SIDEWALK CROSS-SLOPE DESIGN:

ANALYSIS OF ACCESSIBILITY FOR PERSONS WITH DISABILITIES

by

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ABSTRACT

Current and proposed Americans with Disabilities Act (ADA) guidelines offer no specific guidance on acceptable maximum cross slopes where constraints of reconstruction prohibit meeting the 2-percent maximum cross-slope requirement for new construction. Two types of sidewalk test-section data across a sample of 50 individuals were collected, combined with an earlier sample of 17 individuals, and analyzed here, with an emphasis on cross slopes. These examined heart-rate changes and user perception of discomfort levels, and they relied on a random-effects model and an ordered-probit model, respectively. Model estimates were used to deduce critical or unacceptable cross slopes for critical conditions and critical populations of persons with disabilities. Predicted values for the most severe or constrained cases ranged from 5.5 to 6 percent cross-slope. These cases included 5 percent primary slope (main grade) and 45-ft long sections; and they were traversed by cane/crutch/brace and manual wheelchair users up to 80 years of age. When primary slopes were reduced to 0 percent in the perception estimates, the critical cross slopes for the critical case rose to 6 percent. For most other persons with disabilities, the critical cross slopes ranged from 6 to 9 percent or more. These values substantially exceed the ADA Accessibility Guidelines' 2-percent maximum-cross-slope standard for public sidewalks.

KEYWORDS

sidewalk, cross-slope, persons with disabilities, accessibility

INTRODUCTION AND OBJECTIVES

The maximum cross-slope of sidewalks is a subject of serious conversation. Title II of the Americans with Disabilities Act (ADA) requires that the programs, activities and services of public entities be accessible to and usable by individuals with disabilities (28 CFR 35.149-35.150). And cross slopes are an important feature of the public rights of way, which provide such access. The ADA Accessibility Guidelines (ADAAG) provide standards for accessible design that meet the intent and requirements of ADA. ADAAG Section 14, which pertains to Public Rights-of-Way, sets a maximum cross-slope standard at 2 percent. Existing right-of-way (ROW) constraints can at times create situations of "technical infeasibility" under these guidelines. A particular concern of agencies responsible for public sidewalks has been provision of a continuous 2 percent or less cross slope when constructing or reconstructing sidewalks in existing, space-constrained rights-of-way, particularly in urban areas with numerous driveway crossings. Public agencies face a high burden of responsibility in meeting accessibility requirements, but face a lack of guidance when the guidelines for new construction cannot be met in a reconstruction or retrofit situation. Many public agencies voiced their concerns regarding the cross-slope standards in comments on the proposed Section 14, making it one of most controversial portions of the proposed guidelines (Taylor *et al.,* 1999).

Taylor *et al.*'s (1999) and Kockelman *et al.*'s (2001a) extensive literature reviews and continuing efforts in this area have concluded that there is essentially no research to support

ADA’s 2 percent cross slope requirement, although a need for research on the effects of cross slope on sidewalk users with disabilities was noted as far back as 1979 (Brown *et al.,* 1979). Related studies have relied on populations of young males, providing little information on maximum limits for the broadest range of sidewalk users with disabilities, particularly in an aging society.

To better inform the cross-slope design debate, a large sample of sidewalk users with disabilities was used in this work; their data was analyzed via sophisticated behavioral models, providing rigorous results. This paper describes the work and the results, after first placing the work in its legal and practical context.

LITERATURE REVIEW

Basis for Cross Slope Requirements

The proposed ADA guidelines in their different manifestations have consistently maintained a 2 percent maximum cross slope requirement, carried over from previous accessibility guidelines (UFAS, 1984) and variously expressed as 1:50 or (more recently) 1:48 (PROWACC, 2001). This requirement possibly derives from construction standards for a minimum required slope for drainage purposes, but review of the literature has not determined the original basis for this requirement (Taylor *et al.,* 1999; Kockelman *et al.* 2001a).

The Design Guide (Access Board, 1999) makes numerous statements regarding cross slope as a major barrier for pedestrians who use mobility aids or have difficulty walking. The Guide states that cross slopes exceeding 2 percent significantly impede forward progress on an uphill slope and compromise control and balance in downhill travel and on turns; and that crutch users have more difficulty with cross slope on a downhill running slope (Access Board, 1999, p. 37). In addition, the Guide states “Driveway aprons … with steep, short side flares, can render a section of sidewalk impassable, especially when encountered in series. Compound cross slopes…may cause tipping and falling if one wheel of a chair loses contact with the ground or the tip of a walker or crutch cannot rest on a level area. Wheelchair users whose upper trunk mobility is limited can be thrown from their seats by differentials in cross slope occurring over a small distance. Manual chairs, although more maneuverable than battery-heavy power chairs, are much more likely to tip on compound slopes” (Access Board, 1999, p. 44) Presumably there was some research to support this detailed statement, but it was not referenced in the report and is unknown to the authors of this paper.

The authors find it arguable whether cross slope is the most significant problem in wheelchair mobility, but note that it was identified as such in a 1979 report on budget requirements for research needs (Brown *et al.,* 1979). Recently, the Access Board designated a Public Rights-of-Way Access Advisory Committee (PROWACC) to recommend guidelines for newly constructed or altered pedestrian facilities covered by Title II of the ADA or the Architectural Barriers Act (ABA). PROWACC’s 2001 report cites Brubaker et al. (1996) as indicating “that a 3 percent cross slope requires 50 percent more effort than a 2 percent cross slope” (PROWACC 2001, p. 99). What the study actually indicated was that, while power required to propel a wheelchair increased more than 100 percent from a level surface to a 2-degree (3.49 percent) cross slope, energy cost was only 30 percent greater than for a level surface. Neither of these indications supports the statement for a 50 percent increase in effort with one percent increase in cross slope, although this statement has been made elsewhere (Access Board (video), 1997).

Chesney and Axelson (1996) focused on developing a method to measure effort required by wheelchair users in traversing a variety of surfaces. Their conclusions indicate that the work required to negotiate a specific ramp angle may be used as a criterion for short-distance wheelchair travel. Such effort may be comparable to the short distance required to traverse a driveway. They also acknowledge the need to assess the impact over much longer distances, such as for single trips and for all trips during the day.

One interesting result of Chesney and Axelson's work is that the work-per-meter value on a two-percent primary grade does not change for marginally different cross slopes. This supports the possibility that a cross slope greater than 2 percent might be acceptable by wheelchair users when traversing short distances, and it also contradicts the statement that a 3 percent cross slope requires 50 percent more effort than a 2 percent (Access Board, 1997).

Population and Needs of Mobility Aid Users

Much evidence exists to corroborate the need for improved sidewalk accessibility and to suggest research needed for such improvements. Kaye *et al.* (2000) noted that one-third of the wheelchair and scooter users in the 1994 National Health Institute Survey of disabilities (NCHS 1998) reported wheelchair accessibility problems outside the home. Only 3.2 percent of other mobility aid users reported problems. 82 percent of wheelchair users reported that their local transportation system is difficult to use or to get to. 66.9 percent said it is very difficult. Among mobility aid users in general, 68.3 percent reported difficulty with access to public transportation and 45.2 percent reported very difficult access. 39.9 percent of mobility aid users and 58.1 percent of wheelchair users reported that their difficulties with walking are or would be a problem for them in using public transit. While the majority of wheelchair use is of manual wheelchairs, the greatest percentage of these is among the elderly. Elderly wheelchair users report poorer health and are more likely to require assistance in daily activities, including assistance with mobility (Kaye *et al.,* 2000; NCHS 1998).

The percentage of the U.S. population with disabilities is predicted to rise over the coming decades; and use of mobility aids increases with age (McNeil, 1997). In addition, while use of mobility aids has grown due to an aging population, growth in use exceeds what can be attributed to aging alone. From 1980 to 1990 use of crutches grew by 14 percent; canes by 53 percent; and wheelchair and walker use doubled. The level of increase indicates that improved survival of trauma patients has added to the numbers of mobility aid users, and that improvements in design, image and affordability have led to increased usage by the people who needed but did not use mobility aids previously (Russell, *et al.,* 1997).

Studies of Mobility Aid Users

In an Australian study Bails *et al.* (1987) looked at the usability of public facilities by mobility aid users. Subjects were grouped as blind, ambulant, electric wheelchair users or manual wheelchair users. Ambulant included users of sticks (canes), frames (walkers), and crutches. Responses of difficulty of access during field tests were recorded on a 1 to 5 scale, where 1 represented very easy access and 5 impossible for a subject to achieve access. Where more than 20 percent of a subject group could not use a feature, or had a degree of difficulty greater than 3, the test results were treated as practically significant and the subject of a possible amendment to Australian code (Bails *et al.*, 1983). A later study focused on the needs of children mobility aid users in adult facilities used similar methodology, with the subject groups further broken down by age. A decision was made to aim for a minimum sample of ten subjects per group. But no statistical confidence levels were estimated using the results, and no multivariate models of access and response were constructed; such models would have allowed the researchers to control for a variety of factors at once, and draw keener conclusions.

A particularly relevant study pertains to research conducted on ramp slope for the US Access Board (Sanford, 1996). This study focused specifically on running slope, rise and distance but also looked at cross slope and other relevant factors. It used 1990 National Health Institute Survey (NHIS) data for choosing sample percentages across age, gender, fitness, disability, and type of mobility aid. The resulting 192 participants were distributed by age and gender among seven categories of mobility aids and included an eighth category of individuals with mobility impairments who do not use aids.

The test trials took place in a controlled indoor setting, rather than mimicking outdoor travel conditions. This study measured effort by pulse rate and oxygen saturation, and also measured subjective responses of difficulty rated on a 1 to 10 scale. Study data indicated that the greatest impacting factors in ascending a 30-foot long ramp are positive slope, distance, and manual wheelchair use. A conclusion was that most of the population could probably handle greater ramp slopes, with the primary exception of elderly female manual wheelchair users; but the author did not recommend changes to guidelines for ramp slope and length due to a need for further research on the functional limitations of older wheelchair users. Recruitment efforts for the study suggested that although there are a high percentage of older female manual wheelchair users, the number who travel independently outdoors may be relatively small. There was, however, no data other than anecdotal evidence to discount older women as potential ramp users (Sanford, 1996).

SURVEY METHODOLOGY

This study was designed in a prior project phase (Kockelman *et al.* 2001a) with the objective of evaluating the usable range of sidewalk cross slopes based on user perception and effort. This first phase administered perception tests to a variety of mobility aid users through on-site and Internet-based surveys. Tests of effort as measured by heart rate also were administered in on-site tests. The study used, and continued to use in the recent, second phase, an ordered response model of user perception of sidewalk-section crossing difficulty and a weighted linear regression model of heart rate deviation from resting rate. Model estimates permit determination of reasonable cross-slope maxima for users of a variety of mobility aids (Kockelman *et al.* 2001a).

Changes to the Study Design

Data for the first phase were collected using three types of survey instruments: an Internet-based survey in which respondents provided their perception of crossing comfort based on photos of sidewalk sections; a field survey in which participants stated their perceptions of ease of sidewalk use before and after crossing various sidewalk sections; and a field survey that recorded changes in heart rate in response to traversing distinct sidewalk sections. The Internet study generated a reasonably large sample size, but the attributes of the sidewalk sections were deemed too difficult to faithfully judge based on digital photos. Thus, this second phase of the study retained only the two types of field survey.

The two field sites in the first phase were chosen due to locations along bus routes identified as having high numbers of riders with disabilities. These two sites were retained for this study, with small modifications in the selection and measurement of individual sidewalk sections. The route through the parking lot used for the heart-rate study was re-configured to have five long sections to be traversed in sequence, non-stop. Heart-rate studies were conducted only on this parking lot traverse and not on sidewalk sections as was done in the previous study; these longer sections are more desirable since they better allow the working heart rates to stabilize, and thus generate more robust measures of response. All study participants in this phase were encouraged to complete tests at all three sites, giving a broader range of comparative data.

Subject Recruitment

Even though survey sites were selected for ease of transportation of subjects to and from the sites, there was great difficulty in recruiting subjects for the first phase of this study. A possible explanation has been previously noted in the literature review portion of this paper as a high percentage of mobility aid users reporting difficulty of access to public transportation (Kaye, *et al.*, 2000). Participants in this phase of the project were offered individual transportation where possible, resulting in increased recruitment even though more time and effort were involved in actual testing than in the previous phase. Due to a desire to recruit a larger number of older subjects to reflect the aging of the population, initial recruitment efforts targeted residents of nursing homes, assisted living centers, and retirement communities.

Population Sampling

While the aim of subject recruitment was primarily a larger sample, an important goal was to better represent the population of mobility aid users as a whole. Recruitment efforts produced subjects across a wide range of age and mobility aid types. A target sampling frame reflecting the population profile of U.S. mobility aid users (Table 1) was developed by calculating percentages of respondents to the 1994 National Health Institute Survey – Disability (NHIS-D) across age, gender and mobility aid type (NCHS 1998).

The sample of individuals with disabilities actually achieved is shown in Table 2; this is based on the 57 subjects participating in either the first or second phase of the study. While the actual sample does not mimic the frame well in each of the possible 48 categories, the major frame categories have been reasonably well surveyed. And no survey is ever perfectly representative of the population from which it is drawn. However, observations can be weighted during analysis to correct for sample deviations from population percentages. This was done here, in the regression analyses of results, to reflect the proper population of persons with disabilities. Each observation's weight is the ratio of the population fraction the person represents and the person's own representation in the sample. In other words, Table 1's values are divided by Table 2's values for each observation, based on the gender-age-mobility category of the observation. By weighting the data during analysis, any biases in parameter estimates related to measured variables are removed.

Field Surveys

The field surveys were conducted under actual outdoor travel conditions during daylight hours and required subjects to traverse a series of delineated sections with varying cross slopes and other attributes. Table 3 provides the basic statistics for the attributes of the 21 test sections used. As evident, a variety of cross slopes and primary slopes were obtained, particularly on the Guadalupe Street sites, where conditions were most rigorous. Images of all sites can be found in Kockelman *et al.* (2001b).

Subjects were instructed to traverse the sidewalk sections at a comfortable pace, pausing as needed and simulating the way they would typically use a sidewalk. After traversing each section, subjects were asked to rank their comfort level on a scale of 1 to 5, with 1 signifying "very comfortable" and 5 signifying "very uncomfortable".

Ease of sidewalk use is the objective of ADAAG design standards in this area, so the surveys focused on perceived comfort of subjects in traversing the sections. However, there was a need to establish a link between perceived comfort (or lack thereof) and a more scientific measure of physical effort. According to Kirkpatrick and Birnbaum (1997), the most reliable indication of physical effort is heart rate measurement. Because heart rate increases in a linear fashion in relation to work and oxygen uptake during exercise, its measurement is therefore an appropriate way to test the correlation between perceived and actual effort (Williams and Wilkins, 1998*)*. Athletic-type pulse meters, which measure the heart rate in the earlobe and display the rate in beats per minute, were used to record heart rates.

Research on heart rate measurement indicates that heart rates stabilize after 2 minutes of activity, but that 5 to 6 minutes of activity provide the most accurate measure of physical effort (Astrand, *et al.,* 1970). To get distances across a continuous sloping surface that would provide the necessary time of activity, a route of five sections was configured in a parking lot with both primary and cross slope. Subjects traversed each section in both directions (out and return), extending the exercise (and thus further stabilizing the working heart rate) – but largely negating the effect of primary slope (since outbound slopes were the opposite of inbound slopes). Sections were traversed in succession without stopping. If a subject had to stop to rest, the test was stopped at that point, as the effect of continuous activity on heart rate would have been lost upon continuation. A resting heart rate was obtained and recorded before starting the test. Heart rates were recorded at each end of each section traverse; and traverse times were recorded for each total section traverse. As in the sidewalk sections, comfort-level responses were recorded for each section.

DATA ANALYSIS METHODOLOGY

In order to predict comfort perceptions and heart-rate changes for sidewalk sections, this work relies on two statistical methods. One is a linear regression with correlated random effects that minimizes the sum of weighted least squares (WLS) of residuals. This was used to estimate heart rate changes of the subjects before and after crossing sidewalk sections. The other model is more difficult to estimate because it is based on an ordered response structure for user perceptions of comfort; it requires maximizing a non-quadratic likelihood function. Table 4 describes all variables and their definitions used in the two estimation models.

Random Effects Model of Heart Rate Changes

The heart rate changes were calculated by subtracting the heart rate at the starting point from that at the ending point of the long, parking-lot survey sections. These changes can be explained by several explanatory variables, such as the section's primary slope, its cross slope, its length, and the gender, age, and physical shape of the participant.

The standard regression technique of ordinary least squares (OLS) is not best suited for this form of survey data since the error terms of the regression are very likely to be correlated across subjects, test sections, or both. Therefore, two-way and one-way random effects models were investigated here; these estimate the correlations and construct an appropriate covariance matrix estimate to serve as a weight matrix. Then a weighted least squares (WLS) regression is run, resulting in more efficient predictions and (hopefully) unbiased estimates of estimator variance. (For a more detailed description of these statistical models, see, *e.g.*, Greene 2001.)

In a two-way random-effects model, the error terms are divided into three components: an individual-specific error, a test section-specific error, and a purely random error.

$$\begin{aligned} &Y_{in} = \vec{X}'_{in}\vec{\beta} + v_{in} \\ &\text{where } v_{in} = \alpha_i + \lambda_n + u_{in} \end{aligned} \tag{1}$$

In this model Y_{in} is the heart rate change of participant *n* on survey section *i*, $\vec{X}_{in}$ is the matrix of explanatory variables detailing this participant and the section, and v_{in} is a total error term. The total error term is hypothesized to consist of α_i, an error specific to the test section *i*, λ_n, an error specific to individual *n*, and u_{in}, a purely random error uniquely specific to person *n* on test section *i*.

Using the correlations of these different random components, three different weight matrices were prepared here. One was for the one-way random effects based on a test section-specific error term, another was for an individual-specific error term, and a third was for the two-way random-effects model shown in Eq. (1). The weight matrices were used for weighted-least-squares (WLS) estimation of the heart-rate-change models. As described in the results section of this paper, the one-way random effects corresponding to individual participants were much stronger than those corresponding to the five heart-rate test sections. Thus, this one-way random effects model was the model chosen for all conclusions. Please refer to Greene (2001) and/or Kockelman et al. (2001b) for more details on this statistical technique.

Ordered Probit Model of Discomfort

In the assessment of test section difficulty via participant discomfort, the allowed response levels are discrete but ordered, across five levels: “very comfortable” (index 1) through “very uncomfortable” (index 5). Underlying each of these five values is hypothesized to be a latent value of discomfort. The boundaries distinguishing these underlying and unobserved continuous perceptions of discomfort are estimated as “threshold” values, via an ordered probit model. In such models, unobserved variation (in participants and test sections here) in latent discomfort is incorporated via a standard normal error-term distribution, as follows.

$$T_{in}^{*} = X_{in}'\beta + \varepsilon_{in}, \qquad \varepsilon_{in} \sim iid\ N(0,1) \tag{2}$$

where T_{in}^{*} is the latent discomfort of an individual *n* traversing section *i* and X_{in} is a vector of attributes describing person *n* and section *i*.

Since the latent value T_{in}^{*} is unobservable, the resulting observed discrete value of discomfort derives from the latent value T_{in}^{*} falling into a range between two thresholds, ψ_{k} and $\psi_{\mathrm{k+1}}$. These relationships between latent and categorized values are as follows:

$$T_{in} = \begin{cases} 1\,(\text{Very comfortable}) & , if\ T_{in}^{*} \le \psi_1 \\ 2\,(\text{Comfortable}) & , if\ \psi_1 < T_{in}^{*} \le \psi_2 \\ 3\,(\text{Neutral}) & , if\ \psi_2 < T_{in}^{*} \le \psi_3 \\ 4\,(\text{Uncomfortable}) & , if\ \psi_3 < T_{in}^{*} \le \psi_4 \\ 5\,(\text{Very uncomfortable}) & , if\ \psi_4 < T_{in}^{*} \end{cases} \tag{3}$$

where the ψ_{k} are threshold values to be estimated and the T_{in} are the observed discrete response levels. For example, ψ_2 defines the threshold value of T_{in}^{*} that distinguishes responses of “Neutral” and “Uncomfortable”.

The probabilities of any individual-test section observation with attributes X_{in} falling into the different response categories can be computed as follows:

$$\begin{aligned} P_n(1) &= \Pr(\text{Very comfortable}) \\ &= \Pr(T_n = 1) = \Pr(T_n^{*} \le \psi_1) = \Pr(X_n'\beta + \varepsilon_n \le \psi_1) \\ &= \Pr(\varepsilon_n \le \psi_1 - X_n'\beta) = \Phi(\psi_1 - X_n'\beta) \\ &\ \vdots \\ P_n(k) &= \Phi(\psi_k - X_n'\beta) - \Phi(\psi_{k-1} - X_n'\beta) \\ &\ \vdots \\ P_n(5) &= \Pr(\text{Very uncomfortable}) \\ &= 1 - \Phi(\psi_4 - X_n'\beta) \end{aligned} \tag{4}$$

where $\Phi(\cdot)$ is the cumulative standard normal distribution function. These probabilities are used in probit estimation software written for GAUSS matrix language. The estimation is conducted using the method of maximum likelihood, which provides an asymptotically maximally efficient set of parameter estimates – assuming the model specification is correct. All observations were weighted according to the ratio of the participant's population representation divided by his/her sample representation. This correction technique is also needed, for estimator unbiasedness.

RESULTS

Two sets of results are discussed in this section. They correspond to the two different models (i.e., the random effects and ordered probit models), but both are interpreted and applied across the same set of variables. And the emphasis is on deducing critical cross-slopes for a variety of sidewalk users with disabilities. The calculations underlying the critical cross slopes are provided here, and conclusions are drawn in the final section of this report.

Estimation Results

Random-Effects Regression Model of Heart Rates

Using a version of weighted least squares (WLS) regression (where the weight matrix is a set of correlation estimates), three alternative random-effects models were estimated based on the heart-rate-change data. These models were defined above, and, as noted, the one-way random-effects model for individual-specific error terms turned out to be the most appropriate of the three (based on the level of correlation across effects and model parameter signs and magnitudes). To be able to combine the original, 1999 data set and the current, 2001 data, heart rates were taken after each participant had traversed each section in both directions, thereby negating – to some extent – the effect of main slope (since one direction was uphill and the other was downhill). All heart-rate results shown here are based on this out-and-back response, based on a one-way random-effects model specification (permitting within-person or individual-specific random effects). Note, however, that the 1999 data set did not have data on time-till-completion of each test, a variable which assists in the model's prediction of heart-rate stabilization and permits control for participants' speed variations. (One expects a slight fall in rates as test time increases, and one expects higher heart rates for those who traverse the test sections fastest.) Thus, model estimates based on combined data sets do not control for these useful variables, since time data was only collected in the 2001 data set.

Several models' estimates are provided in Kockelman et al.'s (2001b) detailed report on this subject. Table 5 is provided here, and is used for computation of critical main slopes. It is a good example of the results of this model's application to the combined out-and-back heart-rate data when only the 2001 data are used, and thus the variables of TOTALTIME and SPEED can be included.

Higher main slopes were estimated to produce higher heart-rate changes in all models, even though participants went out and back, negating to some extent the effect of main slope. Cross slope estimates, however, generally ran counter to expectations: under almost all model specifications, cross slope was estimated to be negatively related to heart-rate changes (and thus participant oxygen uptake and effort), everything else constant. In several cases, this cross-slope effect was estimated to be *statistically* significant (as was the main-slope effect). However, the cross-slope effect was *not* of great *practical* significance. Table 5's result is not statistically significant; this model predicts every 1 percent increase in cross slope to result in 0.096 fewer heartbeats per minute. In contrast, every increased percent of main grade is predicted to raise heart rates by 17.9 bpm. (Again, each test was run out and back, so half of each test was conducted downhill.)

The reasoning for such apparent heart-rate responses to cross slope may lie in the way the participants tackled the FUMC test sites: if they traversed the more cross-sloped – and, thus, more difficult – sections more slowly, they could avoid increasing their heart rates, to some extent. (The speed variable should control for this in a linear sense, however.) Multicollinearity in explanatory variables can also obscure relationships, and the cross slope is strongly correlated with total section length (LENGTH) and age (LNAGE), with correlation coefficients of +0.776 and +0.778, respectively. Table 5's underlying model does not include a LENGTH variable, but it does include TOTALTIME and SPEED variables, which pick up the effect of length, while recognizing the importance of time.

Another reason for a strange or missing cross-slope effect is the limitation on cross-sloping in the data set. Given the need for long test sections (for heart-rate stabilization) with very consistent or constant cross-sloping on each section, a parking lot was selected for the heart-rate tests. Unfortunately, its cross slopes varied only between 4.85 and 6.15 percent (Table 3), providing minimal variation for empirical discrimination of cross-slope impacts. Fortunately, the shorter perception tests allowed much more variation in cross slopes, and thus resulted in more reasonable model results, as discussing in the following section.

Also counter to expectations, those who professed to be less fit were found to experience lesser heart-rate changes. This may be an effect of various factors, including self-characterization of fitness level. (More fit persons may be biased or hold themselves to different standards, characterizing themselves as somewhat less fit.) Or, in certain cases, less physically fit persons may exhibit less of a heart-rate response to travel activities. This was not the research team's expectation, but it may be the case.

In a result that is consistent with the perception results (described below), males were predicted to experience lower heart-rate increases than the females – after controlling for SPEED choice. The average rate of travel was quite a bit faster for men, with the average time of completion of all five parking-lot sections at 356.65 seconds, compared to 470.21 seconds for women. Evidently, the men worked harder on purpose (which was evident to the test proctor, who noticed several of the men essentially competing for time).

The reference mobility aid is a manual wheelchair (MWC), and persons using this device were estimated to experience higher heart-rate changes than all other user types, though the differences are only statistically significant for comparisons with electric wheelchair and scooter users (AIDEWSC). The results suggest that MWC users are the most critical population for heart-rate response (our proxy for effort) – assuming they begin with the same resting heart rate (and controlling for the other typical attributes, besides aid type).

The model's goodness of fit was not very high: 8.1 percent of the variation in heart-rate changes was effectively explained by the variables controlled for in Table 5. However, most of the variables have statistically significant coefficients (i.e., parameter estimates statistically distinct from zero, signifying a measurable effect): t-statistics exceeding 1.96 or falling below –

1.96 indicate very statistically significant results (via p-values of 0.05 or less). In addition, the level of within-person correlation was predicted to be very high, at +0.757. Thus, it was very helpful to run this as a random-effects model, recognizing the latent information on each individual that remains constant as he/she crosses different test sections.

Ordered Probit Response Model of Discomfort

Table 6 provides the ordered-probit response model results, using the 2001 data. Models were run which included the 1999 data as well, and these are provided in Kockelman et al. (2001b). However, those results showed a significant distinction for the 1999 data. The distinction may be due to the use of different proctors during the tests, differences in respondent perceptions of response meanings, or other subjective issues. However, it is probably most likely that the cross-slope and main-slope data are not perfectly valid for the older, 1999 observations. Sidewalks offer variable cross-sections and profiles (when one is talking about slopes on the order of 2 to 15 percent); and the 1999 participants were permitted to choose different paths when crossing almost all of the sections chosen for study here.

In all model cases, the goodness-of-fit measures (a likelihood ratio index) were above 0.12, suggesting reasonably good fit for these models of highly subjective human response. Positive signs on coefficients indicate that having more of the associated variable adds to the latent discomfort level – and increases the probabilities of observing relatively high discomfort responses (e.g., 4’s and 5’s). And, if the latent discomfort rises enough, the expected discomfort level will pass a threshold (but all response types remain possible).

As expected, an increase in the section cross slope, primary slope, and length heighten user discomfort. And the effect of cross slope is more severe than that of main slope: 1 degree of cross slope is estimated to be worth 3.6 degrees of main slope, according to these results (3.6 = .149/.041).

As suggested in the model, older participants were found to be less comfortable, even if they indicated they were in the same physical shape category (1-5) as younger participants. Of course, “shape” is a subjective term, and many older participants probably considered their abilities relative to their peers, rather than relative to the population at large. Males were predicted to feel more comfortable than females, which is consistent with heart-rate model results. And, as expected, persons in better shape experienced less discomfort.

Manual wheelchair (MWC) users were the reference category of user, and estimated to experience slightly less discomfort than the cane, crutch, brace (CACRB) users[1]. Thus, the CACRB users appear to be the critical class of sidewalk user, when considering personal perception. However, as in the case of the heart-rate models, the MWC and CACRB users are predicted to respond rather similarly, in a statistical sense; this suggests that they are both critical users. Those using walkers (WALK), electric wheelchairs, or scooters (EWSC), were predicted to experience the least discomfort, as well as lower heart-rate effects.

Calculation of Critical Cross Slopes (and Main Slopes)

The estimation results shown in Tables 5 and 6 are of tremendous aid in estimating “critical cross-slopes”, which are defined here as those cross slopes placing specific user types into unacceptable levels of effort and/or discomfort. This section describes such an application, by estimating the maximum traversable cross slopes for various sidewalk situations involving several user types. This analysis is only performed using the assessment/discomfort data, because, as described above, cross slope was not estimated to increase heart rates. However, using a highly similar approach, critical main slopes have been computed based on the heart-rate results. And these results are provided in Kockelman et al. (2001b).

Ordered Probit Model of Discomfort

This critical cross-slope analysis yields the estimates of the maximum allowable cross slopes so that no more than 25 percent of users are expected to be uncomfortable or very uncomfortable. In other words, the probability that a user is *not un*comfortable is 0.75. The choice of a 25-percent threshold probability is a judgment call, and engineers and policymakers may care to design more conservatively, or liberally, depending on the specific situation (which will depend on site constraints and other attributes, including likely users and overall route accessibility). Here equations and a figure are provided here to facilitate the estimation of such probabilities.

The critical cross slope can be calculated for various person-section situations as shown in Table 8. The formula for the calculation is shown in Eq. (6). Two main slopes, 0 percent and 5 percent, are considered as well as all disability types. A significant site length of 40 feet was used. The critical gender, female, was used for these computations, and some very high (and thus critical) ages levels are provided: 70 and 80 years. Designing for 80-year-old users may be considered a conservative choice under many situations, since it reduces the critical cross slopes computed. However, the population of the U.S. is aging, so this set of sidewalk users is likely to increase. All situations involve assumption of fitness level 3. Males on shorter sections in better shape will produce predictions of even higher critical cross slopes than those shown here, in Table 8.

$$
\begin{aligned}
&Need:\ \Pr\left(T_{in}^{*} = X_{in}{}'\beta < \psi_3\right) = 0.75 \\
&\rightarrow Critical\ Cross\ Slope_{in} = \qquad\qquad (6) \\
&\left(1/\hat{\beta}_{CSLOPE}\right)\begin{pmatrix} \hat{\mu}_3 - F^{-1}(0.75) - \hat{\beta}_{MSLOPE} MSLOPE_i - \hat{\beta}_{LENGTH} LENGTH_i \\ - \hat{\beta}_{AGE} AGE_n - \hat{\beta}_{MALE} MALE_n - \hat{\beta}_{SHAPE} SHAPE_n \\ - \hat{\beta}_{AIDWAK} AIDWAK_n - \hat{\beta}_{BLND} BLND_n \\ - \hat{\beta}_{AIDACB} AIDCCB_n - \hat{\beta}_{AIDEWS} AIDEWS_n \end{pmatrix}
\end{aligned}
$$

where *n* indicates an individual, *i* indicates a sidewalk section, and $\hat{\mu}_3$ is the estimate of the threshold distinguishing “neutral” from “uncomfortable” response. $F^{-1}(0.75)$ is the inverse function value for a cumulative standard normal distribution function at a probability of 0.75; thus, its value is 0.674.

Case 13 is a very difficult case and the most critical shown above, in Table 8. It suggests a critical cross slope of 5.14 percent, when primary slope is 5 percent, section length is 40 ft., and the user is an 80-year-old female using the critical mobility aid: a cane or crutch (or leg brace, effectively). For younger users, less severe grades, shorter sections, and different mobility aids, the critical cross slopes are all higher. Table 8's predictions are all well above the tentative ADAAG standard of 2 percent.

Assuming that the critical threshold occurs when 25 percent of users predicted to rate a section uncomfortable or very uncomfortable (and the other 75 percent rate it as not uncomfortable), and assuming the critical user group to be an 80 year-old female of "average" fitness using a cane, crutches, or a leg brace, these results recommend a maximum cross slope for design of 5.1 percent, when main slope is 5 percent, and 6.5 percent, when zero main slope exists. The model results of Table 6 and the implications of Eq. (6) provide the mechanism for these calculations.

Table 8's predictions are consistent with expectations and observations, and they are well within the range of the surveyed cross-slopes (as described in Table 3). And they are well below what is expected to be an *in*accessible cross-slope for the most sensitive of the participants; this inaccessible cross-slope was found to be on the order of 12 percent, a point when a few participants could not negotiate a couple extreme survey sites.

Depending on one's assumption of threshold probability of discomfort, the results can vary. For assumptions other than a 25 percent threshold or to estimate what fraction of certain user classes would be uncomfortable under specific circumstances, one can apply Eq. (6) with Table 6's results in a variety of ways. To facilitate these computations, a series of figures are provided in Kockelman et al. (2001b). Figure 1 plots the estimated probabilities of a variety of CACRB users *not* being uncomfortable versus cross slope in the probability range likely to be of greastest interest (i.e., probabilities of no discomfort between 0.70 and 0.90); notationally:

$$\Pr\left(T_{in}^{*} = X_{in}{}'\beta < \psi_3\right) = 0.70 \text{ to } 0.90 \qquad (7)$$

It is also of some interest to consider how many of the critical user populations are unable to comfortably negotiate paths with no cross slope at all. Clearly, if this is a high percentage, it may be impossible to design pathways for such persons without exposing the users to some discomfort (or such high discomfort that they consider the section impassable). Calculations of this nature have been provided in Kockelman et al. (2001b).

CONCLUSIONS

Two types of sidewalk test-section data across a sample of sixty-seven individuals were collected for this research. Seventeen of the participants provided data for a 1999 survey; the other 50 participated in a more recent (2001) effort of highly similar design. The two data response types monitored in these surveys were heart-rate changes (as a proxy for oxygen uptake and thus effort) and user perception of discomfort levels.

The two response types required distinct statistical approaches: a random-effects and an ordered-probit model. Given some critieria of "acceptable" versus "unacceptable" heart-rate changes and user perception levels, both sets of model estimates can then be "inverted" to deduce critical cross slopes for critical conditions and critical populations of persons with disabilities. This computation was done here for the user perception of discomfort data, since these data's results yielded the positive relation expected (between degree of cross-sloping and the discomfort level). This inversion was based on an assumption that a design criterion would be "unacceptable" if it could be expected to cause 25 percent or more of the users of a critical type to consider the section uncomfortable.

Predicted critical cross-slope values for the most severe cases considered ranged from 5.1 to 7.4 percent or more cross-sloping. The cases examined included 5 percent primary slope (main grade) and 40-ft long sections. They were traversed by 20- to 80-year-old cane, crutch, or leg brace users. When primary slopes were reduced to 0 percent in the perception estimates, the critical cross slopes for these critical user types rose to 6.5 and 8.8 percent. For other persons with disabilities, the critical cross slopes ranged from 6 percent to 12 percent or more.

The results suggest that cane and crutch users *perceive* the most difficulty with cross-sloping; and manual wheelchair users are a close second. Manual wheelchair users were estimated to have the highest *heart-rate* responses to various sidewalk conditions. Together, these two groups represent over 65 percent of the U.S. population of persons with disabilities.

Current cross-slope design guidelines associated with the ADA regulations for public sidewalks indicate a maximum design standard of 2 percent; this requirement is less than one half of the values estimated to be critical here. More reasonable Guidelines and design specifications should probably permit cross slopes of 6 percent or more, when main slope is minimal. When main slopes reach 5 percent, cross slopes of 5 percent may be more reasonable. In terms of a cross slope that is wholly inaccessible to certain users, a critical cross slope for the most sensitive participants in these tests was on the order of 12 percent, a point when these persons could not negotiate a couple survey sites.

The results obtained here suggest that cross slopes greater than 2 percent should be considered a possible design strategy when right-of-way or other construction limitations make 2 percent cross slopes a costly endeavor. Moreover, such cross-sloping should be considered in concert with other factors, such as the length of the section and type of likely users. The results provided in this report provide methods for evaluating the accessibility of any number of sidewalk sections, based on length, cross slope, main slope, and user characteristics. Also, the study provides a method for estimating the percentage of sidewalk users who will experience discomfort when no cross sloping and/or no main sloping exists. Such users may have other mobility issues that the public cannot address through regulation of sidewalk cross-slope design, so a 100-percent-of-users rule may be impossible to meet.

Sidewalk design is a critical consideration when aiming to provide reasonable access to all persons. And access is fundamental to one's full participation in society. It is hoped that this work will facilitate accessible design for all sidewalk users, particularly those with disabilities.

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ENDNOTES

[1] A reference device type was needed since this model will be inestimable without removal of such an indicator. If all 5 device classes observed in the sample population were included in the explanatory variable set, their values would sum to one for every observation. This is equivalent to having a constant term in the model. And the probit specification being used cannot accommodate such a constant term, because the first threshold is not fixed. If this threshold were fixed (to equal zero, for example), one could include a constant term or the reference aid device's indicator variable and the model would be estimable (i.e., all the parameters would be statistically identifiable).

[2] Low starting rates were generally as expected by the participants that exhibited these. At least one of these respondents was extremely athletic; the others simply indicated that such low rates were normal for them.

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Table 1. Percentages of U.S. Population of Persons with Disabilities, by Gender, Age, and Mobility Aid (Based on 1994 NHIS-D Survey)

Mobility Aid Type	**Gender and Age**					
	Male			Female		
	16-35	36-65	66+	16-35	36-65	66+
Cane	0.83%	8.62	12.55	0.61	7.08	21.63
Crutches	0.59	1.90	0.81	0.51	1.17	0.73
Walker	0.19	1.37	3.3	0.17	2.76	11.23
Manual Wheelchair	0.51	2.39	2.69	0.34	2.76	5.86
Electric Wheelchair	0.07	0.32	0.24	0.07	0.37	0.27
Scooter	0.02	0.24	0.34	0.00	0.39	0.44
Leg Brace	0.46	1.46	0.88	0.49	1.17	0.81
White Cane (Blind)	0.10	0.27	0.19	0.05	0.32	0.29

Table 2. Sample Population, by Gender, Age and Mobility Aid

(1999 & 2001 Samples Combined)

Mobility Aid Type	Male			Female		
	16-35	36-65	66+	16-35	36-65	66+
Cane	1.493	5.970	4.478	0.000	8.955	2.985
Crutches	2.985	1.493	0.000	0.000	1.493	0.000
Walker	1.493	0.000	1.493	0.000	1.493	8.955
Manual Wheelchair	2.985	11.94	0.000	1.493	5.970	2.985
Electric Wheelchair	0.000	4.478	0.000	2.985	7.463	0.000
Scooter	0.000	0.000	0.000	1.493	1.493	0.000

Leg Brace	0.000	1.493	0.000	0.000	0.000	0.000
White Cane (Blind)	2.985	2.985	0.000	2.985	2.985	0.000

(N_{obs}=67, Units: %)

Table 3. Basic Statistics for Attributes of Sidewalk Survey Sites

Survey Sites	Attributes	Mean	Std.Dev.	Max	Min	Model
Guadalupe Street (9 sites)	Primary Slope (%)	2.681	2.23	8.300	0.600	OP[*]
	Cross Slope (%)	7.410	4.01	13.77	2.500	OP
	Length (ft)	24.49	9.52	37.0	11.25	OP
South Lamar Boulevard (7 sites)	Primary Slope (%)	-1.267	2.68	2.43	-6.28	OP
	Cross Slope (%)	2.029	1.52	4.86	0.410	OP
	Length (ft)	47.74	27.2	95.75	21.0	OP
Faith United Methodist Church Parking Lot (5 long sections)	Primary Slope[§] (%)	0.815	0.969	1.425	-0.900	RE[**]
	Cross Slope (%)	5.490	0.550	6.150	4.850	RE
	Length (ft) – 1 direction	105.4	11.7	114.6	85.8	RE

[*] OP = Ordered Probit Model of Sidewalk Discomfort Assessment

[**] RE = Random-Effects Model of Heart Rate Changes

[§] Primary slope was somewhat negated in the models because participants traversed the sections forward and back (in order to better stabilize heart rates).

Table 4. Definitions of Variables Used

Variable	**Definition**
Dependent variables:	
Sidewalk Assessment	1 = Very comfortable to cross, 2 = Comfortable, 3 = Neutral, 4 = Uncomfortable, 5 = Very uncomfortable
Heart-Rate Change	Change in heart rate (beats per minute [bpm])
Explanatory variables:	
Facility-related variables:	
MSLOPE	Average main slope (or “grade”) of the test section (%)
CSLOPE	Average cross slope of the sidewalk (%)
LENGTH	Total length of a test section for one direction
SPEED	Total section length divided by section completion time (ft/sec)
TOTALTIME	Total time negotiating FUMC sections until heart-rate reading taken (sec)
Personal variables:	
AGE	Age of the survey participant (years)
MALE	1 if the subject is a male, 0 otherwise
SHAPE	The self-assessed physical fitness level of the subject (5 scales: 1 = very poor shape; 5 = in great shape)
AIDMWC	1 if the subject used a manual wheelchair, 0 otherwise
AIDEWCSC	1 if the subject used an electrical wheelchair or scooter, 0 otherwise
BLIND	1 if the subject is legally blind, 0 otherwise
AIDCACRB	1 if the subject used a cane or crutch or brace, 0 otherwise
AIDWALK	1 if the subject used a walker, 0 otherwise

Table 5. One-Way Random Effects Regression Model Results for Heart-Rate Changes

(Based on 2001 Data)

Variables	Coefficients	Std. Err.	t-stats
UNO	59.85	26.06	2.30*
MSLOPE (2-way)	17.90	6.241	2.86*
CSLOPE	-0.0958	1.897	-0.051
SHAPE	6.013	2.367	2.54*
AGE	-0.218	0.1476	-1.48
MALE	-6.929	5.662	-1.22
TOTALTIME	-0.0675	0.0534	-1.26
SPEED	-43.99	19.85	-2.22*
AIDWALK	-6.415	11.33	-0.566
BLIND	-6.126	26.20	-0.234
AIDCCB	-4.693	8.759	-0.536
AIDEWS	-26.67	16.41	-1.62
N_{obs}	190		
Adjusted R^2	0.081		
ρ (within person correl.)	0.757		

Note: The reference mobility aid device is an AIDMWC.

[*] Statistically significant at the 0.05 significance level.

Table 6. Ordered Probit Model Results for Discomfort

(2001 Data only)

Variables	Estimates	Std. Err.	t-stats
Thresh01	0.628	0.246	2.556*
Thresh02	1.739	0.250	6.955*
Thresh03	2.397	0.257	9.344*
Thresh04	3.159	0.272	11.634*
MSLOPE	0.041	0.023	1.782*
CSLOPE	0.149	0.012	12.137*
LENGTH	0.011	0.003	3.469*
AGE	0.006	0.002	2.499*
MALE	-0.364	0.090	-4.022*
SHAPE	-0.112	0.034	-3.267*
AIDWALK	-0.694	0.163	-4.265*
BLIND	-0.281	0.407	-0.691
AIDCACRB	0.180	0.130	1.387
AIDEWCSC	-0.428	0.239	-1.791*
Num. of Observations	743		
Log-L (Constant)	-981.670		
Log-L (Restricted)	-855.895		
LRI**	0.128		

[*] Statistically significant at the 0.05 significance level.

[**] Likelihood ratio index.

Table 8. Critical Cross Slopes based on Perception of Discomfort

(2001 Data Only)

Variables	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13
MAINSLP (%)	0	0	0	0	0	0	0	5	5	5	5	5	5
LENGTH (ft.)	40	40	40	40	40	40	40	40	40	40	40	40	40
AGE	20	30	40	50	60	70	80	20	40	50	60	70	80
MALE	0	0	0	0	0	0	0	0	0	0	0	0	0
SHAPE	3	3	3	3	3	3	3	3	3	3	3	3	3
AIDCCB	1	1	1	1	1	1	1	1	1	1	1	1	1
Critical CSLOPE (%)	8.812	8.428	8.044	7.660	7.276	6.892	6.508	7.448	6.680	6.296	5.913	5.529	5.145
AIDMWC	1	1	1	1	1	1	1	1	1	1	1	1	1
Critical CSLOPE (%)	10.020	9.636	9.253	8.869	8.485	8.101	7.717	8.657	7.889	7.505	7.121	6.737	6.354
BLIND	1	1	1	1	1	1	1	1	1	1	1	1	1
Critical CSLOPE (%)	11.911	11.527	11.143	10.760	10.376	9.992	9.608	10.548	9.780	9.396	9.012	8.628	8.245
AIDEWSC	1	1	1	1	1	1	1	1	1	1	1	1	1
Critical CSLOPE (%)	12.900	12.516	12.132	11.748	11.364	10.981	10.597	11.536	10.768	10.385	10.001	9.617	9.233

Figure 1. Probability that Critical Class of Users would be Uncomfortable (or worse) on a Standard Sidewalk Section, as a Function of Cross-Slope