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Meeting the intent of ADA in sidewalk cross-slope design

Kara Kockelman, MCP, BS, MS, PhD CE; Yong Zhao, MS CE; Chessie Blanchard-Zimmerman, MCP
University of Texas at Austin; Department of Civil Engineering, Austin, TX 78712

Abstract—Recent work has indicated that prior research is insufficient to support the ADA Accessibility Guidelines' (ADAAG) 2% maximum cross-slope requirement for sidewalks. In addition, the present ADAAG are inflexible in that they do not consider deviations from this maximum for short sections of sidewalk, such as at driveway crossings, which can be of significant concern for state and local departments of transportation. Based upon these findings, a study was undertaken to evaluate the usable range of sidewalk cross-slopes by explicitly considering user perception and effort. Twenty subjects ranging widely in age and type of mobility aid participated in field surveys where they traversed different sidewalk sections varying in cross-slope, primary grade, length, width, and other characteristics.

This paper illustrates the use of weighted-least-squares and ordered-probit regression models for analysis of disabled-user response to sidewalk characteristics. The results of these models permit estimation of maximum sidewalk cross-slope consistent with the intent and spirit of ADA. These are estimated to be 4%—where feasible—and 10%—where unfavorable construction conditions exist. Such results should prove useful for consideration of the final requirements of ADA on this topic. However, larger sample sizes and a stronger recognition of the population of interest are necessary before definitive, legislated maxima can be ascertained.

Key words: *Accessibility, Americans with Disabilities Act, cross-slope, sidewalk design.*

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Address all correspondence and requests for reprints to: Kara Kockelman, Assistant Professor of Civil Engineering, University of Texas at Austin, Department of Civil Engineering, 6.9 E. Cockrell Jr. Hall, Austin, TX 78712; email: kkockelm@mail.utexas.edu.

INTRODUCTION

The ADA Accessibility Guidelines (ADAAG) clearly state that accessible sidewalks require limited cross sloping (1). Honoring its spirit and intent, state transportation agencies aim to be in compliance with the ADA when designing and constructing roadway projects that include pedestrian facilities. Unfortunately, existing infrastructure and terrain conditions, restricted right-of-way (ROW), and city ordinances often prevent these agencies from achieving the standard of a two-percent cross-slope at all points along an accessible route. Currently, one primary area of concern is maintaining the prescribed cross-slope where sidewalks intersect with driveways.

Background

Until now, virtually no research has been undertaken as to the effect of cross-slope on the accessibility of sidewalks to persons with disabilities (2). Prior research is insufficient to support the ADA's two-percent cross-slope requirement and does not offer a maximum limit for cross-slope in situations where the two-percent requirement may be relaxed (2). Existing studies have used fairly homogeneous populations of young males with good upper-body strength and stamina as their test subjects (3,4). Because of these deficiencies, the validity of existing requirements for less physically capable users and users with different mobility aids may be questioned. A reasonable maximum slope standard is urgently needed for design standards and construction cost estimation.

In the absence of an accepted standard for this type of design and construction, transportation agencies have often followed a "do the best you can" approach to providing sidewalk accessibility. However, this approach leaves the entity vulnerable to costly, damaging lawsuits. Accessibility is a civil right, and ADA court history has established a high standard of "undue burden" when it comes to noncompliance (5). The experimental research detailed in this paper was conducted in order to develop maximum and desirable limits for sidewalk cross-slope at driveway crossings. Based upon findings in the previously submitted review of methods, the research team designed and administered a study to evaluate the usable range of sidewalk cross-slopes under the current ADAAG with regard to user perception and effort.

This paper details the research undertaken with analyses based on a weighted linear regression model of heart rate deviation from resting rate and an ordered-response model of perception of sidewalk-section crossing difficulty. Model results permit estimation of reasonable cross-slope maxima for different sidewalk users with various disabilities.

METHODOLOGY

The research methodology is based on the use of linear and nonlinear procedures to estimate thresholds of sidewalk cross-slope. The linear regression model involves the heart rate changes of subjects after having traversed distinct sidewalk sections. The nonlinear model analyzes sidewalk assessment from an on-site field survey; its ordinal assessment is a five-point scale, with categories ranging from easy-to-cross to impossible-to-cross.

Linear Regression with Weighted Least Square Estimation

The first method described here involves linear regression models of heart-rate response. The change in heart rate is an important indicator of energy consumption as a result of crossing a sidewalk section (3,6). The variation in heart rate, Y_i (the difference between the post-test heart rate and the resting heart rate on test i), is modeled here as a linear function of several important explanatory variables, $\vec{X}_I$. Notationally,

$$Y_i = \vec{X}_i'\vec{\beta} + \varepsilon_i \qquad [1]$$

Where $\vec{\beta}$ is a column vector of coefficients to be estimated and ε_i is an error term representing the random variation about the average heart rate change expected in the ith test. The distribution of the error $**_i$ is assumed to be normal, with mean zero and constant variance.

The OLS estimates are not efficient, and their standard errors are biased low in the presence of dependent error terms. This occurs here because all subjects participated in multiple tests. Thus, correlation across error terms exists for each individual, and the error terms may be thought of as containing two parts: individual-specific biases and purely random error. Notationally,

$$\begin{aligned} &Y_{in} = \vec{X}_{in}'\vec{\beta} + u_{in} \\ &\textit{where } u_{in} = \varepsilon_n + \varepsilon_{in} \end{aligned} \qquad [2]$$

Here, Y_{in} is the heart rate change of individual n in ith experiment, u_{in} is the total error, ε_n is the error specific to individual n, and ε_{in} is the purely random error.

A weighted-least-squares (WLS) estimation can accommodate this lack of error-term independence, where the weights are estimates of the variances associated with each observation's error term. This technique is called "feasible generalized least squares" and is asymptotically as efficient as maximum likelihood estimation (when error terms are normal; reference 7). If it is assumed that the variance of each individual's error term and the variance of each experiment's error term are constants, i.e., var(ε_{in})=σ_I^2var(ε_n)=σ^2 and the correlation of error terms arising when individual n takes two tests, p and q, is the following:

$$corr(u_{pn}, u_{qn}) = \rho_{pq}\ \forall n; \qquad [3]$$

then a weight matrix W can be constructed as follows:

$$W = \begin{bmatrix} {}^{1} & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & {}_{N} \end{bmatrix}, where \quad {}_{n} = \sigma_{avg}^{2} \begin{bmatrix} 1 & \rho_{1q} & \rho_{1I} \\ \rho_{p1} & \ddots & \rho_{pI} \\ \rho_{I1} & \rho_{Iq} & 1 \end{bmatrix} \quad [4]$$

The WLS estimate of parameter vector $\vec{\beta}$ is the following:

$$\hat{\beta}_{WLS} = (X'WX)^{-1} X'WY \quad [5]$$

where X is the matrix of the explanatory information and Y is a column vector of the heart-rate differences.

Ordered Response Probit Analysis

In the second type of analytical model used here, categorized assessments (ranging from “easy-to-cross” to “impassable” [see **Table 2**]) of distinctly sloped sidewalk sections are modeled using an ordered-response probit structure. The procedure, popularized by McKelvey and Zavoina (8), also involves parameters representing the unobserved thresholds between assessment categories.

The ordered-response mechanism is based on the hypothesis that a continuous variable Y_I* represents the unobserved or “latent” response for an individual n on a sidewalk section i. The latent response is assumed to be a linear function of relevant explanatory variables and a standard normally distributed random error term ε_{in}. The variance of ε_{in} can be set to 1.0 since Y_I* is not observed (and hence its scale is unidentifiable; reference 9). Given a respondent’s ranking or assessment, Y_{in}, of a sidewalk section i, the latent response (Y_{in}*) and threshold bounds (μ_k) are as follows:

$$\begin{aligned} Y_{in}^{*} &= \vec{X}_{ni}'\vec{\beta} + \varepsilon_{in} \\ Y_{in} &= k \ if \ \mu_{k-1} < Y_{in}^{*} \quad \mu_k \ (k = 0,1,...K) \end{aligned} \quad [6]$$

where $\vec{X}$ is a column vector of explanatory variables, $\vec{\beta}$ is a corresponding column vector of coefficients to be estimated, and the μ’s are threshold bounds (with $\mu_1 = -\infty, \mu_K = +\infty$). The probability associated with each term is determined by the threshold bounds and the latent response Y_I*. In equation form,

$$P(Y_{in} = k) = \Phi(\mu_k - E(Y_{in}^{*})) - \Phi(\mu_{k-1} - E(Y_{in}^{*})) \quad [7]$$

where Φ is the cumulative standard normal distribution function and $E(Y_{in}*) = \vec{X}_{in}'\vec{\beta}$.

The estimation maximizes the loglikelihood function given by:

$$1\mathrm{n}L = \ _{in} \ 1\mathrm{n}L_{in} = \ _{in} \ 1\mathrm{n}[P(Y_{in} = k)] \quad [8]$$

The possible assessments of sidewalks range from “easy to cross” to “appears impassable”—and their five levels represent the dependent, ordinal-response variable. Since our objective is to understand the effects of cross-slope and estimate a maximum reasonable cross-slope, the cross-slope variable plays a critical role among the explanatory variables. Having estimated the threshold bounds (μ_k), the maximum cross-slope is estimated so that:

$$P(\vec{X}_{in}'\vec{\beta} + u_{in} \quad \mu_3) \quad 0.20 \quad [9]$$

—in other words, *no* more than 20 percent of the sidewalk users will feel uncomfortable when they traverse such a cross-slope (since the third threshold indicates a move to the “will take significant effort” response, and the fourth indicates a shift into the “appears impassable” response level). Note that this choice of a 20-percent cutoff is not necessarily optimal; further research on the population of interest (i.e., persons with disabilities who are likely to want to use sidewalks) is needed to justify this assumption.

Data provided by the 1990 National Health Interview Survey’s (NHIS) Assistive Devices Supplement indicate that, of the 6.4 million persons using assistive devices “for getting around,” 79 percent use crutches or canes, 26 percent use walkers, 21 percent use manual wheelchairs, 2 percent use power wheelchairs, and less than 1 percent use scooters (10). In addition, the data indicate that “73 percent of people who use assistive devices are 55 and older.” (11). Bearing these figures in mind, it may be reasonable to advocate a cross-slope value that would be traversable by 80 percent of the assistive device-using population.

EMPIRICAL ANALYSIS

Survey and Sample Description

Analyzed data were collected using two field surveys: one where participants stated their perceptions of ease of sidewalk use before and after crossing various sidewalk sections, and another where their heart-rate changes in response to traversing distinct sidewalk sections were recorded before and after they traversed distinct sidewalk sections.

Survey Population

The greatest obstacle to the completion of this research was the difficulty in recruiting participants. In the process of soliciting participants, sixteen different agencies and organizations were contacted, five public presentations were given (including one televised presentation), and 2,000 pieces of literature were distributed, both through direct mail and through more general marketing methods. While the targeted community seemed to be supportive of the research effort, few of its members participated in the survey process. **Table 1** gives a brief description of the types of persons who did participate in one or more of the surveys.

Respondents to the field survey ranged in age from 27 to 59 years, and included 10 women and 9 men; all were Caucasian. The on-site perception surveys were held in two locations, so as to encourage participation. Some participants volunteered for the heart-rate survey and both perception surveys, providing a total of 10 heart-rate surveys and 22 perception surveys. Each survey involved multiple tests (but a few participants did not perform some of these), so the total number of observations in the perception and heart-rate data sets were 126 and 302, respectively.

Four of those surveyed relied on manual wheelchairs, eight used electrically powered wheelchairs, one used both types of wheelchairs, one used a scooter, two used canes, and one used crutches. On this topic, it should be noted that the geometry of assistive devices can significantly impact a user's response. For example, the location of rear wheels relative to the user's center of gravity will affect turn tendency on cross-slopes. The length and fit of crutches and canes also varies across users, and can impact exertion levels and response. However, none of these details were measured or controlled for in the experiments run here, so the results are for the "average" person and equipment tested of a given disability. With larger samples, such information could be accommodated explicitly.

Field Surveys

Perception surveys were held at locations along bus routes identified as those having high numbers of riders with disabilities. These surveys required the participants to traverse a series of delineated sections with varying cross-slopes and attributes. Participants were instructed to traverse the sidewalk sections at a comfortable pace, pausing as needed and simulating the way they would typically use a sidewalk. Before and after each section,

Table 1.
Participant distribution by type of disability and mobility aid, and by age

Type of Disability and Mobility Aid	Number of Respondents*	Age	Number of Respondents
Blind, Seeing Eye Dog	2	27	1
Cerebral Palsy, Manual Chair	1	28	1
Cerebral Palsy, No Aid	1	32	1
Congenital Heart Disease, Manual Chair	1	35	1
Head Injury, Power Wheelchair	2	41	1
Head Injury, Scooter	2	42	1
Muscular Dystrophy, Power Wheelchair	2	43	2
Cerebral Palsy, Power Wheelchair	1	44	1
Neural MD, Cane	1	45	2
Paraplegic, Manual Chair	2	27	1
Blind, Seeing Eye Dog	1	46	2
Polio, Power Wheelchair	2	29	3
Polio, Manual Chair	1	50	1
Single Amputee, Crutches	1	52	1
Spinal Cord Injury, Power Wheelchair	1	59	1
Visually Impaired, Cane	1		

*Note: One respondent participated using both manual and power wheelchairs, bringing this total to twenty.

the participants' heart rates, and the participants' subjective assessments of the sidewalks, were recorded.

The following variables were observed for each sidewalk section: cross-slope, primary slope, width, length, set-back distance, participant's heart-rate change, and participant's sidewalk assessment. Each participant's age, gender, fitness level, type of disability, type of mobility aid, and resting heart rates were also recorded, as explanatory variables. **Table 2** provides more specific information on these definitions of these variables.

Because ease of sidewalk use is the objective of design standards in this area, the surveys focused on participants' perceived comfort in traversing the sections. However, the research team also hoped to establish a link between perceived comfort (or lack thereof) and physical effort. According to Kirkpatrick and Birnbaum, the most reliable indication of physical effort is heart rate measurement (12). Heart rate increases in a linear fashion in relation to work and oxygen uptake during exercise, and its measurement is therefore an appropriate way to test the correlation between perceived and actual effort (13). However, while heart rates generally increase with work undertaken, participants can vary their pace and thus moderate their heart rates. Athletic-type pulse meters, which measure the blood flow 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 while one's resting heart rate is most accurately measured upon waking, a reasonably close measurement can be taken after having the participant sit quietly for a few

Table 2.
Definitions of dependent and explanatory variables

Variable	Definition
Dependent variables:	
Heart-rate Change	Change in heart rate (beats per minute)
Sidewalk Assessment	1 = Easy to cross, 2 = Pretty easy to cross, 3 = Will take some effort, 4 = Will take significant effort, and 5 = It appears impassable for me
Facility-related explanatory variables:	
Cross-slope	The vertical slope to the guideline of a sidewalk (%)
Primary slope	The main slope along the guideline of a sidewalk (%)
Length	The length of a sidewalk section (m)
Width	The width of a sidewalk section (m)
Set-back	The set-back distance of a sidewalk section (100 m)
Transition	The transition distance between cross-slopes (m)
Traffic volume	The average traffic volume of parallel street (veh/hour)
Speed	The average traffic speed of parallel street (km/hour)
Flare	1 if the sidewalk section has a flare, 0 otherwise
Personal explanatory variables:	
Age	The age of the survey participant
Gender	1 if the participant is a male, 0 otherwise
Manual wheelchair	1 if the participant uses a manual wheelchair, 0 otherwise
Power wheelchair	1 if the participant uses a power wheelchair, 0 otherwise
Cane	1 if the participant uses a cane, 0 otherwise
Crutch	1 if the participant uses a crutch, 0 otherwise
Walker	1 if the participant uses a walker, 0 otherwise
Scooter	1 if the participant uses a scooter, 0 otherwise
Leg brace	1 if the participant uses a leg brace , 0 otherwise
Foot brace	1 if the participant uses a foot brace, 0 otherwise
Artficial leg	1 if the participant uses an artificial leg, 0 otherwise
Low audition	1 if the participant has low audition, 0 otherwise
Physical fitness level	Participant's self-assessed physical fitness level (5-point scale, from 1 = "very out of shape" to 5 = "in great shape")
Frequency	The sidewalk travel frequency of the participant in a week
Travel length	The regular sidewalk travel distance of the participant in a day (km)

minutes—a technique used with this work's participants (12). Moreover, while heart rates stabilize after two minutes of activity, five to six minutes of activity provide the most accurate measure of physical effort (14). Because the first set of perception surveys were designed along actual sidewalks, the individual sections—and the time spent by the participants traversing them—were fairly short in length. These 15 sections provided grades ranging from 0 to 7 percent, cross-slopes between 1 and 12 percent, sidewalk widths between 4 and 16 feet, lengths between 12 and 120 feet, and setbacks (from the street edge) between 0 and 50 feet. They represent actual, street-adjacent sidewalks with traffic and very realistic conditions.

In order to more accurately measure the physical effort associated with various cross-slopes—by means of more stabilized heart rates—the research team developed the second field survey to involve substantially longer sections. A serious obstacle to the project was selection of an easily accessible survey location with enough area to accommodate long sections and enough surface change to provide varied cross-slopes. This proved to be quite difficult, since large, paved lots must be constructed in such a way as to be accessible to disabled users. Ultimately, the selected location (for almost just under half of the perception survey sites and all of the heart-rate surveys) was a church parking lot. This was chosen for its convenience for participants (adjacency to a perception survey site and proximity to many participants' residences) and its provision of variety in grades and cross slopes. However, due to the serious difficulty in finding locations where cross-slopes and grades can be maintained for long distances, the lot's traversable distances may not be as long (and the ranges not as varied) as would be ideal. These tests varied in length, from 125 to 292 feet, and exhibited constant grades, ranging from 0.4 to 4 percent, and constant cross-slopes, ranging from 0.5 to 3.6 percent.

Results

The results of the weighted-least-squared and ordered-probit regressions models, for heart-rate change and sidewalk assessment, respectively, are presented here.

Linear Regression Model with WLS Estimation

As shown in **Table 3**, the weighted and adjusted R^2 value is rather high, indicating that the explanatory variables in the model explain much of the variation in recorded heart-rate changes. The coefficient of distance suggests that the average heart-rate change will increase if the sidewalk section distance increases. The coefficient of age suggests that older users may experience greater change in heart rate than will younger users. The effect of physical fitness level suggests that the higher the level of physical fitness, the less the heart rate increases in response to cross-slopes. The variable of gender, however, was not statistically significant and was removed from the regression.

Table 3.
WLS regression model results

Variable	Coefficients	Standard Error	t-statistic
Primary slope (%)	1.42	6.04	0.23
Cross slope (%)	3.41	7.75	0.23
Distance	0.51	0.12	4.17*
Age	0.58	1.02	0.57
Physical fitness level (1 to 5; 5 = great shape)	-29.34	5.29	-5.54*
Power wheelchair	-35.49	24.16	-1.47
Cane or crutch	62.12	18.65	3.33*
Scooter	-23.82	23.58	-1.01

N = 126, Weighted & Adjusted R^2 =0.780
*Statistically significant at 0.05 level.
Note: Reference disability is "manual wheelchair" and weighting factor is "resting heart rate".

The coefficients of mobility aid types describe the average heart-rate change for each kind of mobility aid without considering the effects of sidewalk characteristics. The related magnitudes of the parameters imply that people using canes/crutches consume more energy than do people using other aid types. As anticipated, the effects of cross-slope and primary slope are positive, suggesting that higher cross-slopes increase heart rates. The relative magnitudes of the coefficients suggest that the effect of the primary slope on heart rates is smaller than that of the cross-slope. However, this difference is not statistically significant (as partially evident via the two variables' weak t-statistics). And, more importantly, the main grade was traversed in both directions during this set of experiments (i.e., both uphill and downhill during each observation recorded); so the opposing grades moderate one another's effects and render the grade variable merely an indication of absolute grade.

It should be noted that without tests of 5 or more minutes duration, heart rates of the participants probably did not stabilize during these experiments. In fact, during short periods of exertion, heart rates often are biased high and the results are likely to suggest more exertion is necessary than would be required under a rate-stabilized scenario. If sites can be found for much longer tests and exertion periods, this weakness of the data could be remedied. Also, because the site used for the heart rate surveys was less than ideal, participants were required to travel along some paths that were perpendicular to the main grade of the area, and some paths that were parallel to the main grade. Additionally, the limited dimensions of this particular site necessitated that they travel out from and back to a point of origin for each section. In such situations, the measured main grades and cross-slopes are highly correlated; thus, the model suffers from multicollinearity. However, because it is believed that the main grade and cross-slope play important roles in producing change in heart rates, these two explanatory variables were retained in the final model and their coefficient estimates should not be biased.

Ordered Response Model

For the ordered probit model, the likelihood ratio index (LRI)—a goodness-of-fit measure very similar to an R^2—is 0.10. Thus, the model specification is useful for predicting user assessment.

From **Table 4** one finds again, as expected, that the effects of primary slope and cross-slope are positive, suggesting an increase in traversing difficulty as the primary slope and/or cross-slope increase. The relative magnitudes of the coefficients suggest that the effect of the primary slope is larger than that of the cross-slope.

Table 4.
Ordered response probit model results

Variable	Coefficients	Standard Error	t-statistic
Primary Slope (%)	0.15	0.03	4.99*
Cross-slope (%)	0.11	0.02	5.84*
Logarithm of Age	1.91	1.57	2.00*
Gender	-0.98	0.17	-5.64*
Physical Fitness Level (1 to 5; 5 = great shape)	-0.20	0.10	-1.93*
Manual wheelchair	0.19	0.16	1.19
μ_1	3.71	2.32	1.60
μ_2	4.32	2.32	1.86*
μ_3	4.82	2.33	2.07*
μ_4	5.82	2.34	2.49*

N = 302, Likelihood Ratio Index (LRI) =0.10
*Statistically significant at 0.05 level.
Note: Reference disability is “cane/crutch.”

The variable of distance traversed was statistically insignificant, suggesting that heart rates may have stabilized before the completion of most of, if not all of, the sections. Due to its insignificance, it was removed from the final regression model (the results of which are shown here).

Among individual-specific variables, the negative coefficient of gender suggests that a male will feel more comfortable crossing a sidewalk section than will a female. The mobility aid variable has positive effects, suggesting that traversing sidewalks will be more difficult for people with manual wheelchairs than for people with this model’s default mobility aid type: cane/crutch. This implication is different from the result of the WLS model, where cane/crutch users experienced greater heart-rate increases. All things considered, a user’s honest perception is probably a more reliable indicator of sidewalk accessibility than heart rate, so one may choose to conclude that manual wheelchair users are the design population for sidewalk cross-slope policy. Moreover, an anonymous reviewer of this work noted that cane/crutch users exhibit very high heart rates during sidewalk ambulation of any kind. Thus, these users’ heart-rate results are likely to be distinctive, particularly at low levels of cross-slope and grade; and the apparent differences in heart-rate and perception results suggested here are probably not contradictory but, rather, expected.

MODEL APPLICATION

WLS Model Application

The WLS regression model can be used to estimate average heart-rate changes for sidewalk users with different disabilities as a function of cross-slope. Since heart rate changes are highly related to energy consumption and therefore indicate the difficulty that people with mobility impairments will face, a maximum desirable cross-slope may be estimated by assuming some critical heart-rate change. While there is no medically proven method for determining this critical range, the accepted method of ascertaining the maximum heart rate for able-bodied individuals is the following (12,16):

$$\begin{aligned} &Female : Max\ Heart\ Rate = 226 - age \\ &Male : Max\ Heart\ Rate = 220 - age \end{aligned} \qquad [10]$$

Journal of Rehabilitation Research and Development Vol. 38 No. 1 2001

The heart-rate target zone for physical training is defined as between 60 percent and 80 percent of one's maximum heart rate (12,13). Note, however, that these heart-rate equations and target zones may not be highly reliable for individuals with physical disabilities or those performing special tasks (for example, significant arm exercise in the propulsion of manual wheelchairs). Ideally, peak heart rates for individual participants may be predicted by collecting individuals' heart-rate data across a series of workload tests. These values could then be used to more reliably ascertain critical heart-rate levels and changes.

Based on the test sample (age and resting heart rate) and assuming 80 percent of the age-adjusted maximum heart rate to be the critical upper level of heart rate change here, the average critical heart rate change—as a response to traversing varying cross-slopes—is about 75 percent. Similarly, use of 75 percent of the maximum heart rate as the critical upper level results in an average critical heart rate change of about 60 percent for the test-sample subjects.

Table 5 illustrates several different cases that were calculated by inputting these 75 percent and 60 percent heart-rate changes. As Case 8 illustrates, for a person who uses a cane or a crutch, who is in the middle category of physical fitness, and who traverses a 15-m (50-ft) sidewalk section with a 5-percent primary slope, the critical cross-slope is about 5.3 percent. This percentage is greater than that of the current ADAAG requirement. If the sidewalk section is as long as 45 m (150 ft), the maximum cross-slope for a manual wheelchair user in the middle fitness category is estimated to be 8.5 percent.

Two points bear mention here; these have to do with choice of an acceptable threshold for heart-rate changes and the heart-rate response of the population of interest. While 75 percent may be an acceptable target zone for training or exercise, it may be higher than acceptable for persons negotiating sidewalks simply for reasons of access to activities and services. Additionally, the heart-rate responses of persons with mobility impairments may be very different from those of others. An anonymous reviewer suggests that such persons' responses tend to be high even at low levels of cross-slope and grade. Strong evidence for use of a specific threshold is not available to the authors, so 75 percent was used here. However, a different threshold can be used. Given such a number, this work illustrates application of a valuable methodology for assessing critical design features.

When researching sidewalk accessibility issues, it may be most appropriate to consider those who face the greatest difficulty navigating, who use a specific aid on a consistent, long-term basis, and who desire to use sidewalks most regularly. Some anecdotal and analytical evidence suggests that manual wheelchair users may best fit this description. (For example, the crutch user in this survey commented that she would be obtaining a prosthetic device in the near future and would then no longer use crutches; and another respondent falling in the NHIS crutch-and-cane category explained that he uses a cane occasionally, but prefers to go without it. Moreover, as indicated in **Table 4**, the perception surveys suggest that manual wheelchair users have the most difficulties navigating sidewalks.) However, different disabilities may engender different thresholds and responses to distinct variations in design. For example, cane and crutch users may be particularly conscious of travel distances, while wheelchair users may be more sensitive to main grades. More information is needed on these topics.

Ordered Probit Model Application

The ordered-response model of sidewalk assessments can be used to examine how changes in sidewalk facility characteristics impact sidewalk users with disabilities. This section demonstrates the application of the model by estimating the maximum cross-slope that can be applied to

Table 5.
Case study using the WLS model results

Variables	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Primary Slope (%)	0	5	0	5	0	5	0	5
Distance	15 m	15 m	30 m	30 m	45 m	45 m	15 m	15 m
Physical fitness level (3 = "average shape")	3	3	3	3	3	3	3	3
Power wheelchair	0	0	0	0	0	0	0	0
Manual wheelchair	1	1	1	1	1	1	0	0
Cane or crutch	0	0	0	0	0	0	1	1
Scooter	0	0	0	0	0	0	0	0
Critical cross-slope (%)	25.7	23.6	18.1	16.0	10.5	8.5	7.4	5.3

sidewalk-construction standards with regard to people with mobility impairments.

Assuming that the critical slope can be calculated as a threshold measurement at which no more than 20 percent of sidewalk users with disabilities will feel that the section is difficult to cross, inputting different personal and facility characteristics yields maximum cross-slope values for each situation. For example, using both gender variables and sidewalk primary slopes of 0 percent and 5 percent—and assuming sample-average values for other variables—eight cases can be calculated (**Table 6**).

These results suggest that the critical cross-slope for 60-year-old manual wheelchair users is about 2.2 percent when the primary slope of the sidewalk is about 5 percent, and 9 percent when the main grade of the sidewalk is 0 percent. Considering that the average age of the test sample is 40 years (with a standard deviation of about 10), the resulting critical cross-slopes for 0 percent and 5 percent main grades are 12.1 percent and 5.3 percent, respectively. These thresholds are significantly higher than the ADAAG cross-slope standard of 2 percent. Moreover, an assumption of the disability aid being cane or crutch would further raise the critical levels of cross-sloping, according to this model.

SUMMARY AND CONCLUSIONS

This research illustrates the use of two statistical methods for assessing the accessibility of different sidewalk designs for persons with disabilities. The findings are preliminary, but they do suggest that an ADA-based 2-percent maximum cross-slope may be too conservative for most disabled users, particularly in relatively short sections where terrain and/or other conditions do not permit such gradual slopes. In determining whether to adhere to the 2-percent maximum cross-slope requirement under unfavorable site conditions, transportation agencies may face a tradeoff involving risk of costly lawsuits. However, liability should be low when travelways are designed and constructed according to guidance that is based on solid scientific research. Supporting research into sidewalk cross-slope accessibility demonstrates a "good faith effort" on the agency's part, and should offer some protection against legal liability (15).

The experimental research detailed in this paper was conducted in order to estimate maximum and desirable limits for sidewalk cross-slope at driveway crossings. Research was conducted using WLS regression of disabled-user heart-rate data and an ordered-probit model for response to sidewalk characteristics; and, as illustrated, the results of these models permit estimation of maximum sidewalk cross-slopes for specific user cases and are consistent with the intent and spirit of ADA.

Persons using different types of mobility aids and having different levels of functional ability are capable of traversing a range of cross-slopes. While many of those with disabilities who were sampled here are able to traverse sidewalks having up to a 20-percent cross-slope, many are not. In recognition of the tradeoff between construction feasibility and user comfort, a 10-percent maximum cross-slope may be recommended, based on this research. Such a slope is estimated to preclude the use of those who describe themselves as being in very poor physical shape. However, anecdotal evidence gathered in this study suggests that persons in this category either do not rely on sidewalks to meet their daily travel needs or do not normally rely on their own propulsion when traveling on sidewalks. In order to accommodate the largest number of possible users, a 4-percent maximum cross-slope is recommended. Where a 4 percent maximum is not feasible and the primary slope is less than 5 percent, a 10-percent maximum cross-slope appears to be very reasonable. However, if variations due to imperfect construction are likely to lead to much higher in-place

Table 6.
Case study using the ordered probit model results

Variables	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8
Primary Slope (%)	0	5	0	5	0	5	0	5
Age	30	30	40	40	50	50	60	60
Gender	Female	Female	Female	Female	Female	Female	Female	Female
Physical fitness level (3 = "average shape")	3	3	3	3	3	3	3	3
Manual wheelchair	1	1	1	1	1	1	1	1
Cane & Crutch	0	0	0	0	0	0	0	0
Cross-slope (%)	14.3	7.4	12.1	5.3	10.4	3.6	9.0	2.2

slopes, engineers and planners may need to specify something less than these maxima in order to ensure that actual construction practices deliver accessible sidewalks.

In addition to maximum accessible cross-slopes, this research also yields design guidelines. As illustrated by the ordered-probit model results (**Table 4**), the most easily accessible sidewalks are those where cross-slope is minimized, and width is maximized. The demonstrated relationship between the increase in heart rate and the increase in cross-slope further supports this recommendation (**Table 3**). Because of sample-size limitations and other experimental issues, this work may be viewed as a prototype. Larger sample sizes, longer heart-rate tests, and a stronger recognition of the population of interest are necessary before definitive, legislated maxima can be ascertained. However, the models and methods applied should be of significant use to the rehabilitative research and development community.

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REFERENCES

1. Access Board. Americans with Disabilities Act (ADA) Accessibility Guidelines for Buildings and Facilities; State and Local Government Facilities. Interim final rule. U.S. Architectural and Transportation Barriers Compliance Board, Washington, DC, 59 FR 31676, June 20, 1994.
2. Taylor D, Kockelman K, Heard L, Taylor B, Zhao Y. Review of methods formeeting the American with Disabilities Act sidewalk cross-slope requirement. Center for Transportation Research, The University of Texas at Austin, for the Texas Department of Transportation; 1999.
3. Chesney DA, Axelson PW. Preliminary test method for the determination of surface firmness. IEEE Transactions on Rehabilitation Engineering 1996;4(3):182–7.
4. Cooper RA. Racing wheelchair crown compensation. J Rehabil Res Dev 1989;26(1):25–32.
5. Kinney v. Yerusalim [CA 3 1993], cert. Denied, Hoskins v. Kinney, No. 93-1439 [US SupCt 4/18/94]; Helen L. v. DiDario [CA3 1995]; and L.C. v. Olmstead, No. 1:95-CV-1210-MHS [DC NGa 3/26/97].
6. Axelson P, Kirschbaum J, Wong K. Access for everyone: meeting the ADA. Conference Proceedings: Bicycle Federation of America, Washington, DC; 1998. p. 181–5.
7. Oberhofer W, Kmenta J. General procedure for obtaining maximum likelihood estimates in generalized regression models. Econometrica 1994;42:579–90.
8. McKelvey RD, Zavoina W. Statistical model for the analysis of ordinal level dependent variables. J Math Sociol 1975;4:103–20.
9. Maddala GS. Limited-dependent and qualitative variables in econometrics. New York: McGraw-Hill; 1983. p. 47.
10. National Center for Health Statistics. 1990 National Health Interview Survey [CD-Rom Series 10, No.4]. Hyattsville, MD: Public Health Service; 1993.
11. Jones ML, Sanford JA. People with mobility impairments in the United States today and in 2010. Assist Technol 1997;45–7.
12. Kirkpatrick B, Birnbaum BH. Lessons from the heart: individualizing physical education with heart rate monitors. Human Kinetics. Champaign, IL; 1997.
13. American College of Sports Medicine. ACSM's resource manual for guidelines for exercise testing and prescription (3rd ed.). Baltimore: Williams and Wilkins; 1998.
14. Astrand P, Rodahl K. Textbook of work physiology. New York: McGraw-Hill; 1970. p. 620–1.
15. Miller v. City of Johnson City, Tenn. [DC ETenn 1996].
16. Chilton L. Personal interview. July 23, 1999.

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