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666 Dundee Road, Suite 103, Northbrook, IL 60062-2702

(847) 677-4730 FAX: (847) 647-2047

e-mail: infoserv@triodyne.com

www.triodyne.com

Slip and Fall Characterization of Floors

By Ralph L. Barnett*

and Peter J. Poczynok, P.E.**

ABSTRACT

During ambulation, every maneuver causes the feet to impose a tangential loading at each contact with the floor. If the frictional resistance at the contact point is less than the associated tangential loading, slipping occurs and sometimes falling. There are five disciplines, some recently developed, that enable one to develop the general theory for predicting the number of walkers who will slip within a given time period on a statistically homogeneous and isotropic floor. These include force-plate studies, floor duty cycles, tribometry, extreme value theory of slipperiness, and floor reliability theory. When used with some additional bookkeeping notions, the general theory will be extended to real floors traversed by walkers with multiple ambulation styles and wearing a variety of footwear.

INTRODUCTION

Slipping is a local failure phenomenon amenable to classic formulation, i.e., slipping occurs whenever tangential floor loads exceed tangential resistance. Two separate disciplines, force-plate studies and duty cycles, are involved in the characterization of floor loading. The first reflects how various classes of walkers with different ambulation profiles transfer tangential loads to floors; the second describes how floors are actually used by typical groups of people during a specified time frame. Both are stochastic processes.

Tangential floor resistance is supplied by frictional forces that are the product of the normal force applied to the surface and the coefficient of friction between the footwear and the floor surface. Fortunately, normal floor forces require no consideration; their effects on loading and resistance cancel. The coefficient of friction is measured using a plethora of tribometry devices that expose a floor candidate to a footwear swatch. Friction coefficients are statistically distributed; they are represented as a "bell-shaped" curve. This curve provides a tradeoff between floor reliability and the minimum friction resistance required for an individual to take a single step. Floor reliability is defined as the probability of not slipping.

To execute an n-step perambulation across a surface without slipping requires that a walker survive the step with the lowest friction. This observation has led to a new formulation of "slip and fall" theory as a problem in extreme value statistics where floor reliability for an individual is related to the floor loading associated with his locomotion

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* Professor, Mechanical & Aerospace Engineering, Illinois Institute of Technology, Chicago, IL; Chairman, Triodyne Inc., Northbrook, IL

** Senior Mechanical Engineer, Triodyne Inc., Northbrook, IL.

style, the properties of the bell-shaped friction curve, and the number of steps taken in his journey.

Moving from an individual walker to an entire population of walkers requires the simultaneous consideration of statistical distributions of floor loading and floor resistance. This topic is treated in classic reliability theory which has recently been applied to the floor reliability problem.

In a fixed time frame, real floors are frequented by multiple populations of walkers who exhibit various styles of locomotion. To predict the reliability of these floors requires an orchestration of the five building blocks currently available; force-plate studies, floor duty cycles, tribometry, extreme value theory of slipperiness, and floor reliability theory. These disciplines are briefly reviewed in this paper which then applies the technology to a single surface exposed to multiple footwear and ambulation styles.

"SLIP AND FALL" CONCEPTS

Force-Plate Studies

Instrumented floor surfaces are used to measure the vertical forces *V* and the horizontal forces *H* imposed by large numbers of walking candidates. The maximum ratio of *H/V*, $(H/V)_{\max}$, is recorded for each candidate and represents the frictional resistance required to prevent slipping. Let the required frictional resistance or applied floor loading be designated as μ_a. The collection of data for $\mu_a = (H/V)_{\max}$ can be characterized by a probability density function $\tilde{f}_\beta(\mu_a)$ where the subscript β designates a particular community or population of walkers distinguished perhaps by gender, age, health, walking speed, or locomotion style. As usual, the probability that the applied floor loading does not exceed a specific value of μ_a, $\Pr\{(H/V)_{\max} \leq \mu_a\}$, is given by the cumulative distribution function $\tilde{F}_\beta(\mu_a)$.

The general nature of force-plate studies has been summarized by Barnett (Ref. 1). This work references a typical force-plate study by Harper, Warlow, and Clark (Ref. 2) who measured $(H/V)_{\max}$ for men and women during straight walking and turning profiles. They characterized their data using a normal distribution which was used by Barnett and Poczynok (Ref. 3) in their investigation of floor reliability. No particular advantage is gained by using specialized distributions since eventually numerical methods must be employed. Nevertheless, the use of the normal distribution takes the following form:

$$\tilde{f}_\beta(\mu_a) = \frac{1}{\sigma_\beta\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\mu_a-\bar{\mu}_\beta}{\sigma_\beta}\right)^2} \qquad \text{Eq. 1}$$

where $\bar{\mu}_\beta = \overline{(H_\beta/V_\beta)}_{\max}$ is the mean value of the $(H_\beta/V_\beta)_{\max}$ distribution, σ_β is its standard deviation, and μ_a takes on values from minus to plus infinity. Also, the cumulative distribution function takes the form

$$\tilde{F}_\beta(\mu_a) = \frac{1}{\sigma_\beta\sqrt{2\pi}} \int_{-\infty}^{\mu_a} e^{-\frac{1}{2}\left(\frac{\mu-\bar{\mu}_\beta}{\sigma_\beta}\right)^2} d\mu \qquad \text{Eq. 2a}$$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{(\mu_a-\bar{\mu}_\beta)/\sigma_\beta} e^{-t^2/2} dt \equiv \Phi\left(\frac{\mu_a-\bar{\mu}_\beta}{\sigma_\beta}\right) \equiv \Phi(z) \qquad \text{Eq. 2b}$$

where Φ is the standardized normal cumulative distribution function which is a tabulated function that is widely available. It should be noted that

$$\Phi(-z) = 1 - \Phi(z) \qquad \text{Eq. 3}$$

Tribometry

Tangential floor resistance is proportional to the coefficients of friction μ_r for a floor/footwear couple. Over several decades some five dozen tribometry devices have been developed for the measurement of μ_r in the field and in the laboratory. The critical evaluation of these machines is a major activity in "slip and fall" technology (Brungraber [Ref. 4] and Bucknell University [Ref. 5]).

Conventional "slip and fall" theory is primarily concerned with the average friction coefficient which is not a demanding assignment for a tribometry device. This theory does not address the question 'how many walkers slip;' it merely attempts to establish a go/no-go criterion that indicates whether or not a given floor's slipperiness is satisfactory. Specifically, the theory states that no slip, and hence no fall, will occur whenever the mean coefficient of friction $\bar{\mu}_r$ between a floor and some standard footwear material, such as leather, is greater than a critical friction coefficient μ_c, i.e.,

$$\bar{\mu}_r > \mu_c \ldots \text{ no slip}$$

The critical friction coefficient μ_c is not selected by some rational protocol; it is often established by legislative fiat or consensus.

Conventional slip theory has been shown to be hopeless in the face of friction's stochastic behavior; it cannot even be used for ranking a floor's slipperiness, (Ref. 1). By contrast, the modern slip theory treated in this paper determines the number of walkers who slip on a real floor: it abandons the notion of a critical friction coefficient; it reflects the distance traveled by walkers; and it uses not only the average, but the spread and asymmetry of the distribution of friction coefficients. A theoretical foundation exists that shows that the distribution of friction coefficients must be of the Weibull form (Ref. 1), i.e.,

$$F_k(\mu_r) = 1 - e^{-\left(\frac{\mu_r - z_k}{s_k}\right)^{mk}} \qquad \mu_r \geq z_k \qquad \text{Eq. 4a}$$

$$= \quad 0 \qquad \mu_r \leq z_k \qquad \text{Eq. 4b}$$

where the constants z_k, s_k, and m_k are Weibull parameters and the subscript k designates a particular floor/footwear couple. The associated probability density function is

$$f_k(\mu_r) = \frac{m_k}{s_k}\left(\frac{\mu_r - z_k}{s_k}\right)^{m_k - 1} e^{-\left(\frac{\mu_r - z_k}{s_k}\right)^{mk}} \ldots \mu_r \geq z_k \text{ Eq. 5a}$$

$$= 0 \qquad \ldots \mu_r \leq z_k \qquad \text{Eq. 5b}$$

Equations 4 are used to fit four sets of 400 static friction coefficients that were measured under laboratory conditions following the test protocol specified by ASTM F609-79 [6] for a Horizontal Pull Slipmeter using leather foot inserts under dry conditions.

The results are presented in Fig. 1 as a cumulative distribution curve obtained using 100 ubiquitous new one foot square (30.5cm x 30.5cm) asphalt floor tiles. The data are fitted with a Weibull distribution whose parameters are displayed next to the curve. Figure 2 presents a similar set of Weibull distributions that are associated with 100 new one foot square ceramic Ragione white glazed floor tiles. Our subsequent treatment of floors requires that friction tests be conducted for each surface/footwear combination and that each combination be distinguished by a different k subscript, e.g.

k = 6: concrete floor/composition soled shoes:

$$F_6(\mu_r), f_6(\mu_r), z_6, s_6, \text{ and } m_6.$$

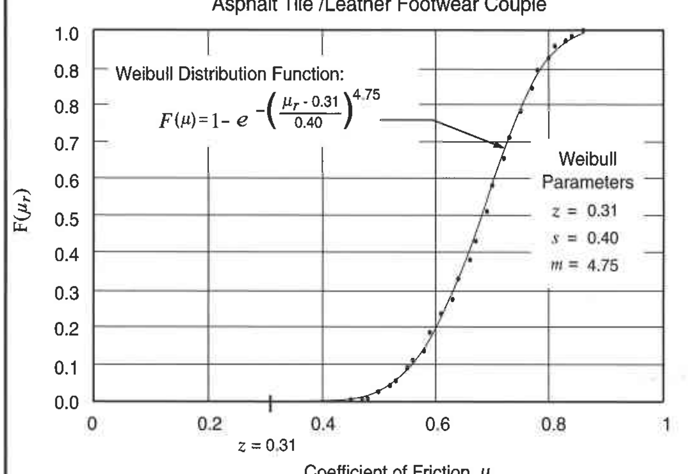

Figure 1 - Weibull Cummulative Distribution Function: Coefficient of Friction

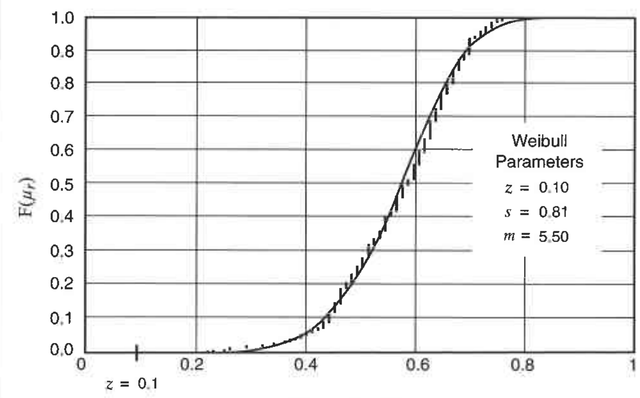

Figure 2a - Ceramic Tile /Leather Footwear Couple

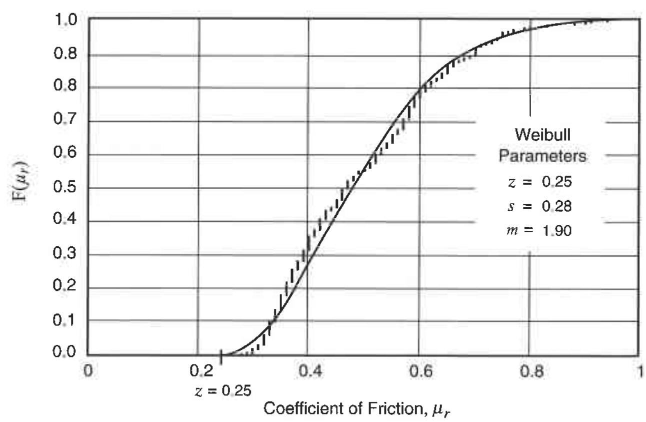

Figure 2b - Ceramic Tile /Rubber Footwear Couple

Figure 2 - Weibull Cummulative Distribution Function: Coefficient of Friction

Slip Resistance

In 2002, Barnett (Ref.1) formulated a new theory of slip resistance based on extreme value statistics. This theory provides that the "bell-shaped" curve of friction coefficients must be of the Weibull form and that the probability that a random friction coefficient M will not exceed μ_r, $\Pr\{M \leq \mu_r\}$, is expressed by $\overline{F}_k$:

$$\overline{F}_k(\mu_r) = 1 - e^{-n\left(\frac{\mu_r - z_k}{s_k}\right)^{mk}} \quad \ldots \mu_r \geq z_k \qquad \text{Eq. 6a}$$

$$= \quad 0 \qquad \ldots \mu_r \leq z_k \qquad \text{Eq. 6b}$$

where μ_r is the resisting coefficient of friction for a particular floor/footwear couple delineated by the subscript k; n is the number of steps taken during a given walk; and z_k, s_k, and m_k are the Weibull parameters obtained from the friction data for the k^{th} floor/footwear couple. It should be noted that

z_k is the zero probability friction coefficient; for applied loading at or below this value there is no risk of slipping. The probability density function associated with Eq. 6 will be designated $\bar{f}_k(\mu_r)$, i.e.,

$$\bar{f}_k(\mu_r) = \frac{nm_k}{s_k}\left(\frac{\mu_r - z_k}{s_k}\right)^{m_k-1} e^{-n\left(\frac{\mu_r - z_k}{s_k}\right)^{m_k}} \quad \ldots \mu_r \geq z_k \quad \text{Eq. 7a}$$

$$= 0 \quad \ldots \mu_r \leq z_k \quad \text{Eq. 7b}$$

Reliability Theory

Combining stochastic floor loading and stochastic friction resistance was first undertaken by Barnett and Poczynok in 2003 (Ref. 3). This was done for a single community of walkers using a specific type of ambulation and footwear on a given homogeneous and isotropic floor surface.

The probability that a walker will not slip, and hence not fall, is called reliability and it will be designated by R. When the applied floor loading μ_a and the friction resistance of a floor/footwear couple μ_r are both stochastic, the floor reliability R may be determined by well established techniques developed in reliability theory. These techniques are all predicated on the observation that failure (slip) will not occur if the loading (stress) does not exceed the resistance (strength); for non-slip this implies that $\mu_a \leq \mu_r$. Using $\tilde{f}_\beta(\mu_a)$ defined by force-plate studies and $\bar{f}_k(\mu_r)$ defined by Eq. 7, the floor reliability becomes,

$$R_{\beta kj} = \int_{-\infty}^{z_k} \tilde{f}_\beta(\mu_a) d\mu_a + \int_{z_k}^{\infty} \tilde{f}_\beta(\mu_a) e^{-n_j\left(\frac{\mu_a - z_k}{s_k}\right)^{m_k}} d\mu_a \quad \text{Eq. 8}$$

where $(1 - R_{\beta kj})$ is the probability of slipping for the β community of walkers exposed to the k^{th} floor/footwear couple while traveling through n_j steps. The first term in Eq. 8, depending on the distribution function, may be expressed in closed form, may require numerical integration, or may be a tabulated function as in the case of the normal distribution. The second term always requires numerical integration or some equivalent evaluation.

Duty Cycles (Real Floors)

The notion of a floor duty cycle was introduced in 2002 [7] for homogeneous and isotropic floors. The study focused on a single floor/footwear couple and one community of walkers. Because of the simplicity of the problem, a one parameter walk profile involving only walking distance (number of steps) was sufficient to characterize the floor. To incorporate various ambulation and footwear styles, the prediction of floor reliability is somewhat more complex. The present paper assumes that a surveillance/counting system is available with the following capability:

a) It will identify all traffic patterns or pedestrian pathways (designated by the subscript j) and their lengths, n_j steps.

b) It will indicate multiple classes of walkers (designated by the subscript β).

c) It will identify every floor surface/footwear couple (designated by the subscript k).

d) It will record the number of ambulations, $T_{\beta kj}$, along each pathway for every walking profile $P_{\beta kj}$ defined as the combination of a walker type (β), footwear style (k), and walking distance in steps n_j.

Consider, as an example, the six traffic patterns or pedestrian pathways ($j = 1,2,\ldots 6$) that are illustrated in Fig. 3 for a simple commercial floor plan. Next to each pathway, its length, n_j steps, is indicated. Observe that there are two branches for pathways $j = 2$ and $j = 5$. Assume that the floor is comprised of ceramic tiles and that men and women wearing leather and rubber soled shoes traverse each pathway in either direction. This gives rise to 24 walking profiles $P_{\beta kj}$ with the parameters tabulated in Table I.

Note that the total number of walking profiles is given by the product of $\beta_{\max}$, $k_{\max}$, and $j_{\max}$; i.e., $2 \times 2 \times 6 = 24$. Assume that a surveillance system has recorded the number of ambulations $T_{\beta kj}$ for each walking profile $P_{\beta kj}$ as tabulated in Table II for a 14 day period.

The total number of ambulations T is given by

$$T = \sum_{\beta}\sum_{k}\sum_{j} T_{\beta kj} = \sum_{\beta=1}^{2}\sum_{k=1}^{2}\sum_{j=1}^{6} T_{\beta kj} = 75{,}027 \quad \text{Eq. 9}$$

where a fixed time frame has been adopted. The data and parameters presented in Tables I and II enable one to calculate the reliabilities and number of slips associated with each walking profile and the conglomerate floor reliability with the total number of slips per unit time.

COMPUTATIONS

Profile Reliabilty, $R_{\beta kj}$

The reliability $R_{\beta kj}$ for a walk profile $P_{\beta kj}$ is the probability that no slipping will occur during an ambulation along the i^{th} pathway by walkers of type β wearing footwear style k. The reliability, given by Eq. 8, may be evaluated for a typical profile $T_{2,1,4}$, i.e., for women in leather shoes walking 12 steps on a ceramic tile floor. Taking $\tilde{f}_1$ as the normal distribution given by Eq. 1,

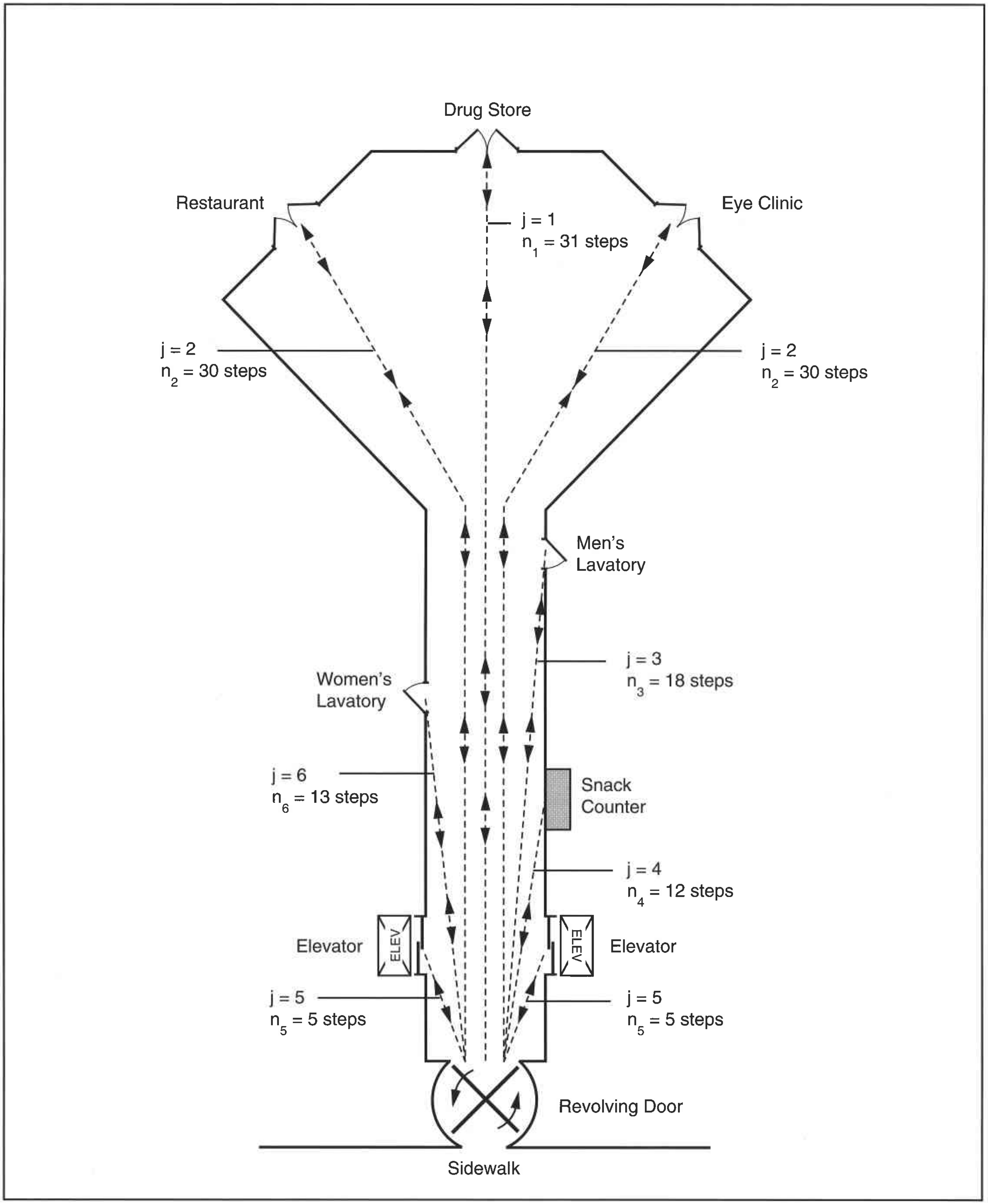

Figure 3 - Commercial Floor Plan - Traffic Patterns, j

Table I - Ceramic Floor: Characterization of Walking Profiles $P_{\beta kj}$

β = 1 ... men, straight walking $\bar{\mu}_1 = 0.17$; $\sigma_1 = 0.04$ (Barnett, 2002)
β = 2 ... women, straight walking $\bar{\mu}_2 = 0.16$; $\sigma_2 = 0.03$ (Barnett, 2002)
k = 1 ... ceramic / leather couple $z_1 = 0.10$, $s_1 = 0.51$, $m_1 = 5.5$
k = 2 ... ceramic / rubber couple $z_2 = 0.25$, $s_2 = 0.28$, $m_2 = 1.9$
$n_1 = 31$, $n_2 = 30$, $n_3 = 18$, $n_4 = 12$, $n_5 = 5$, $n_6 = 13$ steps

$$R_{\beta kj} = \int_{-\infty}^{z_k} \tilde{f}_\beta(\mu_a)\,d\mu_a + \int_{z_k}^{\infty} \tilde{f}_\beta(\mu_a)\,e^{-n_j\left(\frac{\mu_a - z_k}{s_k}\right)^{m_k}}\,d\mu_a$$

$$R_{2,1,4} = \frac{1}{\sigma_2\sqrt{2\pi}}\int_{-\infty}^{z_1} e^{-\frac{1}{2}\left(\frac{\mu_a-\bar{\mu}_2}{\sigma_2}\right)^2}\,d\mu_a + \frac{1}{\sigma_2\sqrt{2\pi}}\int_{z_1}^{\infty} e^{-\left[\frac{1}{2}\left(\frac{\mu_a-\bar{\mu}_2}{\sigma_2}\right)^2 + n_j\left(\frac{\mu_a-z_1}{s_1}\right)^{m_1}\right]}\,d\mu_a$$

$$= \Phi\left(\frac{z_1-\bar{\mu}_2}{\sigma_2}\right) + \frac{1}{\sigma_2\sqrt{2\pi}}\int_{z_1}^{1} e^{-\left[\frac{1}{2}\left(\frac{\mu_a-\bar{\mu}_2}{\sigma_2}\right)^2 + n_4\left(\frac{\mu_a-z_1}{s_1}\right)^{m_1}\right]}\,d\mu_a$$

Table II - Number of Ambulations for Various Walking Profiles, $P_{\beta kj}$

$T_{\beta kj}$ (14 day period)					
j	n_j	β = 1 ... men k = 1 ... leather	β = 1 ... men k = 2 ... rubber	β = 2 ... women k = 1 ... leather	β = 2 ... women k = 2 ... rubber
1	31	10,214	5,282	1,770	5,454
2	30	2,178	1,364	2,034	1,126
3	18	6.306	4,006	———	———
4	12	1,522	572	1,514	598
5	5	8,414	4,818	6,422	3,236
6	13	———	7	5,628	2,562

$$= \Phi\left(\frac{0.10-0.16}{0.03}\right)$$

$$+\frac{1}{0.03\sqrt{2\pi}}\int_{0.10}^{1} e^{-\left[\frac{1}{2}\left(\frac{\mu_a-0.16}{0.03}\right)^2+12\left(\frac{\mu_a-0.10}{0.51}\right)^{5.5}\right]} d\mu_a$$

$$= \quad 0.02275\ 01319 + 0.97670\ 92398 = 0.99945\ 93718$$

where unity replaces the upper bound, infinity, in the second term which will not be reached by the coefficient of friction. The second term was numerically integrated using Simpson's four interval rule with a computer spreadsheet:

$$\int_{x_0}^{x_4} f(x)dx = \frac{2h}{45}[7f(x_0)+32f(x_1)+12f(x_2)$$

$$+32f(x_3)+7f(x_4)]-\frac{8h^7}{945}f^{(6)}(\xi)...\xi\ in(x_o,x_4) \quad \text{Eq. 10}$$

where h, which is the length of each of the four equal intervals, was taken as h=0.0025. This integration rule is developed in Applied Numerical Methods by Carnahan, Luther, and Wilkes (Ref. 8).

Reliabilities for the various walking profiles are tabulated in Table III. The corresponding computational time for these twenty-one reliabilities was approximately one hour.

Number of Slips

The probability of slipping for a profile $P_{\beta kj}$ is $(1-R_{\beta kj})$. The number of slips for a given profile is the product of the slip probability and the number of ambulations undertaken; thus,

$$\text{Slips} = (1-R_{\beta kj})T_{\beta kj} \quad \text{Eq. 11}$$

As an example, the slips associated with the profile $P_{1,1,4}$, i.e., men with leather shoes walking 12 steps on a ceramic tile floor, are

$$\text{Slips} = (1-R_{1,1,4})T_{1,1,4}$$

$$= (\ 0.00172\ 18730\ )\ 1522$$

$$= 2.62$$

The slips have been tabulated in Table IV for each of the twenty-one active profiles.

Table III- Reliability for Various Walking Profiles, $R_{\beta kj}$

$R_{\beta kj}$					
j	n_j	β = 1 ... men k = 1 ... leather	β = 1 ... men k = 2 ... rubber	β = 2 ... women k = 1 ... leather	β = 2 ... women k = 2 ... rubber
1	31	0.99559 45028	0.99579 25174	0.99860 79365	0.99987 52145
2	30	0.99573 41371	0.99589 36610	0.99865 26108	0.99987 87338
3	18	0.99742 35929	0.99724 92296	————	————
4	12	0.99827 81270	0.99804 81835	0.99945 93718	0.99994 74092
5	5	0.99928 36039	0.99911 83541	0.99977 44654	0.99997 72869
6	13	————	0.99790 82251	0.99941 44206	0.99994 33009

Table IV - Number of Slips for Various Walking Profiles, $P_{\beta kj}$

Slips = (1- $R_{\beta kj}$) $T_{\beta kj}$					
j	n_j	$\beta = 1$ ... men $k = 1$ ... leather	$\beta = 1$ ... men $k = 2$ ... rubber	$\beta = 2$ ... women $k = 1$ ... leather	$\beta = 2$ ... women $k = 2$ ... rubber
1	31	45	22	2	1
2	30	9	6	3	0
3	18	16	11	———	———
4	12	3	1	1	0
5	5	6	4	1	0
6	13	———	0	3	0

Probability of Slipping

The total number of slips experienced during the various walking profiles may be expressed as

$$\text{Total Slips} = \sum_{\beta}\sum_{k}\sum_{j}(1 - R_{\beta kj})T_{\beta kj} \qquad \text{Eq. 12}$$

For our example, this represents the sum of the slips listed in Table IV, i.e., 134. Because the duty cycle reflects a fixed time frame, in our case 14 days, the slip data may be presented as follows:

$$\text{Slips/day} = \frac{134}{14} = 9.57$$

$$\text{Slips/week} = \frac{134}{2} = 67$$

$$\text{Slips/month} = \frac{30}{14}(134) = 287.14$$

$$\text{Slips/year} = \frac{365}{14}(134) = 3493.57$$

These yardsticks are only meaningful if the duty cycle truly characterizes the ambulation activity.

The probability of slipping is found by dividing the total number of slips by the total number of ambulations; thus,

$$\text{Slip Probability} = \frac{\sum_{\beta}\sum_{k}\sum_{j}(1 - R_{\beta kj})T_{\beta kj}}{T} \qquad \text{Eq. 13}$$

where the explicit effect of the time frame disappears because of the ratio $(T_{\beta kj}/T)$. However, the time frame continues to have an implicit effect because the slip probability has no meaning if the duty cycle is atypical. For our example,

$$\text{Slip Probability} = \frac{134}{75{,}027} = 0.001786$$

This may also be expressed as

Slip/Million Walkers $= 1786$

or,

Slips/100,000 Walkers = 179

Floor Reliability

The floor reliability is (1–Slip Probability); thus,

$$\text{Floor reliability} = \frac{\sum_{\beta}\sum_{k}\sum_{j} R_{\beta kj} T_{\beta kj}}{T} \qquad \text{Eq. 14}$$

For our example, the reliability of the ceramic tile floor is 0.998214. The average coefficient of friction for the ceramic/leather couple ($z = 0.10$, $s = 0.51$, and $m = 5.5$) is $\overline{\mu} = 0.571$.

Based on conventional standards, $\overline{\mu} > 0.5$, the ceramic floor used in our example of a commercial setting is fully acceptable. Unfortunately, its reliability is remarkably low and leads to approximately 3500 slips/year. By contrast, the ubiquitous asphalt tile floor is 100% reliable and precludes all slips even when exposed exclusively to leather footwear. Using the walk profiles defined in Table V for leather footwear, the reliabilities $R_{\beta,1,j}$ are tabulated in Table VI where they are all equal to unity as a practical matter. Consequently, there are no slips. It should be noted that the average coefficient of friction for the asphalt/leather couple is $\overline{\mu} = 0.676$.

Table V - Asphalt Floor: Characterizations of Walking Profiles, $P_{\beta kj}$

$\beta = 1$ ... men, straight walking $\bar{\mu}_1 = 0.17$; $\sigma_1 = 0.04$ (Barnett, 2002)
$\beta = 2$ ... women, straight walking $\bar{\mu}_2 = 0.16$; $\sigma_2 = 0.03$ (Barnett, 2002)
$k = 1$ ... asphalt / leather couple $z_1 = 0.31$, $s_1 = 0.40$, $m_1 = 4.75$
$n_1 = 31$, $n_2 = 30$, $n_3 = 18$, $n_4 = 12$, $n_5 = 5$, $n_6 = 13$ steps

Table VI - Reliabilities for Various Walking Profiles, $P_{\beta,1,j}$

$R_{\beta,1,j}$ - Asphalt Floor Tile			
j	n_j	$\beta = 1$ ... men $k = 1$ ... leather	$\beta = 2$ ... women $k = 1$ ... leather
1	31	0.99999 99905	1.00000 00000
2	30	0.99999 99908	1.00000 00000
3	18	0.99999 99945	———
4	12	0.99999 99963	1.00000 00000
5	5	0.99999 99985	1.00000.00000
6	13	———	1.00000 00000

CONCLUSIONS

1. A protocol has been developed to predict the probability of slipping on a homogeneous and isotropic floor exposed to walkers with multiple locomotion styles and mixed footwear.
2. The reliability of a floor depends on its duty cycle; it does not depend on a critical friction coefficient.
3. Because the slip resistance of a floor takes the form of a Weibull distribution function, its reliability cannot be expressed in closed form; numerical evaluation is always required.
4. A typical duty cycle was studied for a commercial establishment frequented by men and women wearing leather or rubber soled footwear. When the floor was composed of ceramic floor tiles the following observations were noted:
   - The average friction coefficient for the ceramic/leather couple was $\overline{\mu} = 0.571$ which provides a satisfactory floor by conventional standards.
   - The floor reliability was calculated as $R = 0.998214$. This is a low reliability that leads to 1786 slips per million walkers.
   - All circumstances being equal, men slipped more frequently than women.
   - As expected, rubber footwear is more slip resistant than leather footwear.

- Women in rubber footwear almost never slipped.

- As expected, the more active pathways produced the most slips.

- As expected, the longer pathways produced the most slips.

5. When the conventional asphalt tile was substituted for the ceramic tile, no slipping was predicted. The average coefficient of friction for the asphalt/leather couple was $\bar{\mu} = 0.676$. The perfect reliability of the asphalt floor tiles is also predicted by anecdotal evidence.

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SAFETY BRIEF

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Fact Sheet

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ETC Documents on File for Participant P-0999

July 15, 2004

Participant	Expert's Name	Document Number	Document Type	Document Date	Plaintiff
0999	Smith, James	12345	Deposition	1/2/8[illegible]	Doe, John
	Jones, David	12346	Trial Transcript	3/5/90	Kim, Joe
	Lee, Bruce	12349	R[illegible]e	[illegible]5	
		12350	Exp[illegible]eport	3/1/95	James, Jesse
		12351	[illegible]eposition	4/2/04	James, Jesse
	[illegible]on, Jim	[illegible]5	Publication	1/1/95	
	[illegible]	11444	Deposition Summary	4/4/01	Jones, Sally
		11445	Deposition	4/4/01	Jones, Sally
	Brown, Charles	13333	Resume		
		13335	Trial Transcript	3/18/04	Bailey, Bill
		13336	Expert Report	12/1/03	Bailey, Bill

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