (child) versions of the objects for the finger and foot. These objects were disks, cylinders or rectangular solids, not really resembling the objects they simulated, except in the size of the object placed against the skirt during entrapment testing. For example, the object representing a child's finger was a cylinder with a diameter of ¼ inch.

Object stiffness or resistance to deformation was specified at three levels: 100, 1000 and 10,000 lbf/in. Object forces were chosen to represent plausible values for the lateral forces exerted against the side skirt by an adult or child's respective body part. Table 1 shows that the force of the child object was always lower than the adult object of the same type.

3.2 Experimental Design

There were a large number of possible combinations of variables at each unique value. Two variables had two values each (location and skirt panel stiffness), and three variables had three different values (coefficient of friction, step stiffness and gap). This resulted in 108 possible combinations. Object itself represented more variables with seven types of objects and three levels of stiffness for another 21 possible combinations. Assembling these resulted in 2,268 unique combinations of variables.

With testing typically involving two identical tests at each unique combination, testing all the possible combinations would be impractical. Instead, ADL chose a fractional factorial design, where each level of each variable was tested at least once and some combinations were tested more than once. A total of sixteen different test configurations were specified. These are shown in table 2.

Table 2
Test Conditions

Test	Location	Object Stiffness	Step Stiffness	Skirt Stiffness	Gap	COF
1	A	L	L	L	H	L
2	A	M	M	L	M	H
3	A	H	H	H	M	M
4	A	M	M	H	L	M
5	A	M	M	L	M	M
6	A	L	L	L	L	M
7	A	M	M	H	H	H
8	A	H	H	H	M	L
9	B	L/H	H	L	L	H
10	B	H/M	M	L	M	L
11	B	H/L	L	H	M	M
12	B	H/M	M	H	H	M
13	B	L/M	M	L	M	M
14	B	M/H	H	L	H	M
15	B	H/L	M	H	L	L
16	B	M/H	L	H	M	H

Source: ADL (1999a, table 2-3, page 2-6 and table 2-4 page 2-6).

Notes: Step Stiffness: L=2000-3000, M=3000-6000, H=10,000-12,000 lbf.
Skirt Stiffness: L=2000-3000, H=4000-6000 lbf.
Gap: L=1/16, M=3/16, H=6/16 inch.
COF: L=0.2-0.3, M=0.5-0.6 H=0.8-0.9.
Object Stiffness L=100, M=1000, H=12000 lbf/in.

At location A, each test was performed twice under exactly the same conditions. At location B each test was performed once at one object stiffness and a second time at the other object stiffness. This is why two levels of object stiffness are shown. Recall that complete test performance requires seven escalator runs, that is, one run with each of the generic test objects in table 1. This resulted in a specification for 224 trials (16 tests x 7 objects x 2 replications or stiffness).

The experiments used an apparatus that positioned the object adjacent to the step riser and applied the desired load (object force). The escalator was then started. Two observers were designated to determine if the object was entrapped. The object was determined to be entrapped if it entered the gap, regardless of how deeply it became wedged in the gap.

3.3 Concerns with the Test Plan

When the test plan was proposed by ADL, CPSC staff was concerned that there would not be enough different combinations of variables to estimate a statistical model that would explain the effect of the different variables on entrapment. As mentioned above, to be able to explain the effect of each of the variables and their interactions with each other, some multiple of the 2,268 unique combinations would be required. CPSC staff understood that this went far beyond what was practical, but was concerned that 16 different values of the variables (i.e. 16 cases as shown in table 1) would not be enough.

A second source of concern was interactions between variables. For example, combinations of two or more variables might contribute more toward the entrapment probability than any of the individual variables by themselves. Because there are hardly enough cases to estimate the main effects (i.e. the unique effect of each individual variable by itself), interactions between variables might confound, or appear as, the main effects. There is no statistical test to rule out interactions with such a small number of observations.

3.4 Modified Experimental Design

After completing the first round of testing at Location A, ADL analysts observed that in all but one of the first 52 trials, the first and second outcomes (i.e. entrapment or non entrapment) were the same. ADL decided to suspend replications (i.e. repeated trials under exactly the same condition) in order to study a wider range of test conditions. As a result, at the second location, each of the objects was tested at two object stiffness levels. (See for example, tests 9-16 in table 2.)

3.5 ADL's Statistical Model of the Entrapment Probability

The data were used to fit a mathematical model of the entrapment probability. ADL represented the entrapment probability as

$$Index = \frac{e^y}{e^y + 1} \qquad (1)$$

where

$$y = -6.26 + 2.37(COF) + 9.30(LoadedGap) + 2.49(ObjectSize) \qquad (2)$$

Object Size was defined as 1 for small objects and 0 for large objects. Object size category was shown in table 1 above. *Loaded Gap* was defined in equation (3)

$$LoadedGap = InitialGap + ObjectForce\left(\frac{1}{SkirtPanelStiffness} + \frac{1}{StepStiffness}\right) \quad (3)$$

As noted above, the Index is a model for the probability of entrapment that reflects the effect of gap, object force, skirt and step stiffness and the coefficient of friction. The coefficients (numbers) in the equations were estimated using statistical software for logistic regression analysis.

Equation (2) actually turns out to be two different equations. Equation (2a) below is for the large objects.

$$y = -6.26 + 2.37(COF) + 9.30(LoadedGap) \quad (2a)$$

and equation (2b) is for the small objects.

$$y = -3.77 + 2.37(COF) + 9.30(LoadedGap) \quad (2b)$$

ADL reported the standard diagnostics for logistic regression models (ADL 1999a, Appendix). The coefficients estimated in equation (2) were all statistically significant. The intercept, loaded gap and size dummy had *p-values* less than 0.0001, while the coefficient of friction term had a *p-value* of 0.0395. The signs of the terms were appropriate indicating that increasing the amount of the COF and increasing the value of loaded gap in turn would increase the probability of entrapment. Small size objects were also more likely to result in entrapment than large size objects, as shown in the value of the parameter estimate for the Object Size Variable in equation (2).

3.6 CPSC Reanalysis of the Experimental Data

How well did the model fit the data? Table 2 below shows the actual test conditions and the model predictions.

Table 3
Experimental results from ADL's Task 1 Tests

		Experimental Conditions				Outcomes		Entrapment Probability		
Test	Location	Step	Skirt	Gap	COF	Trials	Entrapments	Observed	Model	Error
1	A	L	L	H	L	8	2	0.25	0.13	0.12
2	A	M	L	M	H	14	4	0.29	0.27	0.01
3	A	H	H	M	M	14	0	0.00	0.16	-0.16
4	A	M	H	L	M	14	0	0.00	0.08	-0.08
5	A	M	L	M	M	14	4	0.29	0.20	0.08
6	A	L	L	L	M	12	5	0.42	0.07	0.35
7	A	M	H	H	H	14	10	0.71	0.56	0.16
8	A	H	H	M	L	14	0	0.00	0.11	-0.11
9	B	H	L	L	H	18	0	0.00	0.10	-0.10
10	B	M	L	M	L	14	2	0.14	0.12	0.02
11	B	L	H	M	M	14	3	0.21	0.20	0.01
12	B	M	H	H	M	24	10	0.42	0.42	0.00
13	B	M	L	M	M	14	2	0.14	0.20	-0.06
14	B	H	L	H	M	28	12	0.43	0.48	-0.05
15	B	M	H	L	L	12	1	0.08	0.03	0.05
16	B	L	H	M	H	14	3	0.21	0.27	-0.06
All						242	58	0.24		

Notes: For definition of experimental conditions, see table 2. Data from ADL (1999a, appendix). The observed entrapment probability is computed as the number of entrapments divided by the number of trials. The model entrapment probability is computed using equations (1)-(3). The model entrapment probability contains the value of the Index.

The specification for the experimental design called for each test to have 14 trials as shown previously in table 2. These were either all seven generic objects tested under identical conditions (replications) or the seven objects tested at two different object stiffness values. There were slight departures from this test plan as shown in table 3.

Table 3 contains the complete experimental results from the 242 trials. The table shows there were 58 entrapments (see also ADL, 1999a, page 2-8). This is an overall entrapment probability of 24%.

In comparing the model predictions with the observed entrapment probability, it is more important to look at cases where the model predicted fewer entrapments than actually occurred. This would result in a positive value in the error column. Specific instances included tests 1, 6 and 7. In test 1, the model predicted a 13% chance of entrapment, while the actual outcomes involved 2 entrapments out of 8 trials (25%). Test

6 showed 5 out of 12 entrapments (42%), while the model predicted a 7% chance of entrapment.

3.61 Reanalysis of the Large Object Model and Data

To determine if the model predicted equally well for large and small generic objects, we separated the experimental results in Table 3 into two separate tables by size category. Table 4 contains the results for the large objects. Definitions are the same as table 3. Model computations use equations (1), (2a) and (3).

Table 4
Experimental results from ADL's Task 1 Tests
Large Objects Only

	Experimental Conditions					Outcomes		Entrapment Probability		
Test	Location	Step	Skirt	Gap	COF	Trials	Entraps	Observed	Model	Error
1	A	L	L	H	L	8	2	0.25	0.13	0.12
2	A	M	L	M	H	8	0	0.00	0.09	-0.09
3	A	H	H	M	M	8	0	0.00	0.04	-0.04
4	A	M	H	L	M	8	0	0.00	0.02	-0.02
5	A	M	L	M	M	8	2	0.25	0.06	0.19
6	A	L	L	L	M	8	5	0.63	0.02	0.60
7	A	M	H	H	H	8	4	0.50	0.34	0.16
8	A	H	H	M	L	8	0	0.00	0.02	-0.02
9	B	H	L	L	H	12	0	0.00	0.03	-0.03
10	B	M	L	M	L	8	0	0.00	0.03	-0.03
11	B	L	H	M	M	8	0	0.00	0.06	-0.06
12	B	M	H	H	M	16	2	0.13	0.24	-0.12
13	B	M	L	M	M	8	0	0.00	0.06	-0.06
14	B	H	L	H	M	16	0	0.00	0.25	-0.25
15	B	M	H	L	L	8	1	0.13	0.01	0.12
16	B	L	H	M	H	8	0	0.00	0.09	-0.09
All						148	16	0.11		

Notes: See table 3.

There were 148 trials with the large objects. These resulted in 16 entrapments, for an overall entrapment probability of 11%. This compares with 24% overall, which includes both small and large objects. It is unsurprising to find a lower entrapment probability among the larger objects because the gap has to be wider to entrap a large object. Note that the regression model contains a positive term for the dummy variable representing small object size, implying that size is inversely correlated with entrapments.

The worst fit occurred with test 6, where the model predicted a 2% chance of entrapment in contrast to the observations of 5 entrapments in 8 trials. This test had compliant step and skirt (both at lowest experimental values), a 1/16" gap and medium coefficient of friction. According to the model (equation (2)), this should have been a combination of variables that resulted in a small number of entrapments. This raised the question about what might be expected with a large object with low skirt and step stiffness, low or medium gap and a high coefficient of friction or some similar combinations. However, the experimental design did not have enough of those conditions to estimate this effect.

In an attempt to improve the model, CPSC staff performed two regressions using the data supplied by ADL. One was limited to small objects only and the other limited to large objects. The "large object" version of equation (2) was estimated as

$$y = -2.47 + 0.32(COF) + 0.82(LoadedGap) \qquad (4)$$

This model has smaller coefficients on COF and LoadedGap than equation (2). The diagnostics for this model showed that neither COF nor LoadedGap terms had statistically significant coefficients. This indicated that the model that was based on large objects only, did not explain entrapments for large objects.

Why was it so difficult to account for large object entrapments? It may be that that the process of large object entrapment may not have been appropriately tested in the experimental design. As shown in table 1, with the exception of the wedge, the smallest size large object was ½ inch, which is larger than the largest gap size of 6/16 inch. As a result, forces are required to open the gap to entrap large objects. This means that the step and skirt must be compliant, that is, must not have much resistance to being opened. This process may be different for small objects that, in some cases, are smaller than the size of the gap.

Also, there might be a need for a "loaded size" term in equation (2). Loaded size would describe the size of the object as it deforms while entering the gap. Like loaded gap, loaded size would have step and skirt stiffness variables and object force variables. But it would also need a term for object stiffness, a variable that had not been used in these models.

The data did not provide any basis for resolving these conjectures. More research is needed on large objects.

3.62 Small Object Data and Model

In table 5, we present results for the small objects. There were 94 trials with small objects that resulted in a total of 42 entrapments (45%). As in previous tables, the "model" column contains the entrapment probability predicted from equations (1)-(3). This is the same value as the Index. The error is the difference between the observed and estimated (model) entrapment probability.

Table 5
Experimental results from ADL's Task 1 Tests
Small Objects Only

		Experimental Conditions				Outcomes		Entrapment Probability		
Test	Location	Step	Skirt	Gap	COF	Trials	Entraps	Observed	Model	Error
1	A	L	L	H	L	NA	NA			
2	A	M	L	M	H	6	4	0.67	0.51	0.15
3	A	H	H	M	M	6	0	0.00	0.31	-0.31
4	A	M	H	L	M	6	0	0.00	0.16	-0.16
5	A	M	L	M	M	6	2	0.33	0.40	-0.06
6	A	L	L	L	M	4	0	0.00	0.17	-0.17
7	A	M	H	H	H	6	6	1.00	0.85	0.15
8	A	H	H	M	L	6	0	0.00	0.22	-0.22
9	B	H	L	L	H	6	0	0.00	0.23	-0.23
10	B	M	L	M	L	6	2	0.33	0.24	0.09
11	B	L	H	M	M	6	3	0.50	0.40	0.10
12	B	M	H	H	M	8	8	1.00	0.77	0.23
13	B	M	L	M	M	6	2	0.33	0.40	-0.06
14	B	H	L	H	M	12	12	1.00	0.78	0.22
15	B	M	H	L	L	4	0	0.00	0.08	-0.08
16	B	L	H	M	H	6	3	0.50	0.51	-0.01
All						94	42	0.45		

Notes: See tables 3 and 4. The first test was not performed with small objects at test 1. Usually there were 6 trials, representing a pair of replications using the three small objects or two tests at different object stiffness levels.

The results for the small objects seem to make sense. When the gap is large, (e.g. in tests 7, 12 and 14), the objects are always entrapped. When the gap is set at medium, the entrapment probability is about 1/3. Medium gaps and high coefficients of friction show more likelihood of entrapment than medium gaps and low or medium coefficients of friction. When the gap is low (1/16"), there were no entrapments.

The model predictions are generally appropriate. Errors with negative signs indicate that the model predicts more entrapments than occurred. This makes the model conservative, that is the errors are on the side of safety. Positive errors are not conservative. Positive errors are found primarily at high values Index . See trials 7, 12, and 14, for example.

It should also be observed that there were no entrapments when the gap was 1/16 inch (the value shown as L in the table).

We also estimated a separate model for the small objects. This was as follows:

$$y = -13.31 + 3.98(COF) + 50.3(LoadedGap) \qquad (5)$$

Both regression coefficients for this model were borderline significant. The *p-value* for COF was 0.0562, while the *p-value* for LoadedGap was 0.0624. Some of this lack of significance may be attributable to reducing the sample size by using only small objects.

Equation (5) puts more weight on the value of the coefficient of friction and the loaded gap than ADL's equation (2b). However, comparison of the predictions between this model and the ADL models (1)-(3), showed that the model in equation (5) made small but not substantial improvement in predicting entrapments.

3.7 ADL revision to the step/skirt performance Index model

Following the presentation of their statistical analysis, ADL indicated that they would not be conducting any further testing with large objects. The validation test would only use small objects and the small object form of the model that they developed (equation 2b).

At this point in the research, the model for the Index was completed. The remainder of the discussion concerns refinement and validation of the Index.

3.8 The polycarbonate based Index

In the development of the statistical approach, it should be clear that the model includes variables that describe both the object and the properties of the escalator. Object properties include the object force, which is a component of the loaded gap variable. Escalator properties include step and skirt stiffness (also components of loaded gap), and initial gap. Coefficient of friction is a property of both the object and the escalator.

For actual measurement in the field to certify escalators as complying with a standard, it would be undesirable to have the Index vary by the object used to measure it.

There should not be a "small object" Index, or an Index based on a wedge, or an Index from an object with a given stiffness or object force. Instead, ADL proposed using a standardized object. This was made from polycarbonate. This means that the Index would be calculated using the object stiffness and the coefficient of friction from the polycarbonate specimen, rather than the particular object used in the test.

The problem raised by the use of the standardized object is that the Index computed using a standard object would not represent the entrapment probability as well as the Index computed from the object used in a test. A comparison between the Index based on the object and the polycarbonate based Index is shown below in table 6. The objects used in the comparison are the simulated human objects that were used in the validation step. Those objects are discussed in more detail in section 4.

Table 6
Relationship between Object Index and Polycarbonate Index

Object	Simulated Human Object Index	Polycarbonate Object Index	Difference
Calf	0.86	0.59	0.27
Calf	0.52	0.20	0.32
Calf	0.45	0.19	0.26
Calf	0.35	0.16	0.19
Calf	0.25	0.12	0.13
Calf	0.23	0.07	0.16
Calf	0.10	0.07	0.03
Hand	0.87	0.59	0.28
Hand	0.54	0.20	0.34
Hand	0.45	0.19	0.26
Hand	0.35	0.16	0.19
Hand	0.25	0.12	0.13
Hand	0.25	0.07	0.18
Hand	0.10	0.07	0.03
Shoe	0.92	0.88	0.04
Shoe	0.91	0.88	0.03
Shoe	0.31	0.22	0.09
Shoe	0.28	0.22	0.06
Shoe	0.12	0.08	0.04
Shoe	0.10	0.08	0.02

Source: ADL (1999a, page 2-19).

These tests involved setting the escalator parameters (gap, skirt and step stiffness and escalator coefficient of friction. The Index based on the simulated human objects was then computed (using equation 2) from the measured coefficient of friction and the force for the object (and the remaining escalator parameters). The polycarbonate object was computed using exactly the same setup for that test, except that the coefficient of friction and object force was measured for the polycarbonate object. These produced different values in the Index.

Table 6 shows that the polycarbonate based Index is always less than the object Index. Differences between the two Indexes are in the third column of table 6. The differences are larger for the simulated calf object and the simulated hand than the shoe. See section 4 below for a discussion of these objects.

Another difference between the polycarbonate Index and the object Index is that variation in the object Index may not be reflected in similar variation in the polycarbonate Index. This again is likely to be a result of differences in coefficient of friction between two different object Indexes (i.e. two different simulated hands), while the polycarbonate object has a single coefficient of friction. For example, see the last two rows for the calf object, where the object Index is either 0.23 or 0.10, while the polycarbonate based Index is constant at 0.07. A similar result is found with the simulated hand object.

In the final report, ADL (1999a, Appendix 6-4) modeled the relationship between the two Indexes. Surprisingly, the relationship presented was log-linear rather than linear. This suggests that equations (1)-(3) might have a different mathematical form if the polycarbonate object was used in the development of the model for the Index.

To summarize, while the relationship between the polycarbonate Index and the object Index is not linear, it is monotonic. Moreover, the polycarbonate Index always has a lower value than the object Index. This means that to the extent that the object Index represents entrapment probability, the polycarbonate Index will underestimate this probability. Using the polycarbonate Index requires an understanding that it has a lower value than the associated object Index.

4.0 Validating the Model

The model was validated with three simulated objects, one representing the looked like the calf, a second the foot and shoe and the third, the hand. All were the size of a young child. The Index was computed using the polycarbonate test object. An important question in validation is how well the polycarbonate Index predicted entrapment of the simulated objects.

Section 4.1 continues the discussion of the polycarbonate based Index raised in the last section; however, the context in this section is the simulated body part objects rather than the task 1 test objects. Section 4.2 addresses the problem about different observed entrapment results with similar values of the Index. Finally, section 4.3 presents and discusses the complete validation data.

4.1 The polycarbonate based Index with simulated body parts

The purpose of the validation was to show the predictability of objects that represented human body parts at different values for the Index. These objects were manufactured by Pacific Research Laboratories, Inc. and consisted of individual polymer bones, foam representing muscle and a separate foam layer representing skin. They were referred to as "Sawbones Skin."

According to ADL (page 2-15), these simulated human objects had reasonably comparable object stiffness as human parts, but had a much higher coefficient of friction than human skin. ADL reported that human skin had a COF between 0.18 and 0.52 against stainless steel, while the Sawbones skin had a coefficient of friction of 0.3 to 0.8. The polycarbonate test object (section 3.8) had a coefficient of friction between 0.19 and 0.44 (ADL, 1999b, page 15).

Since the simulated human objects have higher coefficients of friction than human skin, it would seem likely that they would have a higher chance of getting entrapped than real objects, everything else being constant. Also, the chance of entrapment should be larger than that predicted by the polycarbonate Index, because the coefficient of friction of the simulated objects is higher. The comparison between the polycarbonate Index and the entrapment probability should be revealing.

Table 7 below shows the entrapment results as compared to the polycarbonate Index. The Index values and object types are the same as shown in table 6.

Table 7
Entrapments of Simulated Human Objects and the Polycarbonate Index

Object	Polycarbonate Index	Number of Trials	Number of Entrapments	Entrapment Probability
Calf	0.59	3	3	100%
Calf	0.20	3	3	100%
Calf	0.19	3	3	100%
Calf	0.16	6	2	33%
Calf	0.12	6	0	0%
Calf	0.07	3	3	100%
Calf	0.07	6	1	17%
Hand	0.59	3	3	100%
Hand	0.20	3	2	67%
Hand	0.19	3	1	33%
Hand	0.16	6	0	0%
Hand	0.12	6	0	0%
Hand	0.07	3	0	0%
Hand	0.07	6	0	0%
Shoe	0.88	3	0	0%
Shoe	0.88	3	2	67%
Shoe	0.22	3	0	0%
Shoe	0.22	3	0	0%
Shoe	0.08	3	0	0%
Shoe	0.08	3	0	0%

Source: ADL(1999a, page 2-19).

In table 7, as noted above, the polycarbonate Index should generally show a lower value than the observed entrapment for the simulated objects. For the calf object, entrapments occur at almost every value of the polycarbonate Index, for example at 0.07, at 0.16, etc. The Index does not seem to predict calf entrapments consistently. For hand entrapments, the predictions seem more to have threshold effects. With the Index at 0.16 or below, there are no observed entrapments. A slight increase in the Index to 0.19 produced one entrapment in three trials. Another small increase to 0.20 produced two entrapments in three trials. In these and the Index trial at 0.59, the polycarbonate Index underestimated the entrapment probability for the hand.

The pattern from the shoe entrapment is also unclear. Except for one value, (the Index at 0.88), no shoe entrapments were observed during these tests. Moreover, the Index is inconsistent. At one set of tests with Index values of 0.88, there were 2 entrapments out of three, while at the other set of tests at 0.88, there were no recorded entrapments.

These series of tests raised two questions. First, why did similar Index values produce different entrapment rates? Was this just statistical fluctuation or was there a pattern? And if there was a pattern, did it relate to values of the gap or coefficient of friction?. Second what sort of entrapment behavior would be expected if the Index took on values between the reported values? For example, there were no Index values for either the hand or the calf between 0.20 and 0.59. For the child's shoe, there were no values between 0.22 and 0.88. To resolve these questions, CPSC asked ADL to perform additional tests.

4.2 Different entrapment results with similar Index Values.

At CPSC's request, ADL performed additional entrapment tests. Staff was especially interested in the relationship between the underlying Index components, principally coefficient of friction, and the entrapment events. We asked for tests at Index values of 0.10, 0.15, 0.20 and 0.40, that would hold the Index constant, but would vary the two components of gap and COF. The results are shown in table 8, below.

Table 8
Index, Index Components and the Entrapment Probability

				Calf			Hand	
Index	COF	Loaded Gap	Trials	Entrapments	Probability	Trials	Entrapments	Probability
0.40	0.16	0.320	6	6	100%	6	3	50%
0.40	0.47	0.245	6	6	100%	6	1	17%
0.20	0.22	0.193	6	5	83%	6	0	0%
0.20	0.48	0.130	6	4	67%	6	0	0%
0.15	0.12	0.193	6	0	0%	6	0	0%
0.15	0.38	0.128	6	6	100%	6	0	0%
0.10	0.15	0.140	6	0	0%	6	0	0%
0.10	0.34	0.094	6	6	100%	6	0	0%

Source: ADL(1999c, 1999d).

In theory, the Index should be all that is necessary to predict entrapments. The entrapment probability depends on the value of the loaded gap (i.e. the combination of initial gap, step and skirt stiffness and object force) and the coefficient of friction only through the Index. But table 8 shows that for Index values of 0.15 and 0.10, calf entrapments only occurred at high coefficients of friction. This means that the COF has explanatory power beyond the Index. This suggests that COF was not properly modeled for calf entrapments.

Why would this be? It might be because the calf is a "large" object. The calf provides a large surface to the skirt. However, the model used to predict entrapments was the "small" object version of the entrapment Index. This is not to argue that the large object version of the Index should have been used (i.e. equation 2a), but rather that the Index did not predict large objects very well.

In contrast to the calf, the simulated hand can go into the gap. The hand, it appears, behaves as a "small" object. From the table, it appears that neither COF nor gap makes any difference in the entrapment probability after controlling for the Index. While hand entrapments were recorded at Index levels as low as 0.19 and 0.20 (see table 7), the hand is most likely to be entrapped at Index values over 0.40 according to table 8.

CPSC also received data on shoe entrapments at the same Index, COF and Loaded Gap values. These data are not shown in table 8 because there were no entrapments of this object at those Index values.

To summarize, it appears that the Index is not sufficient to explain calf entrapments. Coefficient of friction seems to play a role beyond that in the Index. Shoe entrapments only occur at very high values of the Index. The Index does seem to predict hand entrapments.

4.3 Results

The data from tables 7 and 8 is combined in table 9, to show the complete results of the validation trials, relating the Index to entrapments.

Table 9
Final Step/Skirt Index Validation Data

Index	Number of Trials	Number of Entrapments	Entrapment Probability
	Shoe		
0.8 - 0.9	3	2	67%
0.5 - 0.8			
0.4 - 0.5	12	0	0%
0.3 - 0.4			
0.2 - 0.3	9	0	0%
0.1 - 0.2	30	0	0%
0.0 - 0.1	3	0	0%
	Hand		
0.6 - 1.0			
0.5 - 0.6	3	3	100%
0.4 - 0.5	12	4	33%
0.3 - 0.4			
0.2 - 0.3	9	2	22%
0.1 - 0.2	45	1	2%
0.0 - 0.1	9	0	0%
	Calf		
0.6 - 1.0			
0.5 - 0.6	3	3	100%
0.4 - 0.5	12	12	100%
0.3 - 0.4			
0.2 - 0.3	9	8	89%
0.1 - 0.2	45	23	51%
0.0 - 0.1	9	4	44%

Source: ADL(1999d, page 5). Blank lines denote Index ranges that were not tested.

The complete validation testing produced reasonable results for the simulated hand, showing increases in entrapments with increases in the Index. The results were somewhat less clear for the calf and the shoe. The calf seemed likely to be entrapped at even low values of the Index. Entrapment also seemed more sensitive to the coefficient of friction than the gap. The shoe could not be entrapped at all, except at very high Index values.