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Prediction of slip resistance in climbing systems

James M. Miller [a], Mark R. Lehto [b] and Timothy P. Rhoades [a]

[a] Department of Industrial and Operations Engineering, University of Michigan, Box 7995, Ann Arbor, MI 48105, USA
[b] School of Industrial Engineering, Purdue University, West Lafayette, IN 47907, USA

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Abstract

The objective of this study was to develop a predictive model describing the slip resistance of various climbing surfaces. In a four-factor experiment, seven commonly used metal grating step surfaces were evaluated, along with four types of shoe soles (crepe, leather, ribbed-rubber, and oil-resistant-rubber); three contaminant conditions (dry, wet-water, and diesel fuel); and direction of force application. The results showed that the available slip resistance coefficients (ASRC) varied primarily as a function of sole material and contaminants. This result and the significant interactions between sole and step surfaces suggest that the appropriate selection of shoe soles and control of contaminants may be the most effective way of attaining adequate ASRC values. A predictive equation was developed using multiple regression which described the evaluated conditions with binary indicator variables. To increase the equation's applicability, the step surfaces were described in terms of generic features such as: painted vs. bare metal surface; ring vs. point protrusions; edge orientation; contact area, and protrusion height gradient. The equation explained 89% of the variance in the original data. In a validation study, the equation explained 80% of the variance in slip resistance for a new step surface under the original set of sole, contaminant, and directionality conditions.

Relevance to industry

Designers and analysts have insufficient data to quantitatively predict slip resistance for various step surfaces, sole materials, and contaminant levels and must consequently resort to subjective estimates or expensive testing. This study helps remedy this situation by providing a simple means of predicting slip resistance.

Keywords

Slips and falls, coefficient of friction (COF), climbing, trucks, safety.

Introduction

Falls on climbing systems used for accessing high profile vehicles may occur when drivers climb into the cab (ingress), out of the cab (egress) or around other parts of their vehicles. Vehicles having this high profile characteristic include agricultural machinery, excavation equipment, and over-the-road trucks. To prevent falls considerable attention has been placed on the development of design and performance criteria for vehicle climbing systems. Recently significant attention has also been placed on other forms of intervention such as driver training and controlling the types of footwear used by drivers (Rhoades and Miller, 1989). Nevertheless, a significant number of fall-related injuries have been documented among the commercial truck driver population (Miller, 1972; Safety Sciences, 1976; BMCS, 1977; Bloswick, 1987).

As a design measure to prevent falls, climbing systems typically include fabricated metal step surfaces which have protrusions, raised edges, drain holes, or other features to enhance slip resistance and help avoid accumulation of debris. Faced with this variety of step surface alternatives, the advantages or disadvantages of choosing a particular material for a specific application may be unclear to the designer. Improvement of the step material selection process requires new methods of modeling the factors influencing the performance of step materials under specified conditions of footwear, contaminants, and user activities. Such modeling could also be used to guide the development of new step materials, or as the basis for restricting the types of footwear used.

Evaluation criteria

In making the difficult determination whether a climbing system is adequate or safe, the available slip resistance must be compared to that which is required (Rhoades and Miller, 1988). Designers using this approach will be applying an objective evaluation methodology and thus have an improved foundation for their choice of slip resistant materials. To apply this approach both the required and available slip resistance must be known. The following discussion will describe these criteria in more detail and expand upon the current status of methods for measuring them.

Required slip resistance. The required slip resistance is that amount of reactive horizontal force necessary to allow a person to complete a particular maneuver without slipping. The required slip resistance coefficient (RSRC) at each moment in time (t) can be expressed as a fraction:

$$\mathrm{RSRC}(t)=\frac{\text{generated horizontal foot forces}}{\text{vertical foot forces}} \qquad (1)$$

The values of RSRC(t) will be dictated by the system's climbing geometries, user anthropometric characteristics, and the particular task being performed. The maximum value of RSRC(t) for a given task defines the required slip resistance. Note that RSRC(t) is dimensionally identical to the coefficient of friction (COF), but is conceptually more general because it incorporates other factors besides friction, such as interlocking, which affect the generated horizontal foot forces.

The traditional approach to estimating the required slip resistance has been to specify a COF value which must be met or exceeded. Pfauth and Miller (1976) reviewed that data and its history and concluded that a (static) COF of 0.5 was the consensus number most often given as a recommended value to which floor and step surfaces be designed. This value of 0.5 probably originated from a 1951 National Bureau of Standards study which provided some early measurements of the ratios of horizontal to vertical forces persons exerted while walking. But beware, these measured ratio values probably had a safety margin applied to them to arrive at 0.5 as an early recommended value for the required COF (Rhoades and Miller, 1988). It is well recognized that the 0.5 consensus value has limited application because the required amount depends upon the task and the way it is performed. Higher levels of slip resistance may be necessary, for example, on ramp surfaces or for tasks such as pushing heavy carts. As for other tasks, measurements of the slip resistance required when people use climbing systems have been collected using force plates, but no widely accepted consensus value for the required level of slip resistance has yet been developed.

Available slip resistance. The available slip resistance coefficient (ASRC) is the maximum ratio of horizontal to vertical force that a particular surface-sole-contaminant condition provides. Consequently, the ASRC is also dimensionally identical to the coefficient of friction (COF). More specifically the ASRC is defined by the following equation:

$$\mathrm{ASRC}=\frac{\text{horizontal foot forces at which slipping begins}}{\text{vertical foot forces}} \qquad (2)$$

Pfauth and Miller (1976) note that the COF has historically been used to quantify slip resistance. They further note that extensive tables are well published which summarize numerous studies of the COF provided by traditional flooring materials such as wood and tile. However, the fabricated metal materials used to construct steps, ladders, work platforms, and flooring have not been extensively evaluated. Because of difficult measurement problems, the manufacturers of metal surface materials provide only limited quantitative information regarding their products. This difficulty arises because the traditional methods for measuring the static COF have been primarily oriented toward evaluating smooth walking surfaces. When surface interlocking is possible, traditional measurements of COF must be cautiously interpreted. Such effects are particularly noticeable when there is a heavily patterned grating on a step surface, or when there is a dominant tread pattern on a shoe sole. Consequently, there has not been data which is useful to a designer in the selection of slip resistant metal surfaces.

The only known formal recognition given to these types of considerations comes from a not well publicized procedure in a Federal procurement specification (Federal Spec RR-G-1602B, 1984). Therein is defined a procedure to determine the antislip value for metal gratings used as floor surfaces. Rather than a single criteria value such as 0.5, acceptance antislip values curiously range from approximately 0.43 to 0.63 depending on the grating material (aluminum or steel) and the tested contaminant condition (dry, mud, ice, grease or detergent).

Objectives of present research

The primary objective of this study was to develop a method for predicting the ASRC of typical metal step surfaces available for use in climbing systems, as a function of various shoe materials and contaminant conditions. Because of the current lack of adequate engineering data, attaining this objective required that the available slip resistance first be systematically measured under a wide set of representative conditions.

Method

Although several methods have been developed to measure slip resistance, no single measurement method has been universally adopted (Miller, 1983). Most field studies have evaluated the static COF (or ASRC), but more recently several researchers have advocated using both static and dynamic measures to analyze walking tasks. While walking, the dynamic COF becomes an important determinant of slipping because heel movement continues up to 0.05 seconds after heel strike. During this interval, the deceleration of the heel is the critical factor related to slip resistance (Brungraber, 1977; James, 1982; Strandberg, 1983). However, in climbing systems the predominant movement of the user's foot is vertical rather than horizontal, and the initial contact is usually at the ball of the foot rather than at the heel. Consequently, there is little longitudinal slipping during ordinary task performance, implying that the static measures of the ASRC should be adequate. This study therefore focuses on static measurement methods.

Even when researchers have focused on static measurement methods, they have used a wide variety of techniques and equipment (Andres, 1985). Most measurement methods do not address sole-step surface interlocking or interference. This latter point becomes important because most of the step materials considered in this study have textured surfaces for which mechanical interference or interlocking could be expected. Measurements of the ASRC of such surfaces will logically depend on the magnitude of the vertical forces compressing the sole and step surfaces together. Strandberg (1983) provides evidence that the magnitude of these vertical forces is quite large at the start of a slip. The reported values were about two-thirds of body weight, meaning that a 150-pound person would exert a vertical loading of 100 pounds. Consequently, standard techniques for measuring COF which use a small vertical dead weight would not accurately reflect the slip resistance experienced by a person.

To avoid such problems, a testing apparatus (figure 1) was developed that was capable of loading sole samples with vertical forces similar to those reported by Strandberg. Throughout the evaluation of the ASRC, a constant vertical loading of 104 pounds was used. This load was attained by placing 100 pounds of dead weight upon a four-pound flat steel holder onto which a sole sample was mounted.

The evaluation procedure consisted of preparing a sole sample by applying a particular contaminant and placing that prepared sole sample onto the metal step surface. The apparatus was then loaded by placing 100 pounds of dead weight

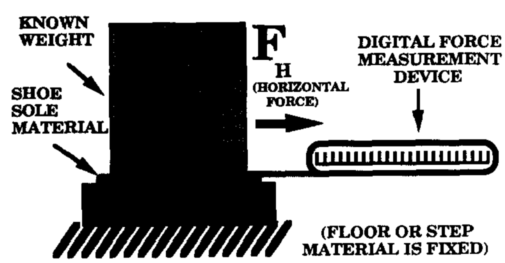


Fig. 1. Apparatus for measurement of slip resistance (or COF).

upon the four pound flat steel holder upon which the sole sample was mounted. Approximately 10 seconds after the weight was placed on the sample, a pulling force was gradually applied to the steel holder in a direction either parallel or perpendicular to the main (long) axis of the step material. The pulling force was gradually increased until movement of the sole sample was detected (which occurs just after the peak force level). At that point, the pulling force was discontinued and the single peak force was manually recorded as read from a digital peak force indicator. This value divided by the total 104 pound vertical force was the value of the ASRC measured for a given test condition.

While this experimental procedure may appear to measure the static COF, it can be expected to yield results quite different from those obtained using traditional COF measurement techniques. This follows because: (1) traditional COF measurement techniques often use smooth sole materials on smooth metal materials; (2) standard COF measurement theory would predict a constant ratio (coefficient) of horizontal to vertical force which is independent of the vertical force, i.e. a leather sole on aluminum will yield a given COF regardless of the vertical loading involved; and (3) a 'standard' COF test would use a vertical weight in the range of 10–15 lbs., versus the 104 lbs. used in this experiment or the 175 lbs. used in the Federal Spec RR-G1602B.

Although the ASRC suggests a somewhat different phenomenon from that which traditional COF laws have attempted to explain, differentiat-

(a)

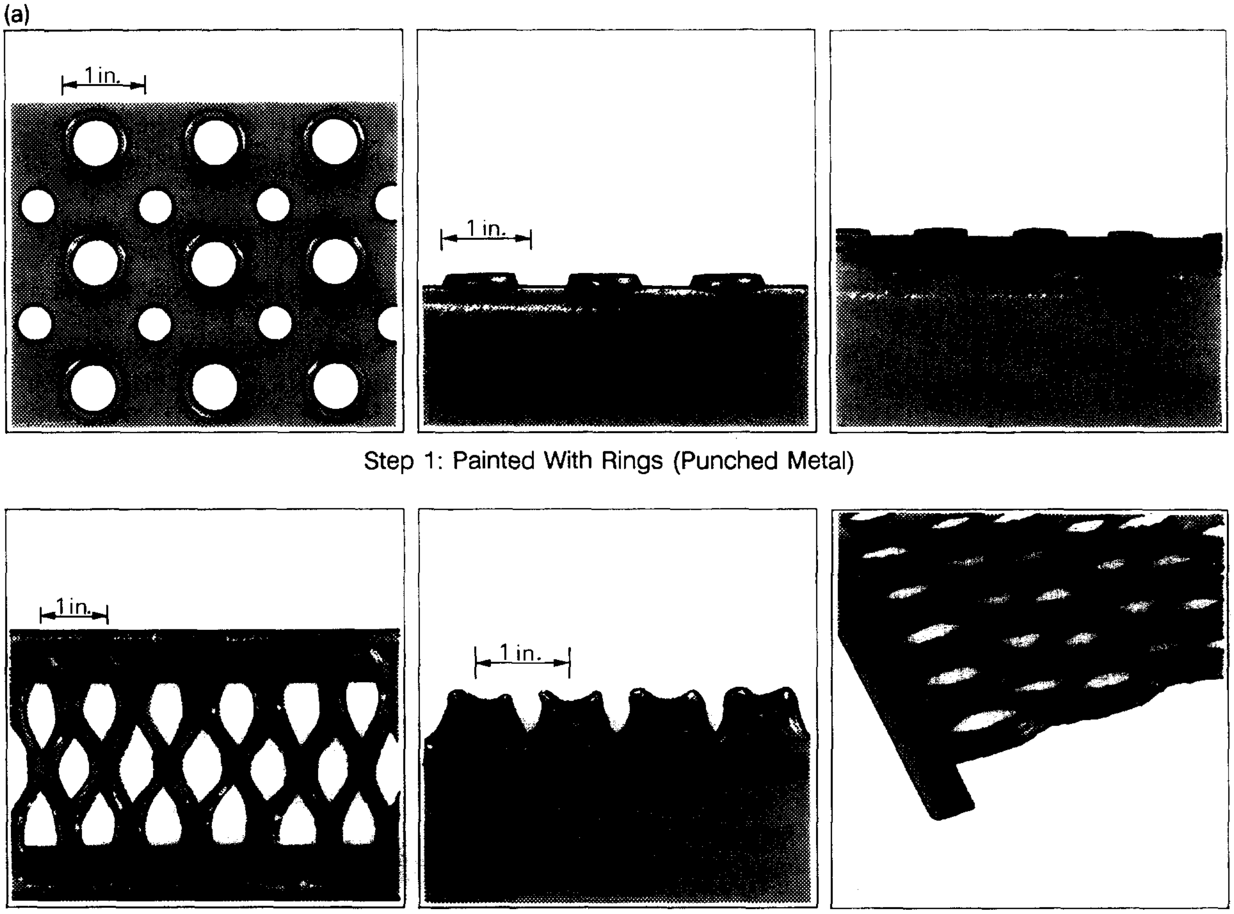


Fig. 2. The evaluated step grating surfaces. (a) steps 1, 2: (b) steps 3, 4: (c) steps 5, 6, and 7.

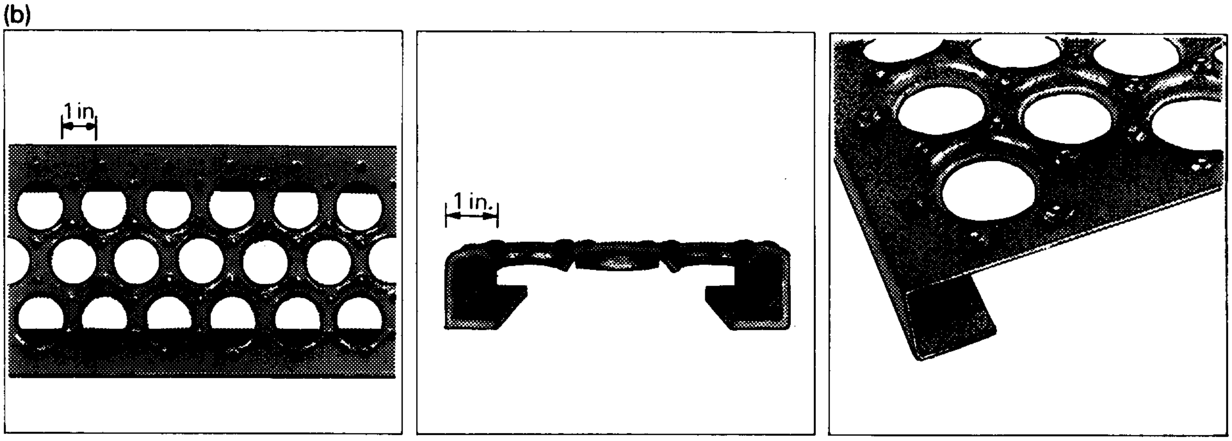
ing between the two measures may be of little relevance to persons primarily interested in the application of the results reported on herein. For such applications, the terms COF and ASRC may be considered as identical.

Experimental design

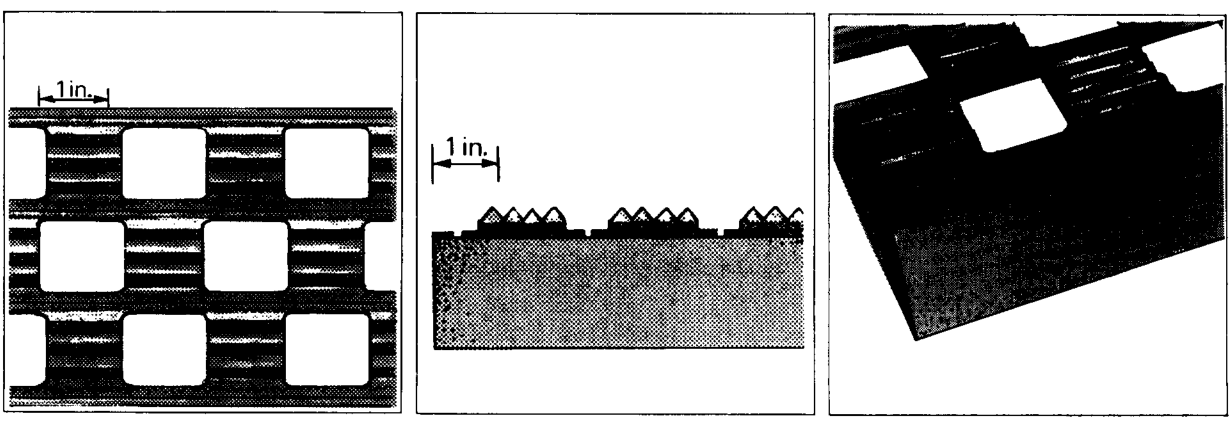
A complete factorial experimental design was used. The four independent variables were step types, sole materials, contaminants, and force direction. Step types distinguished between seven different surfaces (six of which were described by their manufacturers as being slip resistant). The remaining independent variables distinguished between four different sole materials, three different contaminants, and two orthogonal directions of applied force. The dependent measure collected throughout the testing was the ASRC. Five replicate measures were taken for each experimental condition, to allow test/re-test reliability to be measured, as suggested by Andres and Chaffin (1985).

Step types. Seven different metal surfaces were evaluated, representing slip resistant gratings commonly used on steps. Each surface is shown from multiple perspectives in figure 2 and further described in terms of generic features in table 1. (Note: the classification system used for the step materials is discussed in a later section.) The seven types of step materials chosen, while not exhaustive, span a wide range of the commercially available slip resistant metal step materials.

(b)



Step 3: Steel With Points (Open Grip or Morton)



Step 4: Extruded Aluminum With Longitudinal Edges

Fig. 2. (continued).

Sole materials. The tested sole samples were made of either leather, crepe, ribbed rubber, or oil resistant rubber. Each sole sample was approximately 14 square inches in size, which corresponds closely to the toe area of shoes worn by male subjects. (In performing upward climbing task maneuvers, it is the toe area which is primarily involved.) During data collection, different samples were used for each combination of step material and contaminant level. Samples were replaced at any sign of degradation, and five replications were done to uncover any possible effects due to repeated use of a sole sample. Replacement samples were drawn from the same production lot to ensure consistency.

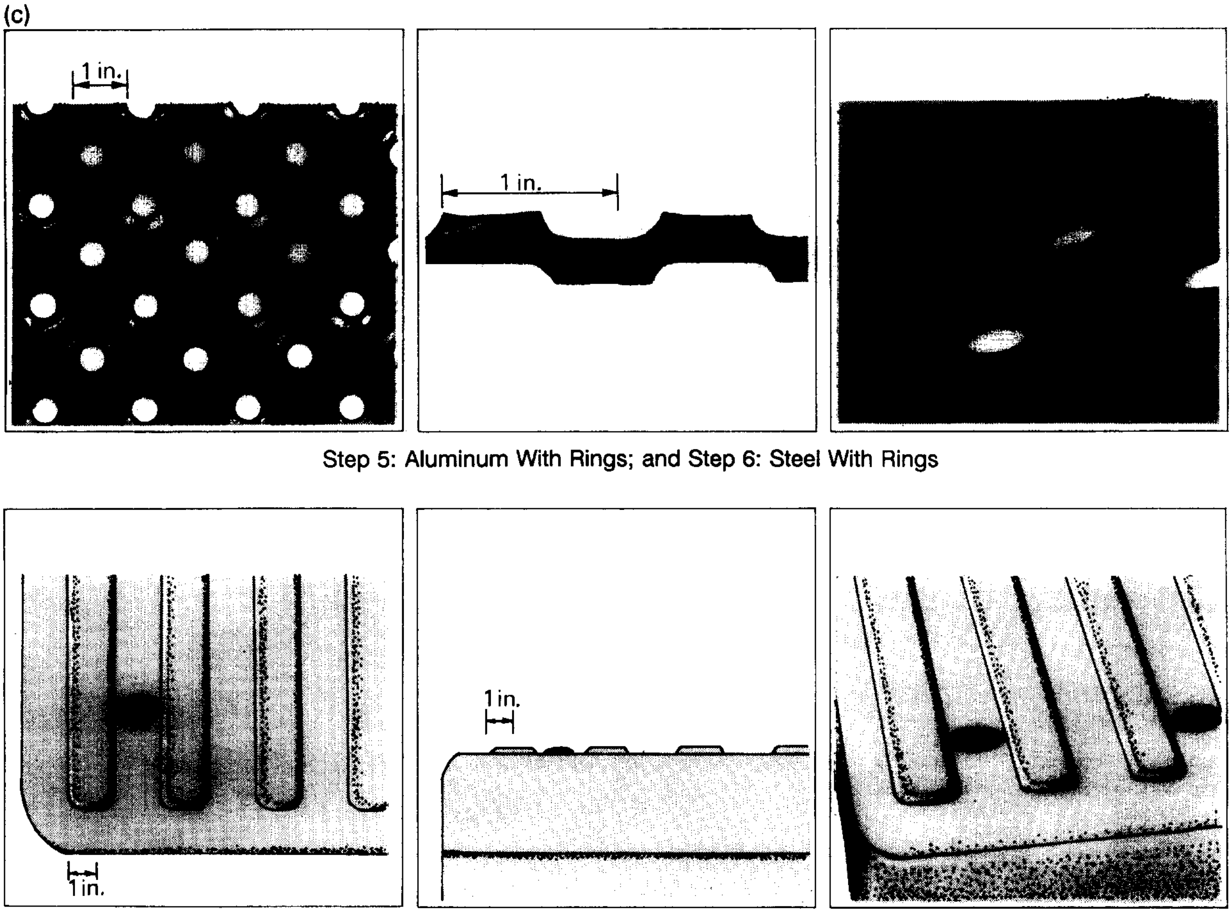
Contaminants. The three levels of contaminants used were: (1) dry (no contaminants), (2) water, and (3) diesel fuel. These contaminants were directly applied to the sole sample immediately before testing as discussed earlier.

Force direction. Forces were applied in both the lateral and longitudinal directions to determine the possible effects of either the texturing in the sole design or the protruding configurations of the fabricated metal step material.

Results

The measured values of the ASRC varied greatly under the various experimental conditions. As apparent from tables 2 and 3, the average ASRC varied greatly for different sole materials, contaminants, and step surfaces. Even greater dif-

(c)



Step 5: Aluminum With Rings; and Step 6: Steel With Rings

Step 7: Painted With Longitudinal Edges

Fig. 2. (continued).

Table 1

Classification of evaluated step types.

Step type	Contact surface	Protrusion type		Edge orientation	Surface area
		Rings	Points		
1	painted	yes	no	none	1.76 $in.^2$
2	steel	no	yes	lateral	0.67 $in.^2$
3	steel	no	yes	none	0.60 $in.^2$
4	aluminum	no	no	longitudinal	3.75 $in.^2$
5	aluminum	yes	no	none	0.90 $in.^2$
6	steel	yes	no	none	0.90 $in.^2$
7	painted	no	no	none	7.00 $in.^2$

Table 2

Summary ASRC (or COF) results with different soles. (ASRC × 100) or (COF × 100).

Condition	Leather			Crepe rubber			Ribbed rubber			Oil resistant rubber			*Row mean*
	Long.	Lat.	*Mean*	Long.	Lat.	*Mean*	Long.	Lat.	*Mean*	Long.	Lat.	*Mean*	
1	52	53	52	59	58	58	78	57	68	89	93	91	67
2	39	51	45	56	66	61	71	87	79	100	100	100	71
3	65	nm	65	75	nm	75	90	nm	90	90	nm	90	80
4	35	31	33	71	76	71	100	49	74	100	63	82	65
5	53	65	59	55	63	59	88	86	87	100	100	100	76
6	66	53	59	71	64	68	98	72	85	100	99	100	78
7	42	33	38	59	72	65	51	57	54	77	64	71	57
Mean	50	48	50	64	66	65	82	68	77	94	87	90	71
Wet													
1	67	39	53	42	37	39	66	51	58	89	87	88	60
2	52	49	51	44	45	45	71	100	85	100	100	100	70
3	74	nm	74	61	nm	61	81	nm	81	100	nm	100	79
4	57	41	49	47	32	40	100	61	81	100	84	92	65
5	63	60	62	47	58	52	77	83	80	100	100	100	74
6	62	51	56	37	42	39	89	61	75	63	64	63	58
7	62	58	60	45	41	42	45	49	48	61	62	62	53
Mean	62	50	58	46	42	46	75	68	72	88	83	86	66
Diesel													
1	42	40	41	22	18	20	46	31	39	67	68	67	42
2	55	58	57	29	27	28	49	68	59	71	89	80	56
3	70	nm	70	49	nm	49	53	nm	53	55	nm	55	57
4	51	32	41	36	19	27	98	23	61	71	36	53	46
5	67	64	66	37	43	40	57	62	59	82	81	81	62
6	65	42	53	44	30	37	68	55	61	78	77	77	57
7	42	42	42	15	09	12	22	18	20	43	33	38	28
Mean	56	46	53	33	24	31	56	43	50	67	64	65	50
Column means	56	48	54	48	44	47	71	60	67	83	78	80	62

Table 3

Mean ASH (or COF) values for tested variables (from table 2).

Independent variable	ASRC (or COF)
Sole material	
Crepe	0.47
Leather	0.54
Ribbed-rubber	0.67
Oil resistant rubber	0.80
Contaminants	
None	0.71
Water	0.66
Diesel	0.50
Step-type	
1	0.56
2	0.66
3	0.72
4	0.59
5	0.71
6	0.65
7	0.46
Force direction	
Lateral	0.58
Longitudinal	0.65
Overall mean	0.62
S.D.	0.22

ferences were found for particular combinations of these experimental variables, indicating that interactive effects were present. The test/re-test reliability was very high, corresponding to a standard error ranging from 0.07 to 0.0 within cells.

ANOVA analysis

Analysis of Variance (ANOVA) was performed on the data using the BMD2V computer program. It was found that each independent variable had a significant main effect and that many interactions were also significant (table 4).

Over the range of factor levels evaluated, sole material accounted for approximately 35% of the variability in the ASRC measurements as a main effect. Furthermore, four of the seven significant interactions (table 4) involved sole materials; the only factor involved in more significant interactions was the type of step surface. The contaminant variable accounted for 16% of the variance as a main effect, and was present in three significant interactions. The step surface variable accounted for 14% of the variance as a main effect, and was involved in five out of the seven significant interactions. The direction of the applied force accounted for little variance, but was present in three significant interactions.

These results clearly demonstrate the importance of sole materials as a determinant of the ASRC, as with only three levels, its main effect accounted for 35% of the variance. They also show that the interactions between sole materials, con-

Table 4

ANOVA summary of statistically significant effects. [a]

Source	SS	MSE	DF	F	Significance
Step type (S)	49170	9834	5	65.9	0.0000
Force direction (F)	6771	6771	1	45.4	0.0000
Contaminant (C)	59434	29717	2	199.2	0.0000
Sole Material (M)	146054	48685	3	326.3	0.0000
S×F	24933	4986	5	33.4	0.0000
S×C	10814	1081	10	7.3	0.0000
S×M	26670	1778	15	11.9	0.0000
F×M	2473	824	3	5.5	0.0040
C×M	29388	4898	6	32.8	0.0000
S×F×M	14162	944	15	6.3	0.0000
S×C×M	12379	413	30	2.8	0.0030
Error	4476	149	30		
Nonsign. effects	20077	34	594		
Total	406801		719		

[a] Only significant effects and interactions are included in table.

taminants, step surfaces, and applied force direction are very important. Certain combinations of these factors result in either very high or low ASRC values. Any valid attempt at predicting the ASRC must, thus, take such interactive effects into consideration.

Regression analysis

As noted earlier, developing a useful means of predicting the ASRC was the primary goal of this research. To attain this goal, multiple regression analysis was performed. This led to the development of an equation that predicted most of the variation (89% of the statistical variance) in the ASRC measurements and guided interpretation of the obtained results. The developed equation and the method by which it was developed and validated are briefly described below. Use of the equation is illustrated in the section following the discussion of the results.

Use of indicator variables. In the regression analysis, each of the experiment factors was recoded as a set of indicator variables (Chaterjee and Price, 1977). The majority of the indicator variables used in this analysis took on the values 1 or 0 to denote the presence or absence of a particular experimental level (i.e. the term CREPE-SOLE took the value 1 when a crepe sole material was used and a 0 otherwise). One exception was the method of encoding the direction of the applied force. Here, a value of -1 was used to encode a lateral force application and a value of 1 to encode a longitudinal force application. Similar methods of encoding step directionality were also used, as discussed later.

Other terms were formed by multiplying indicator variables, thereby denoting the presence or absence of a particular combination of experimental levels. Consequently, the multiple regression equation did not correspond exactly to the ANOVA, since terms formed by multiplying indicator variables will incorporate both main effects and interactions. To prevent confusion and guide development of the regression equation, a systematic procedure was followed in which main effects were brought into the equation prior to introducing significant interactions.

Reclassification of step material types. Regression analysis also emphasized the reclassification of the tested step surfaces in terms of their basic features. This approach evolved into a description of the step surfaces in terms of the surface area, whether or not it was painted, and the presence or nonpresence of protruding rings, points, or edges. The presence or nonpresence of paint, rings, or points were described as (0, 1) indicator variables, while both the area and potential area of contact were described quantitatively. Edges were described using a more complicated indicator variable which took on the values -1, 0, or 1. The value -1 was assigned to longitudinal edges, 0 to no edges, and 1 to lateral edges. As an aside, numerous quantitative measures of the number of edges, points, or protruding rings were evaluated; however, the simple qualitative measures (indicator variables) were, surprisingly, equivalent or better predictors of the influences of these factors on the ASRC than were the quantitative measures evaluated.

Interestingly, an equation using only the indicator variables called 'painted', 'protruding-rings', and 'protruding points' attained a level of prediction ($R^2 = 13\%$, standard error = 0.21) practically equivalent to that obtained using the seven original types of step surfaces. Neither the area of contact, the potential area of contact nor the simple presence of edges was found to be a significant predictor. Consequently, the classifying variables 'painted', 'protruding rings', and 'points' were used as main effects in later analysis. It should be noted, however, that the 'area' and 'edge' related variables were still considered in the later analysis of interactions.

This use of only three classifying variables for step types (with three degrees of freedom) instead of the original seven step types represents a significant simplification of the overall predictive process. It also indicates the practical potential of extending this classification-based approach to the modeling of many seemingly different types of step surfaces which may not be as dissimilar with respect to their ASRC values as would be expected based on their visual appearance.

The final regression equation. The predictive equation, developed following the above procedure, is given in table 5. The equation explained 89% of the variance in ASRC measurements with a standard error of 0.079. Each term in the equation was highly significant with a small standard error, and the variance/covariance matrix did not indicate problems with multi-collinearity.

Each numbered term in the predictive equation (table 5) corresponds to one or more of the indicator variables, the potential values of which are also summarized in the table. The weight multiplied by the value of the indicator variable is the contribution to the ASRC (or COF) value for that particular term in a given situation. At the levels examined, sole materials and interactions between sole materials and contaminants were generally of greatest importance (i.e. had the largest weights in the regression equation).

Validation of equation. To determine whether the regression equation was capable of predicting the ASRC, a validation study was conducted using a new slip-resistant surface. This surface (figure 3) was classified as protruding rings. Note, however, that the diameter of the rings was smaller than for surfaces 1, 5, and 6 (earlier classified as protruding rings) and close to that for the protruding points of surface 3. Consequently, this new surface was

Table 5

ASRC (or COF) prediction equation. Prediction equation: ASRC (or COF) = $\Sigma_{i=1}^{15}(V_i \times W_i)$.

Term (i)	Factor designator	Value (V_i)	Weight (W_i)	Std. error	t-stat	Signif.
1	Constant	(1)	0.74	0.019	38.6	0.0000
2	Leather sole	(0,1)	−0.25	0.022	−11.7	0.0000
3	Crepe sole	(0,1)	−0.15	0.021	−7.2	0.0000
4	Oil resistent sole	(0,1)	0.17	0.018	9.1	0.0000
5	Wet × crepe sole	(0,1)	−0.17	0.028	−6.0	0.0000
6	Diesel × rubber sole	(0,1)	−0.29	0.017	−17.4	0.0000
7	Step rings	(0,1)	0.10	0.016	6.6	0.0000
8	Step points	(0,1)	0.06	0.020	3.0	0.0030
9	Painted step × rubber sole	(0,1)	−0.16	0.017	−9.3	0.0000
10	Point (no edges) step × crepe or leather sole	(0,1)	0.13	0.036	3.7	0.0003
11	Smooth step × leather sole (not wet/water)	(0.1)	−0.11	0.029	−3.7	0.0003
12	Force dir × step edge direction	(−1,0,1)	0.04	0.014	2.5	0.0123
13	Force dir × sole edge direction × step edge direction	(−1,0,1)	0.07	0.028	2.6	0.0101
14	Force direction × step edge direction × hard rubber sole	(−1,0,1)	0.11	0.028	3.9	0.0002
15	force dir × step ring direction × leather or ribbed sole	(−1,0,1)	0.07	0.016	4.5	0.0000
	Multiple $R = 0.94$	Multiple $R^2 = 0.89$		$S.E. = 0.079$		

Meaningful influence grouping: The following groupings indicate the types of physical phenomena to influence the slip resistance coefficients, as described in discussion of results equation.

Simple sole materials influence: terms 2, 3, 4
Sole surface interlocking influence:
  Sole point interlocking influence: terms 8, 10
  Sole ring interlocking influence: terms 7, 15
  Sole edge interlocking influence: terms 12, 13, 14
Sole surface stick influence:
  Rubber surface interaction: terms 5, 6, 9
  Leather surface interaction: term 11.

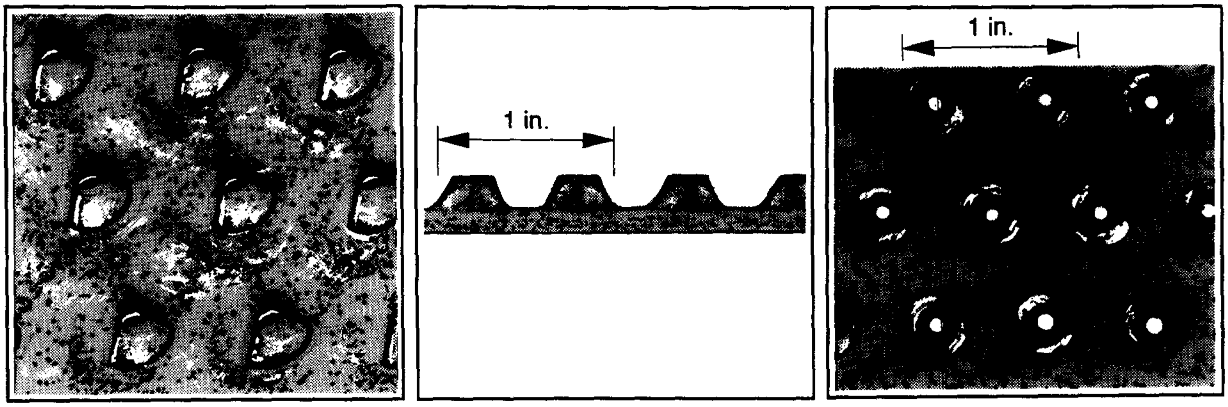


Fig. 3. Step grating surface used in the validation study.

fundamentally different from any of those previously evaluated. The validation study consisted of taking five replicate measures of the slip resistance for this surface under the complete set of sole material, contaminant, and force direction conditions. Predictions for these conditions were then made using the regression equation. The validation data and predictions correlated closely ($R^2 =$ 0.8), and are plotted in figure 4. There was, however, a tendency to underpredict the ASRC which was quite large for wet, leather soles (underprediction of 0.32) and diesel-contaminated, oil-resistant soles (underprediction of 0.27). These results will be discussed in the context of the overall discussion below.

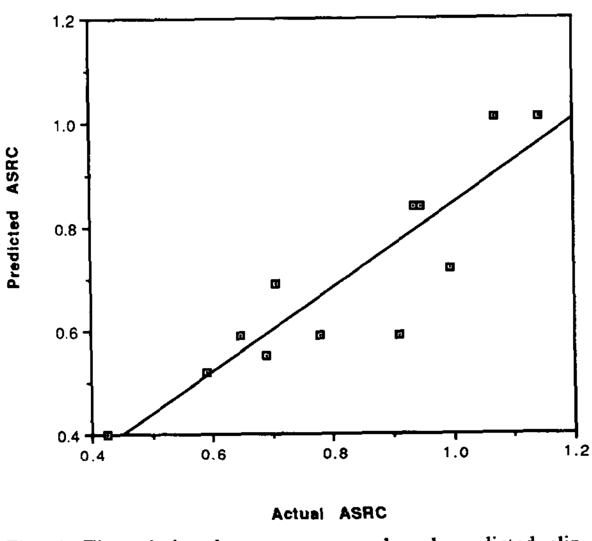


Fig. 4. The relation between measured and predicted slip resistance observed in the validation study.

Discussion of results

One of the major objectives of this study was to develop a better understanding of the factors influencing the ASRC. The final regression equation is certainly useful for this purpose. Simply put, since the original factors were orthogonal and a complete factorial experiment was performed, meaningful analysis of the indicator variables in terms of their predictive weights became feasible. In addition, it provides a groundwork for future research which can expand on the results presented herein.

Initial analysis of the regression results reveals that the terms contained in the equation (table 5) can arbitrarily be classified into three meaningful groupings designated as follows: Simple Sole Materials (Terms 2, 3 and 4), Sole-Surface Interlocking factors (Terms 7, 8, 10, 12, 13, 14 and 15), and Sole-Surface Stick factors (Terms 5, 6, 9 and 11). Each category can also be further divided into meaningful and conceptually useful subcategories, as expanded upon below.

Simple sole materials

Terms 2, 3 and 4 in table 5 describe the differences in the measured ASRC for the different sole materials. Both crepe and leather are associated with significantly less slip resistance. This category of terms reflects a sole-surface effect which appears to be independent of the surface type or presence of contaminants. Other interactive effects of sole materials fall into the categories of sole-surface interlocking and sole-surface stick.

Sole-surface interlocking

Sole-Surface Interlocking refers to the gross mechanical effects which are apparently present at the interface between the sole and step surface. Terms within this category can be subdivided into Sole-Point Interlocking (Terms 8 and 10), Sole-Ring Interlocking (Terms 7 and 15), and Sole-Edge Interlocking (Terms 12, 13 and 14).

Sole-point interlocking. This effect refers to mechanical interaction between sole materials and step surfaces with points. Points were associated with a minor increase in the ASRC for all sole materials (Term 8). Interestingly, points further increased the ASRC when either crepe or leather soles were used (Term 10). This incremental effect seems to be associated with sole hardness (i.e. the sole surface must be soft enough to allow penetration, but not so soft that the points tear through, as did occasionally happen for crepe soles contaminated with diesel). However, further work on this topic is necessary before conclusions can be made. It would also be interesting to evaluate the ASRC for textured sole designs which contain patterns of points or protrusions.

Sole-ring interlocking. This effect is similar to Sole-Point Interlocking, but involves the presence of rings rather than points. Rings were associated with a minor increase in the ASRC for all sole materials (Term 7). Also present was a minor directional effect (Term 15) for certain sole materials. This effect is related to whether one edge of the protruding ring is higher than the other. If the height gradient was perpendicular to the direction of the applied force and the material was ribbed rubber or leather, the ASRC dropped by 0.07. On the other hand, if the (positive) gradient was in the same direction as the applied force, the ASRC increased by 0.07. It was not clear why this minor directional effect was found for these particular sole materials and not for the others.

Sole-edge interlocking. This effect appears to document the mechanical interaction between sole materials and edges on the step surface. As would be expected, this is a highly directional effect. The overall effect (Term 12) corresponded to a small increase in the ASRC when the direction of applied force was perpendicular to the orientation of the edges found on the step, and, conversely, a small decrease in the ASRC when the direction of the applied force was parallel to the orientation of the edge. This effect was much more pronounced when the sole was made of hard rubber (Term 14). An interaction was also discovered between edges or ribs on the sole surface and the edges on the step surface (Term 13). This term shows that the presence of ribbing on the sole increased or decreased the ASRC depending upon whether the applied force was across or with the grain of the surface's edges.

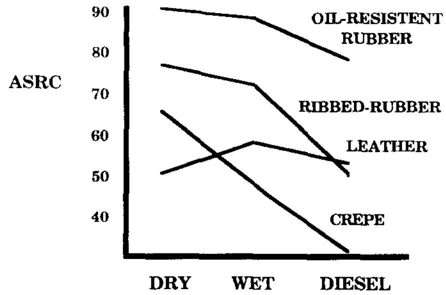


Fig. 5. The interaction between contaminants and sole material.

Sole-surface stick

This latter category of slip resistance factors seems to correspond closely to the traditional COF, and may document the micro-mechanical or chemical interaction between the sole and surface material. As such, contaminants were viewed as altering this interface, the effects of which are quite pronounced and summarized in figure 5. Terms falling into the category of sole-surface stick were subdivided into Rubber-Surface Interaction factors (Terms 5, 6 and 9) and Leather-Surface Interaction Factors (Term 11).

Rubber-surface interaction. This effect documents several strong interactions between rubber soles and contaminants or step surfaces. A large decrease in the ASRC occurred if certain contaminants were present when rubber soles were tested. The ASRC was particularly low for crepe soles when the step surface was wet by water (Term 5), and for rubber soles in general (including crepe) when the step surface was wet with diesel (Term 6). The latter decrease is somewhat less for oil-resistent rubber but only on certain surfaces, for reasons which are as yet unclear. Consequently, the model may underpredict the ASRC in this situation, as demonstrated in the validation study.

Also discovered was a decrease in the ASRC for rubber soles when the surface was painted (Term 9), which further confirms the findings of previous research (Miller, 1983).

Leather-surface interaction. This effect documents interactions between leather soles and contaminants or step surfaces. The ASRC decreased greatly for leather soles when the contacted surface was smooth, except when water was present (Term 11). Other researchers have shown that leather soles are less slippery when they are wet (Miller, 1983). However, as becomes obvious from examining table 2, the advantage disappears when the step surface is not smooth. Interestingly, in the validation study with the new surface with small protruding rings, the advantage of wetting leather reappears. Evidently, the large area of smooth surface on the new surface played a role in increasing the ASRC.

Application

The developed equation is in a form easily applied by the practitioner who possesses only limited qualitative knowledge about a step surface or conditions under which such steps will be used. This potential is illustrated below. To apply the equation, the practitioner simply makes a series of simple 'yes' or 'no' judgements, regarding the presence or absence of particular factors which influence the slip resistance. Given that a particular factor is present its impact on the ASRC is given as a weight in table 5. By totaling the weighted factors, an estimate of the ASRC is then obtained. For example, consider a scenario involving a dry, leather sole used on step grating 7, which is smooth (without ring or point protrusions and without edges). Here, Terms 1, 2 and 11 take on the value of 1 since they correspond to the analyzed situation, and all other terms are 0. The ASRC is consequently described as being:

$$\begin{aligned}\text{ASRC (or COF)} &= \text{CONSTANT} + \text{LEATHER-SOLE}\\ &\quad + (\text{SMOOTH-STEP} \times \text{LEATHER-SOLE} \times \text{NOT WET/WATER})\end{aligned}$$

$$\begin{aligned}\text{ASRC (or COF)} &= (1 \times 0.74) + (1 \times -0.25)\\ &\quad + (1 \times 1 \times 1) \times (-0.11)\end{aligned}$$

$$\text{ASRC (or COF)} = 0.38$$

Alternatively, one could use table 2 and refer to the mean for a dry leather sole used on step 7 and find the same 0.38 value ($38 \times 1/100$). For a wet, crepe sole used on step grating 3 (steel, unpainted, no edges, but with points), all terms except 1, 3, 5, 8 and 10 are 0 and the expression becomes:

$$\begin{aligned}\text{ASRC (or COF)} &= \text{CONSTANT} + \text{CREPE-SOLE}\\ &\quad + (\text{WET} \times \text{CREPE-SOLE})\\ &\quad + (\text{STEP-PROTRUDING POINTS})\\ &\quad + (\text{POINTS(NO EDGES)-STEP} \times \text{CREPE or LEATHER SOLE})\end{aligned}$$

$$\begin{aligned}\text{ASRC (or COF)} &= (1 \times 0.74) + (1 \times -0.15)\\ &\quad + (1 \times 1) \times (-0.17)\\ &\quad + (1 \times 0.06) + (1 \times 1) \times (0.13)\end{aligned}$$

$$\text{ASRC (or COF)} = 0.61$$

Alternatively, one could use table 2 and refer to the mean for a wet crepe sole used on step 3 and find the same 0.61 value ($61 \times 1/100$). Since these examples were actually tested in this research, it is no surprise that the predicted values above are nearly identical to the actual tests. The prediction equations would be expected to be most accurate for the materials shown in figure 2 and the conditions similar to those shown in table 2 (i.e. a standard error of 0.079). Predictions are expected to be less reliable when surface characteristics, shoe sole materials and/or contaminants are different from those evaluated in this experiment. In the validation study, the predicted results were quite good for a step material not originally considered during development of the equation. However, two cases were underpredicted significantly, indicating that predicted values may require validation through direct measurement in such situations.

Conclusions

Prior to the completion of this study, a methodology did not exist for predicting the effect various combinations of slip/fall factors would have on available slip resistance. This effort has developed a practical approach by collapsing the extensive set of results in table 2 into a relatively simple equation which can be used to predict an available slip resistance coefficient (ASRC or COF) with a reasonable degree of confidence. The equation uses indicator variables which allow the applicator to specify in the model: the shoe sole, contaminant, force direction, and type of metal step grating surface. The described approach eliminates the need for repetitive testing of each set of slip/fall related variables and, thus is of significant practical and economic benefit. The extent to which these equations are used for predictions should be limited to the range of the factors tested in this particular experiment. However, that range could be extended by additional research to include other walking or climbing surfaces, shoe sole and heel types or different contaminant conditions. Application tables with experimental results will continue to become more and more complex as the data base grows, while use of the predictor equation approach illustrated can remain essentially at the same level of application complexity.

Based on our results, then, we conclude that over the range of variable conditions tested, metal gratings now available for steps and working surfaces can provide an adequate slip resistance. The appropriate design of such surfaces can serve to prevent the slips and falls of vehicle drivers or other workers needing to ascend or descend to elevated work platforms. It was surprising that most of the evaluated step surfaces provided approximately equivalent slip resistances. This lack of variance may be attributable to previous improvements in the design of the step surfaces which have evolved through evaluation by the manufacturers. Recognize also that in this present effort some of the more extreme contaminant-related conditions involving heavy accumulation of snow, ice or mud were not included in the evaluations. Under such conditions, it is possible that certain step surface materials would perform better than others. Determining such differences could be the objective of a formal evaluation similar to the one presented herein.

Another more subtle but important contribution of this research was the development of a fundamental classification scheme to describe the mechanical roughness or gripping type properties of step and sole designs. This classification scheme was quite beneficial in the development of predictive equations and offers to the manufacturers of metal climbing surfaces a systematic way to begin quantifying the incremental ASRC (or COF) effects that can be attained by changing the fundamental features of step surfaces. However, it must be recognized that this classification is still at a very early level of development. As demonstrated in the validation study, certain step surfaces may possess characteristics fundamentally different from those currently represented in the classification. Extending the work that has been done here is therefore necessary.

The results also pointed out the substantial effects caused by the interactions among the experimental factors. The inference from this is that focusing singularly on the separate control of the step surface, shoe sole or contaminant will not lead to the design of optimal climbing systems. This follows because the interactions between types of step surfaces, sole materials, contaminants, and force-directions were strong; in certain cases, causing the ASRC to be well below the average for a given factor. Sole materials were particularly critical contributors to such deteriorations in slip resistance. Consequently, it might be advisable to restrict the choices of vehicle drivers and other users of climbing systems to a limited set of sole materials. It would, however, be important to knowledgeably choose the allowed sole materials based on the nature of the work tasks involved, since no single shoe sole is best for all foreseeable user conditions just as no step surface will be best for all applications. Task and contaminant conditions, of course, play a critical role in determining what combinations of sole materials and step surfaces will provide adequate safety.

References

Andres, R.O. and Chaffin, D.B., 1985. Ergonomic analysis of slip-resistance measurement devices. Ergonomics, 28(7): 1065–1079.

Brungraber, R.J., 1977. A portable tester for the evaluation of the slip-resistance of walkway surfaces. (NBS Technical Note 953). Washington, DC: National Bureau of Standards.

Brungraber, R.J., 1976. An overview of floor slip-resistance research with annotated bibliography. National Bureau of Standards, Washington, D.C.

Bureau of Motor Carrier Safety (BMCS), 1977. Slips and falls–truck related personal injury accidents.

Bloswick, D.S., 1987. Ladder climbing: A dynamic biomechanical model and ergonomic analysis. Dissertation, University of Michigan, Ann Arbor.

Chaterjee, S. and Price, B., 1977. Regression Analysis by Example. John Wiley, New York.

Federal Specification RR-G-1602B, 1984. Federal specification: Grating, metal, other than bar type. U.S. Government Printing Office, Washington DC.

James, D.I., 1982. Rubbers and plastics on shoes and flooring: The importance of kinetic friction. Shawbury, England: Rubber and Plastics Research Association of Great Britain.

Miller, J.M., 1983. A bibliography of coefficient of friction literature relating to slip type accidents. Occupational Safety and Health Administration, NTIS PB83243626, Washington, DC.

Miller, J.M., 1972. Commercial vehicle occupational health hazards. Society of Automotive Engineers, SAE Technical Report 720164.

Miller, J.M., 1983. 'Slippery' work surfaces: Towards a performance definition and quantitative coefficient of friction criteria. Journal of Safety Research, 14(4): 145–158.

National Bureau of Standards, 1951. Electronic stepmeter reveals mechanics of walking. NBS Technical News Bulletin.

Pfauth, M.J. and Miller, J.M., 1976. Work surface friction coefficients: A survey of relevant factors and measurement methodology. Journal of Safety Research, 8(2): 77–90.

Rhoades, T.P. and Miller, J.M., 1988. Measurement and comparison of 'required' versus 'available' slip resistance. Proceedings of the 21st Annual Meeting of the Human Factors Association of Canada, Edmonton, Alberta.

Rhoades, T.P. and Miller, J.M., (1989). Revisions of TMC recommended practice RP-404 'Truck and truck tractor access systems'. SAE Transactions, Society of Automotive Engineers, Warrendale, PA.

Safety Sciences, 1979. Analysis of personal injury and illness hazards associated with working in, on or about commercial motor vehicles. Prepared for Bureau of Motor Carrier Safety, Contract DOT-FH-11-9535.

Strandberg, L., 1983. On accident analysis and slip-resistance measurement, Ergonomics, 26(1): 11–32.