Building the Methods

Walking and Bicycling: An Evaluation of Environmental Audit Instruments

Anne Vernez Moudon, Chanam Lee

Abstract

Purpose. *This paper reviews existing environmental audit instruments used to capture the walkability and bikability of environments. The review inventories and evaluates individual measures of environmental factors used in these instruments. It synthesizes the current state of knowledge in quantifying the built environment. The paper provides health promotion professionals an understanding of the essential aspects of environments influencing walking and bicycling for both recreational and transportation purposes. It serves as a basis to develop valid and efficient tools to create activity-friendly communities.*

Data Sources. *Keyword searches identified journal articles from the computer-based Academic Citation Databases, including the National Transportation Library, the Web of Science Citation Database, and MEDLINE. Governmental publications and conference proceedings were also searched.*

Study Inclusion and Exclusion Criteria. *All instruments to audit physical environments have been included in this review, considering both recreation- and transportation-related walking and bicycling. Excluded are general methods devised to estimate walking and cycling trips, those used in empirical studies on land use and transportation, and research on walking inside buildings.*

Data Extraction Methods. *Data have been extracted from each instrument using a template of key items developed for this review. The data were examined for quality assurance among three experienced researchers.*

Data Synthesis. *A behavioral model of the built environment guides the synthesis according to three components: the origin and destination of the walk or bike trip, the characteristics of the road traveled, and the characteristics of the areas surrounding the trip's origin and destination. These components, combined with the characteristics of the instruments themselves, lead to a classification of the instruments into the four categories of inventory, route quality assessment, area quality assessment, and approaches to estimating latent demand for walking and bicycling. Furthermore, individual variables used in each instrument to measure the environment are grouped into four classes: spatiophysical, spatiobehavioral, spatiopsychosocial, and policy-based.*

Major Conclusions. *Individually, existing instruments rely on selective classes of variables and therefore assess only parts of built environments that affect walking and bicycling. Most of the instruments and individual measures have not been rigorously tested because of a lack of available data on walking and bicycling and because of limited research budgets. Future instrument development will depend on the acquisition of empirical data on walking and bicycling, on inclusion of all three components of the behavioral model, and on consideration of all classes of variables identified. (Am J Health Promot 2003;18[1]:21–37.)*

Key Words: Travel-related and Recreation-related Walking and Bicycling, Biking, Physical Environmental Factors, Environmental Audit Instruments, Prevention Research

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INTRODUCTION

This paper reviews existing audit instruments used to capture community-level physical environmental factors affecting walking and bicycling. An environmental audit instrument is defined as a tool used to inventory and assess physical environmental conditions associated with walking and bicycling. Applications of such instruments span from research on environmental determinants of active living to policies promoting environments that support walking and bicycling. This review inventories and evaluates individual measures of the built environment used in existing audit instruments. It synthesizes the current state of knowledge in quantifying the built environment and provides health promotion professionals an understanding of the essential aspects of environments influencing walking and bicycling for both recreational and transportation purposes.

Physical inactivity is one of the major preventable health risks among the U.S. population. Over 60% of American adults do not engage in the recommended amount of physical activity.[1] In recent years, community-based interventions targeting moderate and enduring physical activity have received growing attention from the public health sector. As activities easily integrated into the routine of everyday living, walking and bicycling have been understood as more likely to induce frequent, regular, and habitual physical activity than structured types of exercise. In addition, they are relatively easy to perform by and economical to a majority of the population, regardless of age, gender, and socioeconomic status.[2]

Walking and bicycling are also viable means of transportation that offer benefits beyond health gains, such as reduced traffic congestion and air pollution. The potential for increasing the amount of walking and bicycling for transportation purposes is significant. Over 90% of trips taken are made by automobile, yet 27% of these trips are less than 1.6 kilometers (1 mile), a comfortable walking distance, and an additional 13% are less than 3.2 kilometers (2 miles), well within a comfortable cycling distance.[3] Community-based intervention strategies targeting walking and bicycling for both recreation and travel thus hold the potential to increase levels of physical activity.

During the past decade, the potential role of physical environments to promote active living has received increased attention in research, intervention strategies, and advocacy efforts. The quality of the built environment and patterns of development are generally considered major determinants of physical activity. A small number of studies provide empirical evidence of environmental determinants of physical activity, to include: proximity to recreational facilities,[4,5] presence of barriers and facilitators,[4,6–8] and perceived neighborhood characteristics.[6,7,9,10] As indicated in these studies, however, measures and models of physical environments are only at a beginning stage of development in the public health field. Establishing valid and efficient measures and models of the built environment is a key prerequisite to the advancement of future research in this area.

This review first discusses theoretical frameworks that guide the classification of environmental audit instruments. Second, it reports on methods used to identify existing environmental audit instruments in the fields of transportation planning and engineering, urban design and planning, and public health. Third, the review of findings explains the scope of environmental audit instruments and identifies the variables used to define environmental factors. Discussions follow regarding the instruments' relative inclusiveness in capturing the characteristics of the built environment that affect walking and bicycling. Finally, suggestions about directions for future research and instrument design are made.

THEORETICAL FRAMEWORKS

Theories or models of health behavior that serve as a basis for physical activity research and promotion strategies are well-documented.[1] Ecological approaches have provided useful frameworks for community-based environmental approaches. However, most of these theories tend to emphasize intra- and interpersonal determinants of physical activity, but not physical environmental factors. In an attempt to bridge this gap, a behavioral model of environments is presented to help identify and structure the types of variables defining environments for walking and bicycling. Also discussed are the corresponding types of spatial data models needed to measure physical environmental variables and the scale at which the data need to be collected and analyzed.

A Behavioral Model of Environments

Past transportation research has identified determinants of walking and bicycling as (1) intra- and interpersonal factors, (2) environmental factors, and (3) trip characteristics (defining the purpose and length of the trip).[11] All three levels of determinants interact in complex ways to affect the decision to walk or bike. Most environmental audit instruments address environmental factors and trip characteristics, but only a few include personal determinants for specific populations, such as age and cycling skill level.

A behavioral model of environments helps define and analyze environmental determinants of community walkability and bikability. This model rests on the general construct of interactive relationships between human behavior and human environments.[12] In this construct, human environments are understood as ''bricks and mortar,'' or spatiophysical entities shaped by social systems. As such, environments are sociophysical entities, both shaped by and shaping behavior. Environmental audit instruments necessarily focus on the spatiophysical aspects of environment (e.g., recording the presence or absence of sidewalks, and the characteristics of sidewalks). Yet spatiobehavioral and spatiopsychosocial aspects also need to enter the model because of the interactive nature of the relationship between the world of bricks and mortar and that of behavior. Spatiobehavioral factors concern the types and intensity of human uses in the physical environment, captured by volumes of pedestrians, bicyclists, and drivers, and safety issues related to physical conflicts among users. And spatiopsychosocial attributes originate from people's internal response to being in a physical environment, such as perceived comfort, attractiveness, safety, and so on.

Applied to walking and bicycling, this behavioral model consists of three components of environment (Figure 1).[13]

1. The* Origin *and* Destination *of the Walk or Bike Trip. These are spatiophysical and spatiobehavioral aspects that define trip *purpose*. Variables that define trip origin and destination ensure that the audit instrument records *where* people walk and bike. In the realm of physical activity, walk and bike trips can be either recreation/exercise- or transportation-related. Points of origin and destination are different for transport, but can be the same for recreation or exercise (as, for example, in walking ''around'' the neighborhood).

2. The Characteristics of the* Route *Taken for These Trips. These include spatiophysical aspects, such as distance between origin and destination or the design of the roadway, and spatiobehavioral aspects, such as the number of cars, bicycles, or people on the roadway. Trip distance is a defining factor for selecting slow modes of transport, whereas route characteristics (including the characteristics of vehicular traffic along the route) define the *quality* of the route and affect primarily the *safety, comfort, experi-*

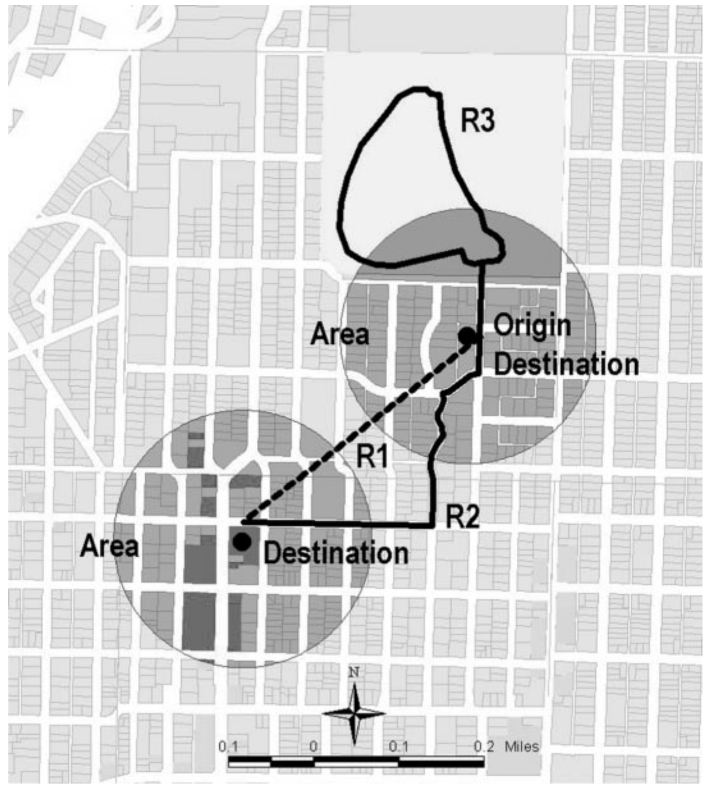
ence, and *perception* of walkers and bicyclists.

3. The Characteristics of the* Area *in Which the Trip Takes Place. These include spatiophysical aspects of the environment, such as the types and the intensity of uses of land (as proxies for activities that take place and their intensity) and the networks of streets (as proxies for choice in moving through space). Area characteristics affect primarily the actual or potential *volumes* of pedestrians and bicyclists, route choices, as well as the availability of alternative means of transport. They begin to address *why* people walk or bike for transportation purposes.

All three components of the behavioral model of environments must be considered to measure comprehensively the effect of the environment on walking and bicycling for transportation. For example, sidewalks as characteristics of the route traveled are a welcome support for pedestrians only if they link the pedestrian trip origin with a destination. Furthermore, they will support a substantial number of pedestrians only if they link origin and destination points that have a substantial number of people around them. Hence, although the presence of origin and destination points, the quality of the route, and the number of people and activities in an area are, individually, necessary, they are not sufficient conditions for travel. For recreational walking and bicycling, the origin and destination component of the environment might not be as important as the other two components because the focus is not so much on reaching a certain destination as it is on being engaged in the act of walking and bicycling. Walking and bicycling for transportation, on the other hand, command complex physical environmental conditions because they combine travel and exercise, thus making the activity attractively multifunctional. Ideally, audit instruments will include variables that measure elements in all three components of the model.

Figure 1

Behavioral Model of Environment



R1: Airline Route to Destination
R2: Street Network Route to Destination
R3: Recreation Route

Spatial Data Models

The three components of the behavioral model of environments correspond to three basic data models to capture spatial data: *points* (e.g., origins and destinations), *lines* (route segments or networks), and *polygons* (areas).[14] As shown in Figure 1, lines capture those parts of the environment where movement of people (and goods) occur, whereas points and areas refer to specific activities or groups of activities. Lines (single routes represented by segments) and networks (multiple intersecting routes) thus correspond to routes used for walking and bicycling, whereas points and areas correspond to the characteristics of the environment at and around the origins and destinations of trips. Networks focus on connections and continuities between routes. Areas or polygons range widely in scale from parcels to planning areas or zones, neighborhoods, districts, cities, and regions.

Understanding and analyzing walking and cycling behaviors typically requires the use of several of the data models described above.

Scales Used for Data Collection and Analysis

Capturing the environment with sufficient detail is essential. Because people on foot or on a bicycle move relatively slowly through the environment (a 1-minute walk at average speed covers 264 feet or about 80 meters), they are afforded an intimate experience of the environment around them that affects where and how long they choose to walk or bike. The scales of environments considered for walking and bicycling range from the immediate surrounds of the pedestrian(s) or the bicyclist(s) to the larger areas that they experience or ''practice'' during the course of a trip.

Two aspects of scale matter for capturing data on environmental factors and to carry out analyses of behavior. First is the *resolution* of the data, which refers to the relative precision in the measurement of environmental factors. These measurements vary according to the ratio of map distance to earth distance used in the investigation. Second is the *extent* of the geographic area under consideration.

Data resolution of environments experienced at slow speeds is fine-grained to include, for example, trees and other landscape features along the route, and perhaps also the types and conditions of building and infrastructure materials touched, seen, and generally sensed by pedestrians and bicyclists. Collecting such fine-grained or microscaled data is typically difficult or onerous. Unfortunately, a general lack of empirical knowledge on how fine the grain of such data needs to be has lead researchers to select the level of data resolution based on budget limitations and data availability.

The extent of the area considered for analysis should include at least the length of the walking or cycling trips taken. Average distance covered is approximately 1 kilometer (0.62 mile) for pedestrians, and varies from 2 kilometers (1.24 miles) to over 6 kilometers (3.73 miles) for bicyclists.[15–18] Overall, the fine-grained detail at which pedestrians and, to a lesser extent, bicyclists experience the environment, combined with the relatively small extent of areas covered by walking and cycling trips, demand the use of spatial units of analysis that are smaller than those typically used in past car-oriented transportation and health research. Changing scale both in terms of area extent and grain size (resolution) can have a considerable effect on measures of environments.[19,20]

METHODS

Data Sources

Sources for identifying audit instruments ranged from academic literature databases to Web-based sources. Academic Citation Databases included the National Transportation Library (TRIS Online),[21] the Web of Science Citation Database, and MEDLINE. Key words used for the literature search were audit, measurement, tool, instrument, assessment, environment, physical activity, exercise, environmental determinant, and physical environment. Audit instruments were also identified from review articles, conference proceedings, personal communications, and governmental publications, such as the Federal Highway Administration publications and the Centers for Disease Control and Prevention (CDC). The initial literature search was conducted between March and May 2001 and updated periodically until May 2002.

Inclusion and Exclusion Criteria

Instruments to audit physical environments included in this review come from the fields of urban design and planning, transportation, and health. They are described in articles or written documents extracted from the literature search using the various sources mentioned earlier. This review includes instruments that consider recreation/exercise- and transportation-related walking, bicycling, or both. Excluded are general methods devised to estimate walk and bike travel that do not qualify as audit instruments[11] and methods used in empirical studies of land use and transportation that not only do not qualify as audit instruments[22] but also focus primarily on vehicular travel behavior. However, findings from these types of research are discussed, in so far as they inform the relative predictive power of environmental variables used to construct audit instruments.

This review excludes a fairly large body of literature on instruments and methods to capture environments devised for general research on behavior-environment and, specifically, on such topics as environmental cognition, perception, and preferences.[23–27] Because this review focuses on tools for auditing communities or neighborhoods for their walkability and bikability, research on walking and bicycling in interior places (gyms, airports, or malls) or in wilderness or open space outside of towns, cities, or metropolitan areas is not considered either.

Data Extraction and Synthesis

Variables appearing in the selected instruments to define environmental factors affecting walking and bicycling are extracted using the exact words and definitions whenever possible. Only occasional minor changes to the wordings were necessary to make the review consistent and cohesive. Variables are grouped on the basis of spatiophysical, spatiobehavioral, and spatiopsychosocial aspects of environment-behavior interrelationships. They are also classified by components of the behavior model of environments for walking and bicycling described earlier.

RESULTS

Table 1 lists the 31 instruments reviewed and summarizes the topics that structure this evaluation. The results of the evaluation are discussed in two parts: the scope of environmental audit instruments, defining their contents on the basis of 10 characteristics discussed individually, and variables used to define environmental factors, inventorying variables and data sources used in the instruments to capture environmental factors affecting walking and bicycling.

Scope of Environmental Audit Instruments

Previous reviews of environmental factors for walking and bicycling include that of Turner et al.,[28] who concentrated on environmental audit instruments for walking and bicycling as a means of transportation only, and that of the Federal Highway Administration,[11] which evaluated available methods to estimate demand for nonmotorized travel. The treatment of environmental factors in these latter methods varies significantly depending on the scale at which demand is considered (e.g., regional to local), the particular focus of the method (e.g., oriented toward travel demand vs. the supply of transportation facilities), the data used (e.g., travel data versus preference surveys), and so on. Cross-checking, as part of this review, of physical environmental variables used in audit instruments with those used in methods to estimate demand for nonmotorized travel confirms that audit instruments are inclusive of all variables assumed to be associated with, or to contribute to, the prediction of levels of walking and bicycling.

The following discussion highlights the characteristics of the instruments shown in columns 1 through 10 of Table 1.

Instrument Date, Type, and Field of Origin. Instrument Characteristics numbered 1 through 3 in Table 1 indicate the date that the instrument was published; whether the instrument addresses walking, bicycling, or both; and its field of origin. Most instruments date from the 1990s. Those included that precede this date are considered because they have had an effect on the next generation of instruments or because they have features not present in other instruments.

Most instruments treat environments for walking and bicycling separately. Dixon-LOS[29] and the DOT's checklists, DOT-WC[30] and DOT-BC,[31] use similar concepts for separate instruments that in effect "pair up" environments relating to the two modes of travel. Instruments from transportation and urban design and planning seek to address only the transportation dimension of walking and bicycling. Coming from the field of health, Pikora-SPACES[32] and Anderson-EI[33] address physical activity and aim at both the recreation/exercise and transportation components of walking and bicycling.

Purpose. Four categories frame the purposes for which the instruments are created (Instrument Characteristic 4 in Table 1). The first category includes those instruments designed to conduct inventories of environment for research (IN) and contains two instruments. The eventual outcome of the research is to identify the amount of walking and bicycling that individuals do for both transport and recreation. Pikora-SPACES[32] is called a "scan" because it provides checklists for field data collection. It is an inventory of roadway characteristics as well as elements of the environment immediately along the roadway. Data are collected for a "neighborhood" defined within 400 meters of the subject's residence and entered by street segment. There are no spatiobehavioral data related to vehicular traffic which could affect the walking and cycling environment. The data collection process for these instruments is relatively simple, but time consuming.

Route quality assessment tools (RQ) constitute the second category, containing 15 instruments, all emanating from transportation engineering. They seek to measure and rank roadway design for walkability and bikability (dependent variable). Assessments are based on the pedestrian's and bicyclist's perception of safety and comfort. Most of these instruments use roadway segments and intersections as units of analysis, but some include network data models. Field data collection is made easy because most instruments focus on relatively short street segments. Two instruments focus on paths that are separate from automobile facilities. Botma-LOS[34] concentrates on bicycle paths in Dutch cities but considers also possible conflicts with pedestrians. Bandara-GSPCS[35] deals with "skyways" or elevated pedestrian paths that can be found in a number of northern U.S. and Canadian cities.

The third category, area quality assessment tools for policy and planning (AQ), contains 11 instruments, only one of which applies to bicycling. These focus on assessing the qualities of areas to support urban transportation planning policies that vie to increase walking and bicycling as a means of transport. All these instruments are applied to areas of cities and towns where either walking or bicycling already takes place or urban planning policies encourage their taking place in the future. The instruments' primary purpose is to find areas with the greatest overall volumes of pedestrians and bicyclists (dependent variable) and to ensure their safety and comfort. Processes of data collection and analysis range from simple to complex. Some instruments rely on simple surveys to be filled in by the residents of specific neighborhoods or districts, whereas others depend on complex databases of type and intensity of land uses, street networks, road characteristics, and so on, as well as field-collected data. Portland-PEF[36] precedes the other three Portland instruments, which include a hands-on approach to identifying areas for walking, an analytical approach to do so, and a hands-on approach to identify barriers to walking, respectively. Moudon's instruments include two data-driven approaches to identify areas for walking (Moudon-PLL-1[13] and Moudon-PLL-2[13]) and one decision support tool to prioritize improvement investments for nonmotorized transportation facilities (Moudon-PIP[37]).

Three other instruments fall into the last category, focused on estimating latent demand (LD) for walking and bicycling as modes of travel. Of the large number of research projects to estimate nonmotorized transport,[11] only those that are readily usable tools to quantify walking and cycling travel at the neighborhood level are included. The primary dependent variable is the potential volumes of pedestrians and bicyclists. These instruments attempt to circumvent the paucity of data on these means of travel and use two kinds of proxies to estimate demand: data on vehicular traffic counts and transportation mode share ratios, and environmental factors defined as attractors and generators of walking and cycling travel. They borrow concepts of land use types as attractors and generators of pedestrian and bike travel from the Institute of Transportation Engineers (ITE) standards,[38] which define the number of trips associated with certain land uses. Mode share ratios are then applied to ITE trip generation standards for each trip purpose, adjusted by a distance probability factor.[39] One data limitation of these instruments is that available mode share ratios underestimate walk trips because they are computed for areas much larger than those covered by walk trips.

The different primary dependent variables behind the construction of

Table 1

Summary of Environmental Audit Instruments Reviewed

		Instrument Characteristics*										
		1	2	3	4	5	6	7	8	9	10	
Instrument ID	**Instrument Name**	**D**	**T**	**F**	**P**	**LOS**	**DM**	**UA**	**TC**	**A**	**IU**	**Comments**
Allan-WPI[57]	Walking permeability indices	01	W	T	AQ	N	P, L	N	N/A	Y	PT	Measures of route directness between key origins and destinations in a city. Physical and time distances considered.
Bandara-GSPCS[35]	Grade-separated pedestrian systems	94	W	T	RQ	N	P, L	N	Y	Y	PT	Gravity model that compares distance between selected land uses on grade-separated systems and on street.
Botma-LOS[34]	Bicycle path level of service	95	B	T	RQ	Y	L	N	?	?	PT	Ranking of bicycle paths and trails based on bicyclist and pedestrian behaviors. Method used to validate audit and ranking not explained.
Bradshaw-WI[58]	Walkability index	93	W	P	AQ	N	A	A	N	Y	PP	Simple assessment of land use and transportation facilities in neighborhood. Complemented by survey of resident's attitudes about safety.
Anderson-EI†[33]	Measuring environmental indicators	02	W/B	H	IN	N	L	S	Y	Y	R	Inventory of elements of the environment on and along the roadway. Adapted from Pikora-SPACES.
Dixon-LOS (Bike)[29]	Bicyclist performance measures	96	B	T	RQ	Y	L	S	Y	Y	PT	Ranking of road segments based on roadway characteristics and traffic conditions. Method used to validate audit and ranking not explained.
Dixon-LOS (Ped)[29]	Pedestrian performance measures	96	W	T	RQ	Y	L	S	Y	Y	PT	As above.
DOT-BC[31]	Bikeability checklist	N/D	B	T	AQ	N	N/A	A	N	?	N	Simple survey of neighborhood characteristics for lay communities.
DOT-BCI[45]	Bicycle compatibility index	98	B	T	RQ	N	L	S	Y	?	PT	Ranking of road segments based on roadway characteristics and traffic conditions. Model tested on 200 subjects using concept of "comfort level." $R^2 = 0.89$. Elaborate guide available to use method.
DOT-WC[30]	Walkability checklist	N/D	W	T	AQ	N	N/A	A	N	?	N	Simple survey of neighborhood characteristics for lay communities.
Eddy-LOS[59]	Level of service for bicycle use	96	B	T	RQ	Y	L	S	N	Y	PT	Simple formula to rank road segments based on roadway characteristics and traffic conditions. Method used to validate audit and ranking not explained.
Ercolano-Sketch-plan[60]	Pedestrian sketch-plan method	97	W	T	LD	N	L	N	Y	?	PT	Method to identify walk trips based on vehicular trips (access and egress from cars) and land use patterns. Actual and latent demand derived for route segments (from vehicular traffic counts) and for areas (from land use).

Table 1

Continued

Instrument ID	Instrument Name	Instrument Characteristics* 1 D	2 T	3 F	4 P	5 LOS	6 DM	7 UA	8 TC	9 A	10 IU	Comments
FDOT-LOS[61]	Florida pedestrian level of service	01	W	T	RQ	Y	L	S	Y	Y	PT	Ranking of road segments based on roadway characteristics and traffic conditions. Model calibrated and tested on 75 subjects for perception of safety and comfort.
Fort Collins-LOS[62]	Pedestrian level-of-service	N/D	W	P	AQ	Y	A	S	?	Y	PT	Simple assessment of roadway characteristics, visual interest of environment, and sense of security. LOS for a given area yielded from the ranking. Target LOS provided for different types of pedestrian planning areas and corridors.
Khisty-PM[42]	Qualitative level of service	94	W	T	RQ	Y	L	S	Y	?	PT	Performance measures of pedestrian's perception of safety, security, comfort, convenience, attractiveness, way-finding, and continuity.
Landis-BLOS[44]	Bicycle level of service	97	B	T	RQ	Y	L	S	Y	Y	PT	Ranking of road segments based on roadway characteristics and traffic conditions. Model calibrated and tested on 150 subjects for levels of ''perception'' in real time.
Landis-IHS[63]	Bicycle interaction hazard score	96	B	T	RQ	N	L	S	Y	Y	PT	Ranking of road segments based on roadway characteristics and traffic conditions. Model calibrated and tested via consensus groups and interviews.
Landis-LDS[64]	Latent demand score	96	B	T	LD	N	P, L	N	Y	Y	PT	Latent demand for bicycle trips along corridors based on trip purpose and proximity of generators/attractors.
Mescher-Delphi[65]	Internet-based Delphi technique with GIS	96	B	T	RQ	N	L	N	Y	Y	PT	Method to define and weigh criteria to select bike routes. Applied in GIS to identify optimal bike routes.
Moudon-PIP[66]	Pedestrian infrastructure prioritization decision system	01	W	P	AQ	N	P, L, A	A	N	?	PP	Comprehensive checklist of environmental factors and related policies to be considered in prioritizing pedestrian infrastructure investments. Weights to be assigned to checklist items according to local priorities.
Moudon-PLI_1[13]	Pedestrian location identifier 1	01	W	P	AQ	N	A	A	Y	Y	PP	Land use type, intensity, and proximity analysis to identify areas with potential for pedestrian travel. Based on Census and aerial photography data.
Moudon PLI_2[13]	Pedestrian location identifier 2	01	W	P	AQ	N	A	A	Y	Y	PP	As above, using local GIS databases.
Pikora-SPACES[32]	Systematic pedestrian and cycling environmental scan	01	W/B	H	IN	N	L	S	Y	Y	R	Inventory of elements of the environment on and along the roadway.

Table 1

Continued

Instrument ID	Instrument Name	Instrument Characteristics* 1 D	2 T	3 F	4 P	5 LOS	6 DM	7 UA	8 TC	9 A	10 IU	Comments
Portland-PDI[40]	Pedestrian deficiency index	98	W	P	RQ	N	L	S	Y	Y	PP	Ranking of street segments in areas with pedestrian-supportive environment based on checklist of roadway characteristics.
Portland-PEF[36]	Pedestrian environmental factor	93	W	P	AQ	N	P, L	A	Y	Y	PP	Assessment of areas with deficient pedestrian environment based on checklist of roadway and network characteristics.
Portland-PPI (1)[40]	Pedestrian potential index	98	W	P	AQ	N	P, L	A	Y	Y	PP	Checklist of land use types and street network characteristics to identify areas with potential for pedestrian travel.
Portland-PPI (2)[40]	Pedestrian potential index	98	W	P	AQ	N	P, L, A	A	Y	Y	PP	Analyses of land use types and intensity, and network characteristics to identify areas with potential for pedestrian travel.
Sorton-Walsh-BSL[67]	Bicycle stress level	94	B	T	RQ	N	L	S	Y	Y	PT	Bicycle compatibility roadway design. Preliminary analysis of roadway characteristics and traffic conditions for association with bicyclist ''stress level.'' Tested on 61 subjects watching tapes of roadway segments.
Teichgraber-Demand[68]	Latent bicycle traffic demand	83	B	T	LD	N	L	A	?	Y	R	Survey of cycling behavior correlated with access to bikeways. Minimal consideration and measurement of access to bikeways.
WA-LOS[69]	Pedestrian level of service	01	W	T	RQ	Y	P, L	S	Y	?	PT	Level of service based on design, location, and user factors; designed to audit road segment.
Wellar-BWSI[70]	Basic walking security index	00	W	T	RQ	N	L	S	Y	Y	PT	Ranking of signalized intersections based on pedestrian expectation of security.

* (1) D, date: N/D, no date. (2) T, type: W, walking; B, bicycling; W/B, walking and bicycling. (3) F, field: T, transportation; P, planning; H, health. (4) P, purpose: IN, inventories of environment for research; RQ, route quality assessment tools; AQ, area quality assessment tools for policy and planning; LD, latent demand estimation for walking and biking. (5) LOS, level of service: Y, yes; N, no. (6) DM, data model: P, point; L, line; A, area; N/A, not available. (7) UA, unit of analysis: S, segment; N, network; A, area; N/A, not available. (8) TC, testing/calibration: Y, yes; N, no; ?, not sure; N/A, not available. (9) A, application: Y, yes; N, no; ?, not sure. (10) IU, instrument user: PP, professional; PT, professional transportation engineer; R, researcher; N, lay people or neighbors.

† Anderson-El was refined after this review was complete and can be found elsewhere.[71]

instruments correspond to different attitudes toward walking and bicycling as means of transport. Instruments in the category of route quality assessment focus on safety and comfort and, hence, seek solely to accommodate these modes in an otherwise car-dominated environment, whereas those in the other categories consider volumes of pedestrians and bicyclists and therefore look to encourage walking and bicycling. Portland-PEF,[36] Portland-PPI(1),[40] and Portland-PPI(2)[36,40] combine assessment of both barriers and potential for nonmotorized travel. Also, latent demand is an important concept to capture future opportunities for physically active transport.

Level of Service (LOS). Many of the instruments assessing route quality at the segment scale (RQ) seek to establish a measure of ''level of service'' (Instrument Characteristic 5 in Table 1). Level of service (LOS) is a standard measure of ''facility capacity'' that was first used in automobile transportation planning to standardize the volume of vehicles that can or

Table 2

Categories of Environmental Factors Used in the Audit Instruments*

Aspects of Behavior-Environment	General Classes of Environmental Factors	Times Encountered†	Component of Behavioral Model of Environments	Type of Measure	Common Data Sources
Spatiophysical	1. Roadway characteristics	74	Route	Obj	DOT, field
	2. Environment along roadway	20	Route	Obj	Local GIS, field
	3. Network	24	O/D, route	Obj	DOT
	4. Area	26	Area	Obj	Census, local GIS
Spatiobehavioral	5. Nonmotorized traffic	8	Route	Obj	DOT
	6. Vehicular traffic	21	Route	Obj	DOT, field
	7. Safety	3	All	Obj	DOT
Spatiopsychosocial	8. Perceptions of environments	31	All	Subj	Survey
Policy	9. Policies affecting environments	26	All	Obj	Local GIS, field

* O/D, origin and destination; Obj, objective measures; Subj, subjective measures; DOT, Department of Transportation; GIS, Geographic Information System.
† Approximate number times variables encountered in instrument review.

should be accommodated on a road or street at a given speed of travel. For cars therefore, LOS measures levels of congestion given posted speed limits and highway capacity. The same concept applied to either pedestrian or bicycle travel makes little sense because they are underutilized modes of travel in the majority of North American cities. Instead, LOS for nonmotorized travel measures levels of safety and comfort. Six levels of LOS are typically used (A through F).

Six instruments address LOS performance measures for bicycling, and five for walking. The only LOS instrument in the Area Quality (AQ) category is Fort Collins-LOS.[41] Instruments yielding LOS at the segment level typically stress *barriers* to walking and cycling travel, measured in terms of amount of vehicular traffic and related road conditions. These barriers are then correlated to perceptions of safety and comfort on the part of pedestrians and bicyclists. Khisty-PM[42] is the only LOS instrument that provides a detailed method to measure pedestrian and bicyclist perceptions of safety, security, comfort, convenience, attractiveness, way-finding, and continuity.

Segment-based measures of LOS are limited because they ignore the origin and destination component of walking or bike travel (trip purpose), the availability of alternative travel routes, and actual or latent volumes of pedestrians and bicyclists.[43]

Data Models, Units of Analysis, Instrument Testing, and Applications. Instrument Characteristics 6 and 7 in Table 1 summarize the data models and units of analysis explained in the theoretical framework section above. Few instruments use all three data models, which are necessary to represent all variables capturing environments for walking and bicycling. Only one third of the instruments use areas as units of analysis.

Instrument Characteristic 8 indicates whether the instruments have been tested or whether the models used have been calibrated. Reporting on tests of validity and reliability is incomplete and suggests that few of the instruments have been subjected to rigorous tests. For example, although most instruments seeking to establish LOS levels state that their models have been calibrated via focus group, surveys, and even real-time experience of environments, only partial results of the tests are available. Respondent and road segment selections remain unexplained. There also are inconsistencies between instruments. For example, both Landis-BLOS[44] and DOT-BCI[45] report that the presence of bike lanes is a significant variable in predicting LOS, but Landis et al.[44] found road surface to be significant as well, whereas DOT-BCI,[45] developed after Landis-BLOS,[44] does not include this variable in the model. Explanations for the lack of rigorous testing and consistency include the limited research budgets provided for instrument development. Some of the instruments have been tested for internal reliability, but as far as we know, none has been validated.

Latent demand instruments have not been empirically tested. Portland's instruments[36,40] have been tested with data from transportation models. Moudon-PLL_1 and PLL_2[13] have been field verified. The issue of the empirical basis for instrument design is further discussed later in this paper.

Most of the instruments from transportation planning have been used and applied (Instrument Characteristic 9), but reporting on these applications is at best sketchy, likely because of the local nature of the applications and the lack of funding for evaluation and follow-up considerations.

Instrument Users. Most instruments are designed for use in the same field as that of origin. However, few discuss what entity within the field might use the instrument. In Table 1, Instrument Characteristic 10 suggests four basic types of user: professional plan-

Table 3

Variables in the Spatiophysical Aspects of Walking and Bicycling

General Category	Variable Name	Data Source/Type
Roadway characteristics		
General	Condition of road; typical section attributes; intersection geometry	Composite
	Road width; roadway alignment	DOT, local GIS
	Roadway character, improvements, and environment	Composite
	Visibility	Field
Street or road segments	Length of segment under consideration for improvement	DOT, field
	Number of links in grade-separated system	Field
	Intersection; midblock	DOT, local GIS
	Midblock	DOT, local GIS
Vehicle lanes	Number of lanes; total number of through lanes; center turn lane	DOT
	Presence and width of shoulder or bike lane	Field
	Number of turn lanes; direction(s) of traffic flow	DOT
Outside lanes	Outside lane width	Field
	Usable width of outside through lane	Field
Bicycle lanes	Presence of bicycle lane/paved shoulder	DOT, local GIS
	Width of bicycle lane/paved shoulder	Field
On-street parking	Off-street parking spaces with unrestricted access per household	Field
	Parking lane; presence of on-street parking	Field
Paths	Path type	Field, local GIS
	Path width	Field
Vehicular access	Uncontrolled vehicular access, such as driveways or on-street parking spaces	Field, local GIS
Transit service	Frequent transit stop	Transit agencies
	Transit corridor	Local GIS
Bus service	Bus stops	Transit agencies, local GIS
Curbs	Curb cuts, ramp, type, and lane width (same as outside lane)	Field
	Driveways or curb cuts; driveway and side streets	Field
Slope	Sloping terrain; intersection	GIS
Barriers	Presence of barrier-free facility; obstructions	Field
	Presence of barriers within the buffer area (usually trees)	Field
Crossings	Crossing aides; opportunities, and width	Field
	Ease of street crossing (several variables within)	Composite
	Flashing crosswalk lighting; intersection markings	Field
	Marked crosswalks (signalized)	DOT, field
	Marked crosswalks (not signalized); marked midblock crosswalks	Field
	Marking/intersection markings	Field
	Types of crossings; unmarked crosswalks	Field
Median	Presence of median	DOT
Signalization	Frequency of signalization	Composite
	Signal phase; stop sign frequency; traffic control devices	Field
Pedestrian signalization	Pedestrian signal delay length	Field
	Pedestrian supportive signalization	Field
	Push button	Field
Sidewalks	Presence of sidewalk	Local GIS, field
Surface	Path condition, smoothness and material	Field
	Pavement factor	Composite
	Street surface	Field
	Surface condition, quality, and type	Field
Environment along roadway		
Buildings	Architecture (local)	Field
	Building features and frontage	Field
	Roadside development; garden maintenance	Field
Lighting	Lighting	Field
	Lighting (street)	Field
	Lighting (pedestrian scale)	Field
Litter	Maintenance; litter	Field
Bicycle parking	Parking for bicycles	Field

Table 3

Continued

General Category	Variable Name	Data Source/Type
Sidewalks	Buffer between cars and pedestrians	Field
	Distance between curb and sidewalk	Field
	Path location; sidewalk width	Field
Street furniture	Benches; furniture (street)	Field
Trees	Trees (shade tree)	Field
	Trees (street tree)	Field
Network		
General characteristics	Connectivity; continuity	Composite
	Other routes available; parallel alternative facility	Composite
Sidewalk networks	Extent of sidewalk network; sidewalk continuity	Composite
Network density	Fineness of grid, distance between intersections	Composite
	Street intersection density	Composite
Access	Access to bicycle facility	Field
O/D accessibility	Actual distance/minimum distance	Local GIS
	Actual distance in time/direct distance in time	Composite
	Actual distance/direct distance	Composite
	Distance between origin and destination via alternative network	Composite
	Distance to elementary school, high school, middle school, and work	Local GIS
	Minimum distance between O/D pair along grade-separated system	Field
	Minimum distance between O/D pair at street level	Local GIS
	Total number of O/D pairs in subnetwork	Local GIS
	Travel distance range from generator or attractor	Local GIS
	Travel route distance on formal pedestrian infrastructure	Local GIS
	Travel route distance on informal pedestrian infrastructure	Field
Area		
Density/intensity	Actual development on the ground: development, streets, freeways, rivers	Local GIS
	Floor area of specific land use at destination	Local GIS
	Housing density, employment, and population density	Census, local GIS
	Intensity of adjacent land uses	Local GIS
Market area	Absolute number of residents or employees within a walkable area	Census, local GIS
Land use type	Connective tissue	Composite
	Destinations; land use types	Local GIS
	Zoning categories and related capacity	Local GIS
Land uses linked by travel	Functional complementarity of land uses	Composite
	Specific land uses that are linked by pedestrian travel	Composite
Proximity	Proximity of residential and nonresidential land uses	Composite
	Spatial complementarity of land uses	Composite
Urban form	Block size	Census, local GIS
	Average parcel size	Local GIS
Land use as travel generator	Average trip generation of attractor or generator	Standard
	Number of generators or attractors on travel distance range	Local GIS
	Number of generators or attractors per trip purpose	Local GIS
	Trip generation intensity of local land use	Standard

ners (PP), professional transportation engineers (PT), researchers (R), and lay people or neighbors (N). The few instruments tailored for lay audiences seem grounded in advocacy. Latent demand instruments, Portland-PPI(2),[40] and Moudon-PLL2[13] require analytical sophistication. Only the DOT-BCI,[45] Pikora-SPACES,[32] and Moudon-PLI[13] provide detailed user manuals.

Variables Used To Define Environmental Factors

All instruments specify a number of variables as individual measures taken to capture the walkability or bikability of environments. This review culls all the variables from the instruments and classifies them in terms of how they fit into the behavior model of environments. A discussion of available data sources and type for each variable addresses issues related to the level of effort required to use the instruments and to the eventual effectiveness of the instruments.

Categories of Variables Used in the Instruments. Table 2 summarizes our findings regarding the types and frequency of use of variables defining environmental factors in the instruments reviewed. It first sorts variables according to three aspects of the relationship between behavior and environment—spatiophysical, spatiobehavioral, and spatiopsychosocial. A fourth class is added pertaining to policy-related variables. A second level of classification groups variables in nine common conceptual categories of environmental factors. Table 2 also summarizes the types of measurement (i.e., the objectivity versus subjectivity of the measures) and the common data sources available.

The frequency of use of variables in the instruments shows that, expectedly, most variables are of a spatiophysical nature (encountered 144 times, see Table 2), focusing on the physical aspects of environments for walking and bicycling. Spatiobehavioral variables appear 32 times, followed by variables of a spatiopsychosocial nature (31 times). Interestingly, variables addressing the planning and development policies associated with the audited environments form an important group (26 times). Frequency of use also shows uneven distribution among components of the behavioral model of environment. The largest number of times variables are used relates to the route taken by walkers and bicyclists (123 times). Variables addressing all three components of the environment for walking and bicycling come next (60 times), followed by area-related variables (26 times), and finally variables combining both route and origin/destination components (24 times).

The prevalence of variables in the roadway characteristics and perception categories might come from the relatively large number of instruments in the Route Quality (RQ) assessment purpose category, where route quality is measured in terms of perceptual performance. Interestingly, none of the instruments addressing route quality relies on crash data (only Dixon[29] suggests the use of crash data). This reliance on subjective rather than objective safety measures might be explained by the separate entities involved in nonmotorized LOS and in transportation safety research. The low number of variables in the nonmotorized traffic category might be explained by the lack of readily available local data and by the focus on accommodating rather than encouraging walking and bicycling.

List of Variables Used. Tables 3 through 6 list all variables found in the instruments, organized on the two classification systems provided in Table 2. The sheer length of these lists explains why the nine categories of environmental factors are needed to comprehend the range of measurements sought in the instruments. The nine categories also help further specify the components of the behavioral model of environments. The left-hand column of Tables 3 through 6 introduces a third level of variable classification to further facilitate the reader's comprehension.

Data Sources and Type. Data sources and types affect the relative ease of use of audit instruments as well as the costs of performing an audit. This in turn necessarily affects the selection of variables to be included in the instrument. Data sources, content, availability, and compatibility listed for the variables are as follows.

Departments of Transportation (DOT). Most of the DOT spatiophysical data are in network models not always compatible with other data models. State, county, and city DOTs typically have separate data sets on the characteristics of their roadways. The quality and availability of these data can vary substantially. Data on traffic signalization, which can be important to define the ease of street crossing, can be difficult to get and often are not geocoded. Signal timing typically varies greatly, and DOTs often do not have records of programmed timing. Related spatiobehavioral data on vehicular traffic also come from these different jurisdictions, and data for nonmotorized travel are typically too aggregated to isolate the effects of environment on walking and bicycling.[46] Metropolitan Planning Organizations (MPOs) are possible additional sources of regional data because they are required by federal legislation to collect transportation data across local jurisdictions. Modeled data at the regional level often serve to compensate for incomplete data sets at the city level.

Local transit data. These data can be difficult to come by. Some MPOs have integrated data sets for transportation, which include transit and land use. However, these typically remain at a coarse resolution because they serve in transportation modeling done at the Transportation Analysis Zone (TAZ) scale. In suburban King County, Washington, for example, the average TAZ size is approximately 2000 acres.

Census data. This national survey conducted every 10 years allows for longitudinal analysis and contains household and demographic information that have been repeatedly mined in transportation and urban planning. Census data, combined with state-level employment data, are often used as proxies for land use type and intensity. The coarse level of resolution and lack of information on land uses other than residential make these data extremely limited for travel by walking and bicycling.

Local GIS. Most cities with populations over 100,000 have built parcel-level data over the past few years. Associated tabular data typically come from assessors' offices and include land use at the parcel and the building levels. However, these databases usually poorly document nontaxable properties. Local departments of public works or transportation might have network GIS databases. There might be compatibility issues between databases with the same or different data structures. Also, some jurisdictions restrict public access to these databases or make access prohibitively expensive.

Local GIS data are typically built and maintained by the cities and towns. County, township, or state GIS databases at a parcel level remain rare, and most do not contain all the data that would be useful for an environmental audit. For example, sidewalk networks, street lighting, driveways and access points into streets and roads, and so on might be recorded by some of the cities in a region, but not by others, thus hindering cross-jurisdictional applications. Also, land use classifications

Table 4

Variables in the Spatiobehavioral Aspects of Walking and Bicycling

General Category	Variable Name	Data Source/Type
Nonmotorized Traffic		
Speed	Average bicycle speed	Standard
	Speed differential (car and bicycle)	Standard
Volume	Peak-pph (persons per hour) intersection and sidewalk midblock use	Field
	Pedestrian volume	Field
Trip purpose	Bicycle trip purpose (e.g., work, personal/business, recreation, school)	DOT, field
Trip source	Source of pedestrian trips: estimate car/walk, walk/bike-only, transit/walk	DOT
Vehicular traffic		
Conflicts	Potential cross-traffic	Composite
	Potential for vehicle-pedestrian conflict	Composite
	Reduced turn conflict implementation	Field
Speed	85th percentile speed	DOT
	Posted speed limit	DOT
	Vehicle speed	Field
	Speed (driving)	DOT
Vehicle type	Motor vehicle mix	Field
	Presence of heavy truck traffic	DOT, field
	Presence of heavy vehicles	DOT, field
	Vehicle type (passenger equivalent)	Standard
Volume	Average daily traffic (ADT)	DOT
	Curb lane vehicle traffic volume	Field
	Directional split	DOT
	Non-curb lane vehicle traffic volume	Field
	Number of commuters	DOT
	Transit ridership	Transit authority
	Vehicle traffic volume	DOT
Volume/capacity*	Auto level of service (LOS)	DOT
	Vehicle LOS levels, combined with number of lanes	DOT
	Volume/capacity ratio	DOT
Safety	Frequency and severity of problems	DOT
	Automobile-pedestrian crash factor	DOT
	History of collisions by location	DOT

* Mixed variables of roadway and vehicular traffic characteristics.

can vary from one jurisdiction to another.

These databases are promising in a near future where the characteristics of land use and elements of the environment along roadways can readily be available. Their fine level of resolution makes parcel or tax-lots excellent spatial units of data resolution for analyzing walking and bicycling in both urban and suburban areas.

Field data. The field data must be collected from field audits, inspections, and observations. Data on many spatiophysical and spatiobehavioral factors need to be field collected. Data on nonmotorized travel have been collected locally in only a handful of published cases.[47–51]

Survey data. Like field data, survey data must be collected as part of the process of developing or applying the instrument. The simplest of instruments requires a self-reported assessment of the environment.

Composite data. These data must be assembled from existing databases or field data before being used in the instrument or model.

Standards. These are data from established standards in transportation planning. As mentioned, the Institute of Transportation Engineers (ITE) publishes ''trip generation'' figures related to specific land uses—such as office buildings, malls, neighborhood retail—that are used to predict future levels of service of given roadways as well as parking requirements related to such land uses. Interestingly, these latter standards have little, if any, empirical basis.[52]

DISCUSSION

The striking finding of this evaluation is the large number of variables (almost 200) used in the instruments to capture environmental factors. This indicates a lack of knowledge about the effect of single variables on walking and bicycling. Yet empirical support is evident for associations between classes of variables and walking and cycling behaviors. Instruments on route quality (RQ) point to associations between route characteristics and psychosocial variables, which could have direct applicability

Table 5

Variables in the Spatiopsychosocial Aspects of Walking and Bicycling

General Category	Variable Name	Data Source/Type
Perception		
Bicycling	Attractiveness for cycling	All survey type data
	Bicyclist experience level	
	Bicyclist characteristic (skill levels)	
	Difficulty for cycling	
	Driver behavior	
	Ease of biking	
	Safe places to bike	
	Roadway share with motor vehicles	
	Safety of bicycling	
	Surface quality	
	Street intersection condition	
Driving	Unrestricted sight distance	
	Visibility from nearby buildings	
Walking	Attractiveness for walking	
	Ease of walking	
	Pleasantness of walking	
	Perception of attractiveness	
	Perception of comfort	
	Perception of convenience	
	Perception of safety	
	Perception of security	
	Perception of system coherence	
	Perception of system continuity	
	Room to walk safely	
	Sense of security; good lighting; clear sight lines	
	Types of views	
	Women's rating of neighborhood safety	
Walking and bicycling	Easiness of following safety rules	
	Ease of street crossing	
	Number of neighborhood "places of significance" named by average respondent	

in the assessments of recreation or exercise walking and bicycling. Instruments assessing area quality (AQ) offer promise of demonstrating associations between spatiophysical and spatiobehavioral variables, and specifically of relating environmental factors with actual numbers of pedestrians and bicyclists or numbers of walking and cycling trips. Variables used in these latter instruments are grounded in a fairly large body of research on land use and transportation. Ewing and Cervero's summary of this research highlights those spatiophysical variables that have been associated with different travel behaviors, namely that (1) density of development or intensity of land uses (land use types being proxies for activities that people are engaged in, and land use intensity being a proxy for numbers of travelers), (2) mixing of land use types (a proxy for the frequency and duration of trips), (3) measures of compactness (affecting proximity between activities), and (4) density of the street network (affecting accessibility to activities) are correlated with less driving or more use of transit, more multiple-occupant automobile driving, and more nonmotorized transport.[22] Frank and Engelke[53] and Handy et al.[54] review similar literature with a specific focus on its applicability for physically active travel. Most of this work, however, remains "autocentric," attempting to capture those components of the environment that affect travel *mode choice* and, specifically, the relative share of driving alone (SOV or Single-Occupant-Vehicle travel) with respect to alternative modes (non-SOV travel). It is neither focused on, nor able to establish, a clear relationship between environmental factors with actual volumes or walking and cycling trips, as unique modes of travel. Nor does it address the relationship between environment and physical activity.

In order to refocus research on the relationship between land use and transportation on physically active travel, changes are needed in travel data collection practices, which are now skewed toward travel covering distances longer than those typically afforded by nonmotorized modes (e.g., only 3% of total trips reported in the otherwise exhaustive travel data collected in the Puget Sound are walking trips). Furthermore, actual data on spatiophysical variables will be needed to replace proxy variables derived from the Census and to include elements of environments at the microscale. Ade-

Table 6

Variables in the Area of Policy that Affect Walking and Bicycling

General Category	Variable Name	Data Source/Type
Political support of walking and bicycling	Abutting communities	All local field data
	Business organizations	
	Elected officials and representatives	
	Local engineering department	
	Neighborhood organizations	
	Planning department	
	Responsiveness of transit service	
	State DOT	
Planning policy	Development standards	Standards
	Pedestrian classifications, region 2040 designations	Local GIS
	Pedestrian-friendly commercial area designation	Local GIS
Planned future development	Projects in the pipeline	Local GIS, field
	Projects under construction, by type	Field
Plans and programs	Community Development Block Grant monies	All local field data
	Capital improvement plan support	
	Local improvement districts	
	Public/private partnerships	
	Safe route to school scheduled or planned	
	Subarea plans	
	Support facilities	
	Redevelopment monies	
	Targeted growth	
	Target special populations: children, older adults, ethnic minorities, households with few cars, etc.	
Transportation policy	Travel demand management (TDM) and multimodal support	All local field data

quate variability in environmental factors also needs to be achieved. So far, most studies use data on West Coast metropolitan areas,[55] which, because they were developed primarily in the automobile era, have comparatively little in the way of transit options and variation characteristics of the built environment.[56] Finally, standard spatial units of travel will also need to be reduced considerably to capture the limited geographic range of walking and bicycling.

Even with adequate data and appropriate units of analysis, however, it is unlikely that single spatiophysical variables will predict behavior. This is because of the high level of covariance between variables in the three components of the environmental model found in ‘‘actual’’ environments, where close proximity between origin and destination, high-quality routes for walking and bicycling, and areas with high volumes of pedestrians and, though to a lesser extent, bicyclists, typically come as a ‘‘package.’’

Covariance between physical environmental variables might be different for recreation/exercise trips. Indeed, trails, parks, and greenways are often found in metropolitan areas of low density and without mix of uses. This means that a great deal of work remains to be done to sort out the predictive power of either single variables or classes of variables.

CONCLUSIONS

This review attempts to be inclusive, but because walking and bicycling are the subject of many on-going research projects in different fields, it is likely this review will need periodic revisiting. It provides a reasonably comprehensive overview of variables and measures of physical environments, some of which are new to the public health field. It evaluates existing environmental audit instruments and identifies directions for developing valid and efficient new instruments. The classification of variables used in this paper can serve as a theoretical framework for future research on the environmental determinants of physical activity and as a basis for designing, testing, and calibrating future environmental audit instruments.

Existing instruments together assemble a large set of variables measuring physical environments associated with walking and bicycling. However, no single instrument covers all constructs of the behavioral model of environments described in this work. Expectedly, instruments from the health field tend to undervalue the transportation components of walking and bicycling, whereas those from the transportation field disregard the physical activity aspects of travel. Most instruments focus on the characteristics of the route traveled. Many are segment-based, considering safety and comfort as dependent variables for walking and bicycling. Few instruments address the origin, destination, and area characteristics of walking and cycling trips that are crucial in determining participation in walking and bicycling for travel or, to a lesser degree but importantly, in active living. Future instruments need to consider both individual and collective amounts of walking and bicycling as they relate to physical environmental factors and perception of safety and comfort.

As suggested in the discussion section, much work remains to be done to reduce the number of variables needed to capture environmental factors. Review results suggest that the behavioral model of environment provides a useful framework to identify components of environments affecting walking and bicycling and the corresponding classes of variables. The lack of detailed and accurate data on both behavioral and objective measures of environments likely represents the single most important issue to address in future attempts to isolate individual or groups of environmental predictors of walking and bicycling. On one hand, augmenting national health surveys with information on specific types of physical activity would facilitate future research in this area. Similarly, travel data would need to include short trips, specifically walking and cycling trips, taking into account trips that feed motorized travel. In both health and transportation data collection efforts, identifying the precise location of respondents is obviously essential to establish correlations between environment and behavior.

On the other hand, work remains to assemble objective data of environments at a grain or resolution fine enough to correspond to those sensed by walkers and bicyclists. Objective measures of environments must also exhibit a sufficient range of variability. Because of high covariance between environmental variables, extensive empirical data are required for testing their relative predictive powers. At the same time, analyses must be carried in spatial units that are small enough to represent this variability. GIS now provides a range of spatial units, including small ones, for collecting and analyzing environmental measures. It also offers new opportunities to define spatial sample frames based on environmental factors to ensure an appropriate range of variability.

The isolation of strong variables and measures of the environment will lead to more effective, and likely simpler, instruments than the ones existing now. However, because of the complex relationships between environment and behavior, future environmental audits might need to be tailored to the characteristics of the physical environment itself (e.g., urban or suburban), to the type of users (e.g., young or old), and to the different purposes of physical activity (e.g., travel, recreation, or combined). The review points to insufficient attention paid to the instrument validation process. Future budgets to develop audit tools need to include this important component of the audit instrument development process.

SO WHAT? Implications for Health Promotion Practitioners and Researchers

This review indicates that, to date, environmental audit instruments consider a great variety of measures of the environment; however, most of these measures have not been empirically validated. The findings suggest that practitioners can learn from instruments devised outside the health promotion field to audit environments for walkability and bikability. Practitioners will need to help test these and new instruments by applying them to and evaluating communities for their recreation- and transportation-related physical activity. This study provides researchers with up-to-date knowledge about methods and variables used to quantify the built environment and, with the strengths and limitations of these variables, to appropriately model environments for walkability and bikability. Health promotion researchers will need to contribute to developing valid and efficient audit instruments through rigorous testing of the measures used.

Existing instruments provide evidence that environmental determinants of walking and bicycling are important to address salient policy issues in transportation, urban planning, and public health. Travel-related walking and bicycling promise to support two public policy issues: improving public health through physical activity and increasing transportation efficiency through sustainable travel. They can help reduce the time constraints associated with and psychological barriers related to regular exercise reported by a large proportion of the working population.

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