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Measuring Streetscape Design for Livability Using Spatial Data and Methods

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MEASURING STREETSCAPE DESIGN FOR LIVABILITY
USING SPATIAL DATA AND METHODS

A Thesis Presented

by

Chester Harvey

to

The Faculty of the Graduate College

of

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In Partial Fulfillment of the Requirements
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Accepted by the Faculty of the Graduate College, The University of Vermont, in partial fulfillment of the requirements for the degree of Master of Science, specializing in Natural Resources.

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ABSTRACT

City streets are the most widely distributed and heavily trafficked urban public spaces. As cities strive to improve livability in the built environment, it is important for planners and designers to have a concise understanding of what contributes to quality streetscapes. The proportions and scale of buildings and trees, which define the three-dimensional extents of streetscapes, provide enduring, foundational skeletons. This thesis investigates how characteristics of such *streetscape skeletons* can be quantified and tested for appeal among human users.

The first of two journal-style papers identifies a concise set of *skeleton variables* that urban design theorists have described as influential to streetscape appeal. It offers an automated GIS-based method for identifying and cataloging these skeleton variables, which are practical to measure using widely available spatial data. Such an approach allows measurement of tens of thousands of street segments precisely and efficiently, a dramatically larger sample than can be feasibly collected using the existing auditing techniques of planners and researchers. Further, this paper examines clustering patterns among skeleton variables for street segments throughout Boston, New York, and Baltimore, identifying four *streetscape skeleton types* that describe a ranking of enclosure from surrounding buildings—*upright*, *compact*, *porous*, and *open*. The types are identifiable in all three cities, demonstrating regional consistency in streetscape design. Moreover, the types are poorly associated with roadway functional classifications—*arterial*, *collector*, and *local*—indicating that streetscapes are a distinct component of street design and must receive separate planning and design attention.

The second paper assesses relationships between skeleton variables and crowdsourced judgments of streetscape visual appeal throughout New York City. Regression modeling indicates that streetscapes with greater tree canopy coverage, lined by a greater number of buildings, and with more upright cross-sections, are more visually appealing. Building and tree canopy geometry accounts for more than 40% of variability in perceived safety, which is used as an indicator of appeal. While unmeasured design details undoubtedly influence overall streetscape appeal, basic skeletal geometry may contribute important baseline conditions for appealing streetscapes that are enduring and can meet a broad variety of needs.

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CHAPTER 1: STREETSCAPE SKELETONS

1.1 Introduction

Streets are the most abundant and distributed urban public spaces. They are where much of the life of a city takes place. The designs of streets, and the three-dimensional built environments surrounding them, streetscapes, are undoubtedly consequential for urban livability. Streetscapes are the “outdoor rooms” one encounters when turning the corner, or stepping out the door *into* the street (Cullen, 1971). While streetscape design is influenced by myriad factors, the overall proportions and scale of these spaces are determined by geometry of buildings, and in some cases trees, which are the largest and most visually dominant objects in urban settings. Buildings and trees provide an enduring *streetscape skeleton* (outlined in Figure 1.1) onto which a skin of design details—pavement markings, architectural styling, awnings, plantings, lighting, street furniture—can be draped.

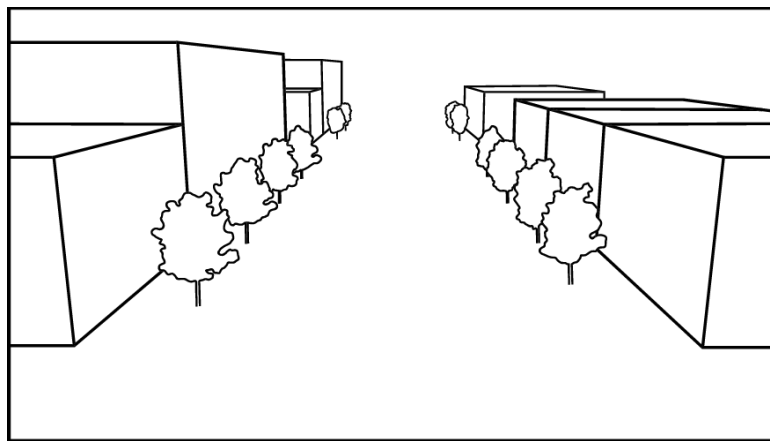


Figure 1.1: A streetscape skeleton defines the space of a street.

There is broad consensus among urban design theorists that the proportions and scale of streetscapes strongly influence user appeal in terms of comfort, safety, and sense of place (Alexander et al., 1977; Dover & Massengale, 2013; A. B. Jacobs, 1993; Lynch, 1960). Nonetheless, there is meager empirical evidence of design-appeal relationships in urban design literature. I see this gap as the result of inadequate techniques for efficient, precise, and replicable measurement of both the design of streetscapes and human perception of them. This thesis investigates strategies for making both types of measurements. It introduces a GIS-based method for measuring streetscape skeleton geometry, and presents a novel streetscape skeleton classification system generalizable across three cities in the northeastern United States. Further, it tests for relationships between skeleton variables and crowdsourced perceived safety data for hundreds of streetscapes throughout New York City.

1.2 Thesis Structure

The following three chapters consist of an overarching literature review and two research papers. Chapter 2 reviews existing methodological approaches for measuring built environment design and human appeal. First, it compares existing built environment measurement methods using field audits and GIS, assessing shortcomings of both to precisely and efficiently measure features at the scale of individual streetscapes. It goes on to call for a novel GIS-based method, making use of high resolution building footprint and tree canopy data that have recently made available in many cities, to provide precise and efficient measurements at the streetscape scale. Second, it investigates approaches to measuring the appeal of the built environment for human users. Traditional strategies

have limitations in spatial scale, precision, and measurement efficiency, similar to those faced by existing built environment measures. However, recently developed strategies to record crowdsourced perceptions using web-based tools may provide appeal measurements that are both spatially precise and efficient to collect over broad geographic extents.

Chapter 3 introduces a novel method for measuring streetscape skeletons using GIS data and tools, and investigates how these variables cluster to define a streetscape skeleton typology that is generalizable between cities in the northeastern United States. First, it examines urban design literature to determine which skeleton variables are theoretically relevant to streetscape appeal and are feasible to measure using readily available GIS data. Second, it describes how skeleton variables for block-length street segments can be measured using an automated GIS-based process. Third, it measures these variables for nearly all surface street blocks in the cities of Baltimore, MD, New York, NY, and Boston, MA, and uses cluster analysis to identify streetscape skeleton types that are consistently distinguishable throughout the region. Finally, it demonstrates that streetscape skeleton types and the functional classifications, widely used for transportation planning, are unassociated with one another, indicating the importance of evaluating and planning streetscapes separately from the roadways running through them.

Chapter 4 assesses the relationship between skeleton variables derived in the previous chapter and crowdsourced streetscape appeal judgments recently collected by researchers at the MIT Media Lab at over six hundred sites in New York City (Salesses, Schechtner, & Hidalgo, 2013). Regression models are used to identify three skeletal

variables that together predict 42% of variability in perceived safety, an indicator of visual appeal. The results demonstrate that a minimal set of skeleton variables, which may be straightforwardly measured and incorporated into design guidelines, may set important baseline conditions for appealing streetscapes across a variety of urban settings.

1.3 Summary of Contributions

This thesis makes several contributions to the interrelated disciplines of urban planning, transportation planning, urban design, and natural resource planning. *Streetscape skeletons* provide a succinct theoretical framework for identifying, measuring, and guiding the design of streetscapes, which occupy a spatial scale situated between the conventional domain of architects, who design microscale elements of buildings and landscapes—massing, fenestration, fixtures, materials—and planners who guide macroscale urban form—grid shape, connectivity, land use density, destination accessibility. Mesoscale streetscape skeleton design receives disproportionately little attention given its influence on the urban landscape. Identifying streetscape skeletons as relevant spatial entities, and providing them with a measureable set of characteristics, may hopefully encourage their thoughtful planning and design.

This research also contributes a precise, replicable, and efficient GIS-based method for measuring streetscape skeletons which may allow them to be incorporated alongside macroscale urban form measures in future assessment of human behavior in built environments. Current analyses of walkability, for instance, are founded largely on

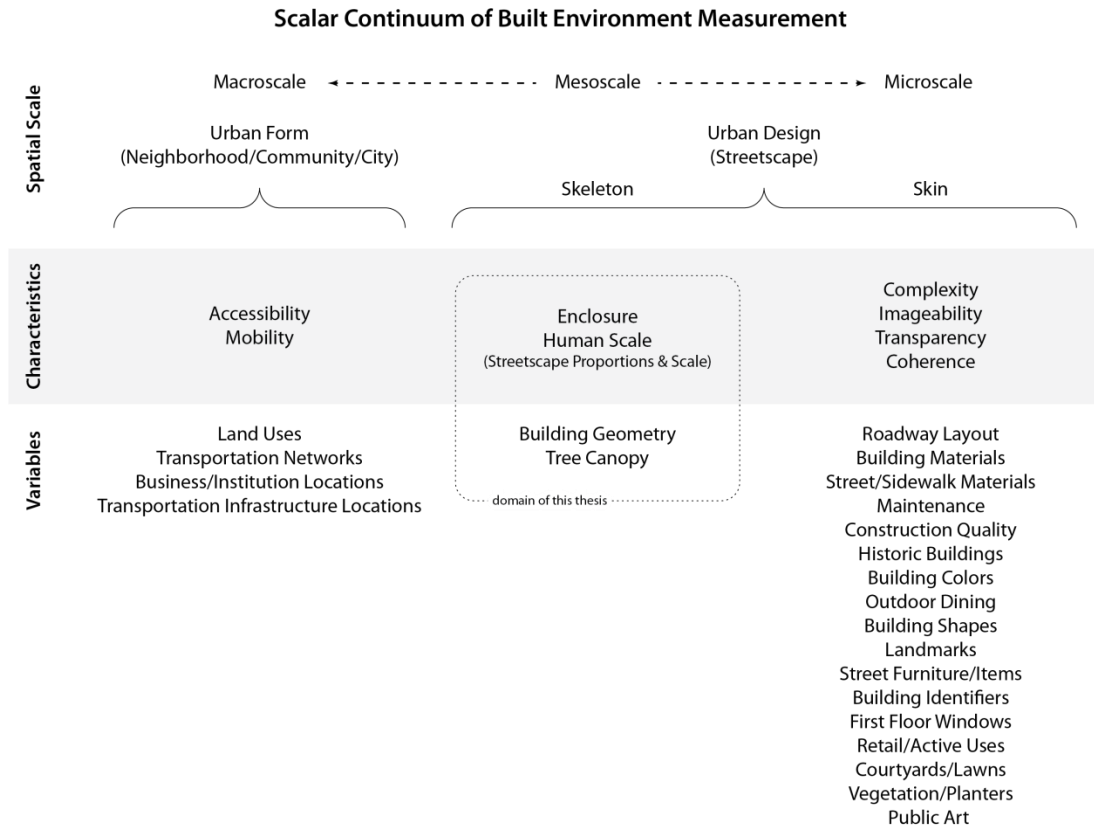
destination accessibility—e.g., the number of restaurants, cafes, grocery stores, or parks that are within walking distance of a given point. Such metrics describe the practicality of walking, but not its aesthetic enjoyment. If a restaurant is close by, but the route is along streetscapes that are vast and bland, would someone want to walk there? Incorporating streetscape skeleton variables into such analyses may produce more accurate indicators of walkability.

Finally, by validating the visual appeal of streetscape enclosure, this thesis offers empirical support for development and design policies that incentivize more upright and compact streetscapes through infill construction, multistory buildings, minimal setbacks, and street tree planting. While the design sensibilities of expert planners and designers have promoted these types of streetscapes for centuries, pragmatic arguments for low density development that improves residential privacy and automobile mobility often overshadow less tangible aesthetic benefits that are distinguishing factors of notably livable places. An objective framework for measuring streetscape aesthetics and their effects is an important first step to including them in cost benefit analyses that drive contemporary development decision-making. This thesis provides a replicable and accessible method for make such objective measurements, and demonstrates the magnitude of influence that skeletal design has in making streetscapes appealing places.

CHAPTER 2: STREETSCAPE MEASUREMENT IN REVIEW

2.1 Introduction

It is difficult to describe what a livable street looks like. Some visualize them according to examples of new urbanism, smart growth, form-based code, and other approaches to urban design that are functional, comfortable, and beautiful to live in (Miller, Witlox, & Tribby, 2013). Nonetheless, there is a struggle among researchers and practitioners to define discrete characteristics of livability. The Partnership for Sustainable Communities suggests that livable communities provide a high quality of life by offering access to transportation choices, location-efficient housing, access to employment, and mixed use development (USDOT, 2009). Within the context of an individual street, however, livability is substantially mediated by design aesthetics. The design of streets, and their contextual streetscapes, impact whether they are merely conduits for accessing distributed features of a livable community, or are livable spaces themselves (Campoli, 2012). Because streets are fundamental to the experience of everyday living—they are the most prolific public spaces in the developed landscape—it is important that we understand the attributes of street design that impact their aesthetic appeal, and in turn livability, for diverse users. While urban designers have theorized extensively about what makes streets appealing as spaces for living, there has been scarce experimental validation of these claims (Southworth, 2003). This may be due, in large part, to the difficulty of measuring streetscape design and its appeal for users at a spatial scale relevant to street-level experience, and lack of methods for efficiently assessing large samples of streets over broad geographic areas.



Urban design characteristics and variables adapted from Ewing & Handy (2009)

Figure 2.1: Built environment scalar continuum.

The built environment can be measured at many scales, all of which are important to the way people perceive aesthetic appeal and make decisions about its use (Figure 2.1). Urban form describes the macroscale built environment. It characterizes the overall layout of communities according to variables such as network connectivity, land use density, and land use diversity. Such measures are chiefly useful for describing accessibility—the practicality of traveling from one place to another. Urban design has practical contributions—space allocated to vehicle lanes and sidewalks affords these uses—but also provides aesthetic conditions that may affect complex and subconscious perceptions of appeal. Urban design variables are ambiguously defined; they are often

described in subjective terms—distinctiveness, focality, intricacy, spaciousness—rather than discrete measurements (Ewing & Handy, 2009). It is difficult to determine what about them is important to measure, or what the appropriate yardstick is for making such measurements. Nonetheless, there is good reason to believe they contribute to emotional responses, and thus user behavior, in ways that are unexplained by practical aspects of urban form. Urban design should not be avoided by planning researchers because it is difficult to describe succinctly and empirically.

Within the realm of urban design, features can still be assessed at multiple scales. At the microscale extreme, design details such as architectural styling, building materials, and fixtures impact the visual texture of a streetscape. At a midpoint between macroscale urban form and microscale architectural design is the mesoscale massing and arrangement of buildings and trees which create “outdoor rooms” (Cullen, 1971). The proportions and scale of streetscapes are theoretically important to perceptions of shelter, orientation, and security. Urban design literature broadly references how *enclosed* streetscapes—contained, well-defined spaces with room-like proportions—are attractive for pedestrian users and social activity (Ewing & Clemente, 2013). Nonetheless, the field lacks a concise language for mesoscale design characteristics that contribute to streetscape enclosure. I propose a novel term, *streetscape skeleton*, to describe the elemental three-dimensional structure of streetscapes, distinct from surficial design elements such as materials and architectural styling. This thesis will explore how streetscape skeletons can be identified, measured, typified, and tested for association with aesthetic appeal, to assess the contribution of their design to urban livability.

Efficient and objective measurement of streetscape skeletons is a formidable challenge. Field audits are the dominant method for measuring urban design at a variety of scales (Brownson, Hoehner, Day, Forsyth, & Sallis, 2009). While there are well-developed replicable methods for conducting audits and validating their accuracy, audits are impractical for collecting large samples because they are inherently expensive, logistically complex, and derive few economies of scale; auditing each additional street segment requires proportional time and organizational effort. As a result, audit data often have small sample sizes and limited capacity for assessment across large or multiple geographies.

Researchers studying built environment effects on travel demand traditionally use GIS to measure characteristics of urban form (Ewing & Cervero, 2010). While these methods are technically efficient, replicable in many cities, and highly objective, the data they are typically based on do not offer scalar precision necessary for measuring urban design at the streetscape level. Nonetheless, they provide a useful model for development of GIS-based urban design measurement, and a framework for future research that investigates the joint implications of urban form and urban design for built environment livability.

To assess how urban design impacts the livability of individual streetscapes, it is likewise important to have robust methods for measuring human perceptions of streetscape appeal. Researchers have examined the appeal of built environments according to diverse measures, including social interaction, transportation mode share, and home values. These strategies are also variously limited by constraints on collection

efficiency, spatial precision, and subjectivity. Measurements of appeal that are spatially precise, efficiently scalable, and draw on samples that are sufficiently large to establish consensus among subjective observations, are particularly advantageous for examining design-appeal associations across streetscapes in diverse geographies. Few such datasets, however, have been collected.

The remainder of this chapter will consider the strengths and weaknesses of existing strategies for making design and appeal measurements, and how they might be improved upon. First, it will provide a detailed examination of audit and GIS methods for measuring streetscape design. Second, it will assess how researchers have measured built environment appeal. Throughout, it will discuss how measurement strategies that are spatially precise and computationally efficient are ripe for development.

2.2 Measuring Streetscape Design

Systematically measuring urban design characteristics that account for the perceptions of street-level users is a formidable challenge for design and planning researchers. The most straightforward, and well-established strategy for measurement is to send human auditors into the field, where they record direct observations using an audit protocol. Dozens of audit tools have been developed to support academic and policymaking research, and they are often reused or modified as off-the-shelf methods for documenting streetscapes (Brownson et al., 2009). While audits present challenges, including huge expense and logistical effort, they are nonetheless attractive as a well-documented strategy for collecting reliable urban design measurements.

Audits tend to be developed in the context of a particular topic. Many record urban design variables that are hypothesized to relate to either walking (Borst, Miedema, Devries, Graham, & van Dongen, 2008; Cerin, Saelens, Sallis, & Frank, 2006; Ewing, Clemente, Handy, Brownson, & Winston, 2005; Ewing, Handy, Brownson, Clemente, & Winston, 2006; Gallimore, Brown, & Werner, 2011; Guo & Loo, 2013; Park, 2008; Schlossberg, Weinstein Agrawal, & Irvin, 2007) or physical activity (Boarnet, Day, Alfonzo, Forsyth, & Oakes, 2006; Boarnet, Forsyth, Day, & Oakes, 2011; Clemente, Ewing, Handy, & Brownson, 2005; Day, Boarnet, Alfonzo, & Forsyth, 2006; T. Pikora, Giles-corti, Bull, Jamrozik, & Donovan, 2003; T. J. Pikora et al., 2002). A handful of studies use audits to examine how urban design relates to broader themes of livability (Forsyth, Jacobson, & Thering, 2010; Rundle, Bader, Richards, Neckerman, & Teitler, 2011; Southworth, 2003). Audit instruments rarely constitute a statistically-validated list of variables related to walking, physical activity, or another behavior. Instead, audits are constructed around theoretical frameworks that combine expert knowledge and common sense to identify variables that are expedient to measure (Clifton, Livi Smith, & Rodriguez, 2007; Day et al., 2006; T. J. Pikora et al., 2002). Measurements useful for studying the broad topic of livability must distill a concise and generalized set of measures pertinent to the appeal of streetscapes for diverse users (Southworth, 2003).

The quantity and diversity of variables that can be measured by audits are one of their most attractive features. Of the twenty audit methodologies surveyed by Brownson et al. (2009), a handful collect fewer than ten measurements while several others collect well over one hundred. Researchers have an incentive to strike an efficient balance

between efficiency of data collection and the descriptive benefits of numerous, detailed observations. Popular methods, such as the Systematic Pedestrian and Cycling Environmental Scan (SPACES) and the Pedestrian Environment Data Scan (PEDS) collect thirty to forty measurements and take roughly three to five minutes to complete for each street segment (Clifton et al., 2007; T. J. Pikora et al., 2002). More lengthy audits generate more detailed data, but are accordingly more time intensive. For instance, the Irvine-Minnesota Inventory (IMI) collects one hundred and seventy-six measurements and requires between twelve and twenty minutes per street segment, but catalogues detailed architectural and urban design characteristics (Boarnet et al., 2006; Day et al., 2006). The expense of conducting an audit encourages measuring any variable that may be testable at a later date, but hampers the practicality of surveying a large sample of streets. Surveying entire communities is impractical, so researchers typically audit only a limited sample of street segments (Brownson et al., 2009).

Human observers allow audits to account for variables that are subjective, nuanced, or otherwise impractical to evaluate from existing spatial datasets. The PEDS tool, for example, asks auditors to record sidewalk material along each segment, choosing among asphalt, concrete, paving bricks or flat stone, gravel, dirt or sand (Clifton et al., 2007). Many municipalities lack any comprehensive inventory of sidewalk infrastructure; even if a GIS layer mapping sidewalk coverage exists it is unlikely to include detailed information on materials or geometry. Qualitative measurements can be included in audits to increase collection efficiency and produce concise results. Rather than independently recording myriad factors that influence the convenience of street crossing,

auditors using the Irvine-Minnesota Inventory judge whether it is “pretty/very convenient” or “not very [convenient]/inconvenient” to cross each street segment (Day et al., 2006). Human observers are singularly efficient at distilling complex observations into generalized conclusions. As GIS data availability expands to include more diverse features it is conceivable that a greater proportion of urban design variables will be practical to measure with automated methods, but audits will likely remain useful for collecting qualitative measurements.

The glaring impediment to audits is that they require enormous resources to deploy. Researchers using audits must weigh the number and depth of measurements against the geographic extent and sample size of street segments they will survey, all while considering the practicality of recruiting auditors, training them, deploying them to the field, and managing data. Controlling observational consistency is additionally complicated when multiple auditors are deployed. A portion of streets are often audited by multiple observers to assess inter-observer reliability (Brownson et al., 2009), although studies sometimes forgo this convention due to lack of resources (Park, 2008). The audit process can be tedious and at times a practical impossibility (Southworth, 2003).

Because audits are resource intensive there is substantial impetus to increase efficiency of data collection. Several researchers have identified benefits of using handheld computers to collect audit data in the field (Brownson et al., 2009; Schlossberg et al., 2007). This improves the consistency of responses and eliminates the later task of entering data from paper forms. Other researchers have investigated how streetscape

images can be used to conduct audits remotely (Clarke, Ailshire, Melendez, Bader, & Morenoffa, 2011; Rundle et al., 2011). While this strategy reduces travel time and safety complications, it presents a unique set of challenges related to variability in resolution, date, and availability of photography, the inability to see sidewalk and building features around obstructions such as parked cars, and the difficulty of precisely judging distance and dimensions. Moreover, they require observations to be visual. In-person audits benefit from their ability to collect information about noise, temperature, wind, and other sensory perceptions. Studies that use computerized audit forms or remote streetscape imagery, but nonetheless require human observers to make judgments, do not substantially overcome the resource intensity inherent to traditional, in-person audits with hard copy forms.

In contrast, other studies use GIS data and tools to make direct, automated measurements of built environment features according to their geometric relationships and tabular attributes. Studies using audit methods often partially draw on readily-available GIS data to minimize auditing resources (Borst et al., 2008; Cerin et al., 2006; Forsyth et al., 2010; Guo & Loo, 2013; Park, 2008; T. Pikora et al., 2003; T. J. Pikora et al., 2002). Moreover, there is a distinct body of literature that exclusively uses GIS methods to measure the built environment for research on walking, physical activity, and broader livability indicators (Brownson et al., 2009). These methods provide a number of efficiency, scalability, and data consistency benefits, but shortcomings in availability of appropriately-scaled data have traditionally made them inadequate for measuring urban design at the streetscape scale.

Instead, GIS-based research on the built environment research is dominated by measurements of urban form, describing neighborhood-scale accessibility, popularly described as the Five Ds (Table 2.1) (Cervero & Kockelman, 1997; Ewing & Cervero, 2010). The validity of this framework for explaining broad trends in travel behavior has been demonstrated by many studies—Ewing & Cervero (2010) compile the results of more than sixty papers with comparable methodologies and findings. Nonetheless, the Five Ds inadequately address how aesthetic perceptions of urban design among individual streetscapes may impact the experience of users and thus modal decision-making and livability. A street may be pragmatic for walking according to these statistics, but attract little pedestrian activity if its streetscape is an uncomfortable place to spend time. It would be prudent to evaluate urban design measurements alongside the Five Ds to test whether their relative contributions to behavioral models.

Table 2.1: The Five Ds of macroscale urban form

Density	Household/population density Job density
Diversity	Land use mix (entropy index)
Design	Intersection/street density
Destination Accessibility	Job accessibility by auto Job accessibility by transit
Distance to transit	Distance to nearest transit stop

Adapted from Ewing & Cervero (2010)

A likely reason why urban design measurements have not been incorporated into GIS-based built environment literature is lack of readily available data at the appropriate scale. Urban form measures, based on widely available street centerline, land use, business location, and census data, are low hanging fruit for planning researchers who are accustomed to gleaning data from municipal governments and regional planning organizations who develop it for their own research and operational uses. The disciplines of architecture, engineering, and urban design, which are largely responsible for the design of streetscapes, have made comparatively little use of GIS. Detailed representations of streetscapes are often dispersed in myriad CAD drawings or other documents, and there has been little practical impetus to aggregate them into spatial databases. While some cities maintain datasets showing roadway characteristics such as bicycle lanes and sidewalks, in many municipalities street centerlines and right-of-way boundaries offer the most precise spatial definition of streets, yet represent little about the aesthetic experience for street-level users. Broadened availability of spatial data representing features at the scale of urban design may provide the greatest catalyst for their inclusion in GIS-based built environment research.

High resolution built environment data is increasingly available in major cities, and researchers have begun developing GIS-based measurements of urban design comparable to those derived from audits. A paper by Purciel et al. (2009) identifies GIS data in New York City that can be used to derive geometric or proxy measurements of urban design characteristics previously identified and measured by Ewing et al. (2006) using an audit protocol. Central to these sources are a tax database, which includes

detailed information about building height, and GIS data mapping building footprints. These can be combined to identify the size, shape, and arrangement of buildings along every street within the city.

Purciel et al. (2009) break ground on the measurement possibilities afforded by GIS data, but their methods vary in robustness. According to Ewing et al. (2006), the length of sight lines and proportion of a street segment lined by building façades contribute importantly to sense of streetscape enclosure and human scale. Evaluated by an audit, these measurements are approximate and are influenced by the spatial relationships of buildings, trees, and terrain. Purciel et al. (2009) use a GIS to reproduce the audit protocol for measuring long sight lines by drawing perpendicular lines at regularly-spaced intervals from each curb and examining whether they are blocked by building footprints. These GIS measurements are validated by replicating them with audited measurements of several hundred New York City blocks (across all boroughs), to which they are compared for statistical correlation. The relatively low correlation of sight line measurements ($r=0.16$) may be due, in large part, to the inability to account for terrain and trees with the GIS method—exit interviews with auditors described these as important to street-level observations (Purciel et al., 2009). Nonetheless, the sight line method provides a valuable example of how geometric relationships contributing to urban design can be systematically evaluated with a GIS.

Other GIS methods used by Purciel et al. (2009) yield more statistically convincing correlations with audit measurements, but rely less on evaluation of geometry. To estimate the proportion of a street lined by building façades, discussed in

urban design literature as a street wall or block face, Purciel et al. use the ratio of building footprint area to total block area as a proxy, yielding moderate correlations ($r=0.54-0.58$) with audited estimations of street wall continuity. This method relies on the assumption that blocks with a greater proportion of building area will have more continuous street walls than those with vacant spaces, though it falls short of accounting for front and back yards that may occupy substantial block area without affecting the consistent alignment of street-facing façades. The authors concluded that measuring street walls based on the geometry of buildings was an unreasonable technical challenge. With advancements in GIS processing capacity, it is worthwhile to revisit this possibility for methodological advancement.

More straightforward GIS measurements developed by Purciel et al. (2009), such as the number and height of buildings along a street segment, have much higher correlations with audited measures ($r=0.95$ and $r=0.85$ respectively) and indicate that GIS tools are a practical alternative to them. GIS methods may provide even greater precision than audits—it is difficult to judge the height of buildings, in terms of scalar units, from a street-level perspective—although such precision may be negligible to the perceptions of street-level users.

The difficulty of validating GIS measures with observational audits underscores the ambiguity of urban design characteristics, and explains the scarcity of design research using quantitative methods. Further, it presents a key obstacle to accounting for urban design alongside widely available measures of urban form. With no standard definitions for qualities such as *enclosure* and *human scale*, it is difficult to measure them with the

consistency and precision necessary to include them in built environment models. Nonetheless, the ambiguity of streetscape design is no excuse to ignore its potentially large contribution to the perceptions and associated behavior of street users. Defining urban design in objective, geometric terms is necessary for developing GIS methods that can efficiently make widespread design measurements for association with measurements of streetscape appeal.

2.3 Measuring Streetscape Appeal

To assess how urban design contributes to livable streets, researchers need to measure perceptions of streetscape appeal among human users or observers. Planning literature draws on diverse measures of built environment appeal, including communality, transportation mode share, physical activity, and real estate prices. Recent research also uses internet-enabled crowdsourcing to measure spatial patterns in built environment appeal according to happiness and aesthetic preference. Similar to design measurements, spatial precision and collection efficiency are important for appeal measurements that can be used to evaluate street livability experimentally.

Classic planning literature discusses the appeal of built environments according to social interaction. Appleyard, Gerson, & Lintell (1981) define livable streets as those which encourage residents to commune with one another, identify the street as part of their home territory, and are aware of its environmental characteristics. These variables are difficult to measure—Appleyard and his colleagues conduct extensive interviews with residents of several dozen San Francisco blocks—yet the broadness of the definition aptly

describes livability as an ambiguous synthesis of social and environmental conditions that allow for fulfilled living. Jane Jacobs, drawing on her experience living in New York City, similarly describes the importance of built environments that encourage communality and sense of place (1961). She explains how “eyes on the street” make neighborhoods safe and welcome places to live. Streetscapes with design characteristics that allow observation of activity from upstairs windows and storefronts provide a safe venue for children to play and business to take place with informal supervision from the neighborhood at-large. Jacobs, like Appleyard, sees streets as appealing when they promote neighborly relationships, reducing the anonymity of unlawful activities and encouraging residents to take ownership of the streetscape beyond their individual properties.

Research conducted by Biddulph (2012) similarly assesses streetscape appeal according to social activity and diversity of use. Using in-person observation and time lapse photography, Biddulph collects observations on the duration and types of activities people engage in on residential streets in the United Kingdom. These are demonstrative of methods used broadly by urban design research investigating the use and appeal of public spaces (Gehl, 2010). The activity data they collect is attached to precise spatial locations, allowing it to be related to specific urban design characteristics. Observational methods also allow nuanced behaviors and conditions to be recorded; for instance, Biddulph recognizes a temporal relationship between children playing and adults socializing in the street. Nonetheless, surveys of this type are incredibly time consuming and allow assessment of only small environmental samples—Biddulph (2012) studies

two communities—limiting the generalizability of results. Time lapse photography strengthens the experimental design of such research by providing a comprehensive account of activity within a particular spatial extent, but the practical limitations of recording and coding photography from multiple locations constrains examination to a small number of streets.

Behavior remains a useful indicator of built environment appeal across broad geographic extents, and is expediently collected by surveys of physical activity and transportation mode share (Cerin et al., 2006; Cervero & Radisch, 1996; Chen, Gong, & Paaswell, 2007). Boarnet et al. (2011), for example, validate audit measures from the Irvine-Minnesota Inventory (IMI) by assessing walking data from 716 subjects who filled out physical activity questionnaires, kept travel diaries, and wore accelerometers as part of the Twin Cities Walking Study. Likewise, Chen et al. (2007) assess the effect of urban form measurements on mode choices recorded in 14,411 household travel diaries as part of a Household Travel Survey in New York City and northern New Jersey. Such behavioral surveys provide concrete indicators of mode suitability among large samples, but they are enormously resource-intensive to conduct. Many studies are consequently designed to use survey data that has already been collected by institutions with broader planning motivations. Such studies tend to use transportation decisions to indicate whether built environments are successful, without considering that use of these environments may be the only practical option for many people. Behavior may not reliably indicate environmental appeal if there are limited practical options for moving from one location to another.

Other studies survey user judgments of environmental perceptions such as attractiveness and safety. Gallimore et al. (2011) investigates how parents and children perceive routes to school, asking them to agree or disagree with survey questions on whether routes are impractical or unsafe. Guo and Loo (2013) similarly ask respondents to identify walking routes on maps and rate them on Likert scales. In both cases, respondents' judgments are compared with environmental characteristics along a route's entire length, yielding little capacity to distinguish the positive or negative contribution of block-scale characteristics. Several studies overcome this deficiency by asking respondents to identify attractive and unattractive street segments in their own neighborhoods (Adkins, Dill, Luhr, & Neal, 2012; Agrawal, Schlossberg, & Irvin, 2008; Borst et al., 2008). This method succeeds in providing high-resolution data on streetscape appeal that is separate from patterns of use. It is impractical, however, to collect data for large samples of users or streets with such an open-ended survey.

Real estate prices provide yet another lens through which to investigate built environment appeal. Hedonic price modeling allows researchers to identify the contribution of location attributes to the transaction price of real estate, particularly residential units. Multiple linear regression is used to control for myriad variables that contribute to the land and improvement value of each property, such as parcel size, number of rooms, and construction materials. Additional variables, such as proximity to the downtown or a natural amenity, can be modeled to test their effect on home prices, all else held constant. Assuming homes in the places with greater appeal have added value, this method can be used to distinguish specific built environment effects.

A number of studies use hedonic modeling to evaluate urban form preferences, generally indicating that homebuyers value low density areas that are prototypical of suburban landscapes (Matthews & Turnbull, 2007). Green, Edwards, and Wu (2009) test the relationship between housing prices and walkability ratings from walkscore.com, which are calculated based on standard urban form variables such as population density, network connectivity, and destination accessibility, in Gresham, Oregon; the Walk Score algorithm does not include urban design variables. In neighborhoods where Walk Scores have any statistically significant correlation with home prices, the relationship is strongly negative. Song and Knapp (2003) similarly find that homebuyers in Portland, Oregon prefer neighborhoods with low residential density and predominantly single-family residential land uses. However, they identify that homes in neighborhoods with internally-connected street networks, small blocks, and pedestrian access to commercial uses command slightly higher prices. The ambiguity of these results is shared by Matthews and Turnbull (2007), who identify that pedestrian access to retail locations raises property values within a distance of approximately 1,400 feet, but the effect is negligible at greater distances. The inconsistent results of these studies may be due, in part, to variability in urban design that is not accounted for by models relying exclusively on measurements of urban form.

A handful of studies evaluate the value of urban design using hedonic methods. Gao and Asami (2007) use an environmental audit to make several dozen measurements, many of them qualitative, of streets in Tokyo and Kitakyushu, Japan. These measurements are consolidated using a principal component analysis to derive aggregate

urban design characteristics. *Compatibility* describes continuity of external walls, conformity of colors and materials, compatibility of building styles, and beauty of skylines formed by buildings; *greenery* describes the presence and continuity of trees and other vegetation. Hedonic models reveal that both characteristics have significant and positive relationships with home values. This is consistent with studies from the Minneapolis and Baltimore regions that indicate positive relationships between urban green spaces and home prices (Sander & Haight, 2012; Troy & Grove, 2008). However, street width appears to be valued much differently in Japan than in the United States. Fullerton & Villalobos (2011) identify a negative correlation between street width and home values in El Paso, Texas, while Gao & Asami (2007) identify the opposite relationship. They explain that narrow streets and dead ends are considered a fire hazard in Japanese cities. Both characteristics are correlated with lower home prices. Conversely, narrower local streets in El Paso are correlated with higher home prices, likely because they provide intimate streetscapes compared with arterial highways. This disparity demonstrates that cultural and environmental context invariably affects nearly any design preference.

Traditional strategies for measuring built environment appeal prioritize either spatial precision or the practicality of collecting large and geographically diverse samples. Innovative strategies for internet-enabled data collection may facilitate both simultaneously. Mitchell et al. (2013) and Frank et al. (2013) identify spatial patterns in happiness scores derived from textual analysis of geolocated Twitter messages. Such happiness measurements, joined to spatially coincident streets, may be useful for

assessing how urban design impacts user appeal. The spatial density and geographic ubiquity of this data make it particularly advantageous for assessing large samples of streets across multiple cities. Mitchell et al. (2013) draw on a database of roughly 10 million geotagged messages collected in every state throughout 2011. In downtown areas of large cities there are hundreds of happiness observations per block, while in other areas the density is substantially lower. Such a dataset is certainly biased against places with lower appeal because people are less likely to visit or tweet from them. Moreover, it is unlikely that streetscape design weighs heavily on the happiness of any individual message. Nonetheless, there is a possibility that thousands of messages, each influenced slightly by the setting where they are written, may indicate that design contributes fractionally to the aggregate happiness of their authors.

Another large dataset, developed by researchers at the MIT Media Lab, draws on crowdsourced judgments of streetscape scenes to measure urban perception (Saleses et al., 2013). Visitors to their website (<http://pulse.media.mit.edu/>) are presented with pairs of streetscape images and asked to rank them based on questions such as, “Which place looks safer?”, “Which place looks more unique?”, or “Which place looks more upper class?” Large numbers of rankings are used to calculate scores for more than 4,000 streetscapes randomly located across four cities in the United States and Austria. While Saleses and his colleagues use these scores to examine urban inequality, they could easily be paired with design measurements for each streetscape to examine the generalizability of design-appeal relationships within and across cities. Similar to the earlier critique of remote streetscape auditing, this process is limited to visual perception

within a limited view, and may not adequately represent other sensory experience (e.g., temperature, noise, smell) or temporal variability in streetscape aesthetics. Nonetheless, it provides spatially precise measurements of appeal that are related specifically to aesthetics and are randomly distributed across large extents, making it one of the best available options for experimentally assessing which design factors affect streetscape appeal.

2.4 Conclusions

There is ample room for development of methods to efficiently measure both the design and appeal of urban streetscapes. Existing urban design research relies on resource intensive field audits to measure design variables as they are experienced by street-level users. GIS methods, while they are well-developed for studying urban form, have tended to be inadequate for representing features at the scale of urban design. More objective definitions for urban design variables, and continued development of GIS methods to measure them, would improve the availability and consistency of streetscape design data, encouraging more researchers to include it in models of perceived livability and behavior. It is unfortunate that such an influential aspect of the urban experience has been inadequately assessed by quantitative research for so long. Nonetheless, it is encouraging that new methods and data put efficient measurement of streetscape design within reach.

Innovative strategies for measuring built environment appeal are similarly ripe for development. Studies investigating the appeal of individual streetscapes traditionally use extensive interviews or surveys to document user perceptions or behavior. These methods

are tedious and resource intensive, making it impractical to collect large numbers of observations in multiple geographies. Internet-enabled crowdsourcing and assessment of social media represent innovative strategies for collecting large and spatially dispersed measurements of environmental appeal. With the rapidly expanding capabilities of big data analysis, and expansion of geocoded social media, it is likely that such methods will play an increasing role in urban planning research.

Pairing streetscape design and appeal measurements to assess what constitutes a livable street would provide an influential empirical base for development policy. By demonstrating general relationships between design characteristics and appeal, cities could assess development plans according to the design of entire streetscapes rather than individual buildings. Identifying the influence of specific design factors might also steer planning priorities. If street wall continuity were, for example, found to be particularly influential for perceptions of appeal, a city might incentivize infill development and more aggressively regulate shallow setbacks. If tree canopy were demonstrated to be useful for defining streetscapes in lieu of enclosing buildings, cities might further prioritize planting and maintenance of street trees as a cost-effective fix for wide and ill-defined streets. By concretely investigating how visual appeal varies with the design of streetscapes, design policy can be driven by evidence of public opinion. While it is unreasonable to suggest that livable design would proliferate on a short timescale or through comprehensive renovation, it might be gradually incorporated into existing streetscapes. However design contributes to the making of a livable streetscape, it can serve as the model for built environment visioning and remediation.

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CHAPTER 3: STREETSCAPE SKELETON MEASUREMENT AND TYPOLOGY

3.1 Introduction

Urban streets can be interpreted as a synthesis of two main components: roadways and streetscapes. Roadways are infrastructure for linear travel, often in motor vehicles, but also by non-motorized users such as pedestrians and bicyclists. They are engineered to be functional for safe and efficient travel. Streetscapes are the three-dimensional outdoor spaces surrounding roadways, outlined on either side by buildings that form “streetscape skeletons.” The overall designs of streetscapes are undeniably affected by myriad design details—building materials, architectural styling, plantings, street furniture—but the elemental proportions and scale of streetscape skeletons are broadly regarded by urban design theorists as important to comfort and social productivity for human users (Alexander et al., 1977; Cullen, 1971; Gehl, 2010; A. B. Jacobs, 1993; J. Jacobs, 1961). Even so, planners often simplistically identify streets in terms of roadway design for motor vehicles according to functional classifications—*arterial*, *collector*, and *local*—established by the Federal Highway Administration (FHWA) (Dover & Massengale, 2013). A complementary typology based on streetscape design may be useful for livability planning.

This study presents a novel approach for measuring streetscape skeletons and an empirically-grounded streetscape skeleton typology—*upright*, *compact*, *porous*, and *open*—that is distinct from roadway functional classes and is generalizable across three cities in the northeast United States: Boston, New York, and Baltimore. Streetscape skeleton types were identified using a multistage process. First, urban design and

planning literature were reviewed to determine which skeleton variables were theoretically important to the way non-motorized users, particularly pedestrians, judge the safety, comfort and attractiveness of streetscapes. Second, a novel GIS-based method was developed to efficiently and consistently measure twelve spatial variables based on existing building and street geometry data. Third, cluster analyses were used to identify four streetscape skeleton types with consistent measurements across the three study cities. Finally, the types were examined for internal patterns and association with functional classes, demonstrating that the designs of streetscape skeletons were independent from the function of roadways throughout the three study cities.

3.2 Streetscape Skeletons in Theory

Which streetscape skeleton variables are relevant to user appeal, and tangibly measureable, is a formidable question for which there are many recommendations but few definitive answers. Ewing & Handy (2009) identify “urban design qualities” and constituent physical characteristics that, according to urban design literature and the opinions of an expert panel, contribute to walkability. Their research is the basis from which Purciel et al. (2009) operationalize streetscape measures using a variety of GIS data sources, and from which I identified measures based solely on GIS building geometry (Table 3.1).

Table 3.1: Skeleton variables measurable with various GIS and perceptual methods

	Method #1: GIS Geometric (Skeleton Variables)	Method #2: GIS Geometric & Proxy	Method #3: Perceptual Field Audit
Literature Source	This study	Purciel et al., 2009	Ewing and collaborators ^a
Variables measured similarly across the methods	Street wall continuity	Proportion of block area within buildings (as proxy)	Proportion of street wall
	Height (average of building heights)	Average height of primary building in each adjoining parcel	Estimated building height
	Buildings per length	Count of buildings	Count of buildings
Variables Measured distinctly by each method	Width (between buildings across the street)	GIS simulation of horizontal sight lines based on building footprints	Number of long sight lines
	Cross-sectional proportion		Proportion of sky visible
	Length (of centerline)		
	Variability in height		
	Variability in width		
	Sinuosity (of centerline)		

^a Clemente, Ewing, Handy, & Brownson, 2005; Ewing, Clemente, Handy, Brownson, & Winston, 2005; Ewing, Handy, Brownson, Clemente, & Winston, 2006; Ewing & Clemente, 2013; Ewing & Handy, 2009

Measurement of streetscape skeletons using GIS poses benefits of efficiency and consistency against limitations on spatial scale and measurement diversity. A chief limitation of GIS methods is exclusion of microscale design characteristics—materials, architectural styling, ornamentation, fixtures, cleanliness—activity, and non-visual sensations that contribute in important and nuanced ways to user experience. Such microscale elements may be considered the “skin” of a streetscape. Field audits are advantaged in capturing these characteristics (Clifton et al., 2007).

Streetscape “skeletons,” based on more macroscale characteristics such as the dimensions and arrangement of buildings, have greater potential to be measured with a GIS because they are based on common data inputs and evaluation of geometric relationships for which GIS tools are well-suited. The relationship between skeleton and skin is analogous to that between a wireframe drawing and an architectural rendering. The former supplies the spatial structure for a scene, defining the size and shape of space; the latter embellishes with visual texture, making it come alive. The boundary between skeleton and skin is undoubtedly nebulous. While characteristics at scalar extremes, such as building height and siding material, clearly contribute to streetscape appeal, characteristics between these scales, such as lamp posts, street furniture, awnings, or vegetation, also contribute. On one hand, these objects define important subspaces within streetscapes. Alternatively, they simply embellish the broader streetscape already defined by buildings that dwarf them in size. For the purposes of this chapter, streetscape skeletons are interpreted as the product of the size and arrangement of buildings, the largest and most visually dominate objects in most urban streetscapes. The following chapter additionally accounts for street trees, which provide a similar scale of spatial definition, including roof-like enclosure provided by overhanging canopy (Arnold, 1993). While the effects of trees are important, trees are not as ubiquitous in urban settings as buildings. Moreover, tree data are not so consistently available. As such, trees were not included in this chapter’s multi-city analysis.

Skeletal dimensions and arrangement of buildings are chiefly responsible for creating the sense of enclosure—aligned façades and cornices that create a room-like

feeling in the street (Ewing & Handy, 2009)—revered by urban design theorists. Alexander et al. (1977) emphasize the power of negative space between buildings, especially when the space has clear shape and definite edges, to instill a sense of place and position for occupants. Enclosure provides streetscapes with spatial identity, allowing them to be described as interior entities, e.g., “I am outside IT, I am entering IT, I am in the middle of IT” (Cullen, 1971). Enclosed streetscapes are esteemed as safe-feeling, memorable (A. B. Jacobs, 1993), and preferred by pedestrians compared with more open corridors (Moniruzzaman & Páez, 2012; Nasar, 1987).

The arrangement of buildings along either side of a streetscape has been the most fundamental pattern of urban design throughout millennia of development. Resulting enclosure may be the sensation which, from the ground, most visibly separates country and city (Cullen, 1971). In this way, enclosure may be essential to the “imageability”—visual memory—of cities and places within them (Lynch, 1960). Enclosure also compresses the streetscape, bringing stimuli closer to users and intensifying the effects of visual complexity. Enclosed streetscapes are esteemed as safe-feeling, memorable (A. B. Jacobs, 1993), and preferred by pedestrians compared with more open corridors (Moniruzzaman & Páez, 2012; Nasar, 1987).

In urban settings, measurements of the massing and arrangements of buildings are useful for representing fundamental aspects of streetscape enclosure. Ewing & Handy (2009) measure enclosure based on street wall continuity, sight lines, and sky visibility; these are, in large part, measures of the space between buildings. While they are straightforward for field auditors to estimate, such measures are difficult to replicate with

a GIS. Purciel et al. (2009) attempt literal GIS operationalization with variable success. A more pragmatic approach is to measure the aggregate proportions and scale of buildings surrounding a streetscape, which affect visibility upward and to the sides. Enclosure is often described on the basis of cross-sectional proportion, the ratio of building height to across-the-street width. Ewing & Handy (2009) catalogue recommendations of minimum height to width proportions ranging from 2:3 to 1:6. While there is no theoretical or scientific consensus on which proportion is most appealing, it is clearly an important measure to evaluate. However, because such proportions provide only a snapshot of enclosure along a specific cross-section, or an average of multiple cross-sections, measures of variability in height and width may also be important for describing enclosure along the length of a block.

While enclosure speaks to the proportions of a streetscape it does not account for scale. The term *human scale* is commonly used in urban design literature, although there are few definitive interpretations of its boundaries (Alexander et al., 1977). Sense of scale can be conveyed by embellishments, such as furniture, planters, and ornamentation, or by the size of encompassing structures and spaces. The latter are more realistically measured using GIS methods. Theorists also discuss scale in the context of speed; a large street may feel appropriate when moving fast in a car, but uncomfortably vast for a pedestrian (Ewing & Handy, 2009). Human scale generally refers to an appealing scale for users on foot.

The height of surrounding buildings is a common metric of streetscape scale. Authors surveyed by Ewing & Handy (2009) recommend between three and six stories as

a maximum building height, or “stepbacks” after the first several stories, to preserve human scale from a street-level perspective. The width of buildings also theoretically contributes to perceptions of scale. A street wall occupied by a single, long façade is less likely to feel human scale than a row of narrower individual buildings, or even diverse façades in a contiguous row.

Several authors prescribe human scale streetscapes, including some specific dimensions, based on limits of perception and social interaction. Jane Jacobs (1961) discusses how low buildings, from which neighbors can keep “eyes on the street” even from upper floors, promote communality and neighborhood safety. Alexander et al. (1977) claim that 70 feet (21.3 m) is the maximum distance for both facial recognition and conversation using a loud voice. Allan Jacobs (1993) defines specific architectural dimensions as “intimate scale:” buildings that are 21 feet (6.4 m) high with a maximum of 24 feet (7.3 m) of frontage, separated by 48 feet (14.6 m) across the street. Blumenfeld (1971) recommends more liberal maximums of 30 feet (9.1 m) high, 36 feet (11 m) of frontage, and 72 feet (22 m) across the street.

While traffic engineers and planners often define street width as the distance between curbs or the width of the right-of-way, urban designers are concerned with the width between opposing building façades. This is the width of the visual field for a street-level user. Because land ownership conventions and setback definitions are inconsistent between cities—parcels in some cities extend through rights-of-way to street centerlines, while land for streets in other cities is owned municipally; setbacks can be defined from

centerlines, curb lines, or parcel boundaries—building-to-building width is a more general measure with equivalent meaning in any setting.

Streetscape proportions and scale also contribute to what Ewing & Handy (2009) describe as *transparency*—whether spaces and activity beyond the street wall can be viewed, or at least imagined—and *complexity*—the variety of sensory stimuli provided by a streetscape. Both are heavily affected by micro-scale details such as window arrangement, architectural decoration, signs, and street objects that are not yet consistently recorded in spatial data. Nonetheless, street wall continuity, which is readily measurable with building footprints, indicates transparency between and behind buildings. Architectural variety or repeating patterns add visual texture, so the number of buildings per length of street is a useful measure of complexity (A. Jacobs & Appleyard, 1987).

Urban design literature suggests that the elemental geometry of buildings reveals much about a streetscape’s potential appeal. Variables such as width, height, cross-sectional proportion, street wall continuity, and buildings per length have great potential to be measured with commonly available GIS data and tools. Replicable and efficient GIS processing allows assessment of large, geographically-dispersed samples of streetscapes that would be impractical to survey using traditional field audits.

3.3 Methods

A novel GIS-based method was used to measure a suite of skeleton variables based on building geometry along block-length urban streetscapes. Cluster analyses were

then used to examine whether there were strong patterns among the variables representative of discrete skeleton types, whether the patterns were consistent throughout the study cities, and whether they were related to functional classes traditionally used to characterize streets. The unit for all analyses was the block-length street segment and the streetscape surrounding it, with a spatial extent spanning lengthwise along the centerline between adjacent intersections and widthwise between the street-facing façades of building to either side. The GIS-method “searched” for buildings up to forty meters from each segment’s centerline. When no buildings bounded one side of a streetscape, such as along a park or waterfront, its width extended forty meters from the centerline in that direction plus any additional distance from the centerline to façades of buildings on the opposite side. Because the streetscape skeleton concept emphasizes how space is defined by vertical objects that provide enclosure by blocking sight lines, horizontal boundaries such as curbs, traffic lanes, sidewalks, and medians were not accounted for. Segments that were longer than five hundred meters, shorter than twenty meters, had no buildings within forty meters of the centerline, or had special characteristics were excluded from analysis. Sections 3.3.2 (Data) and 3.3.3 (GIS-Based Streetscape Measurement) provide more detailed descriptions of how street segments were identified and measured.

Because streetscape enclosure provided by buildings is a primarily an urban phenomena, this study assessed streetscapes within the municipal boundaries of three large cities in the northeastern United States: Boston, MA, New York, NY, and Baltimore, MD. The streetscape skeleton concept is contingent on the potential for streetscapes to be identified as discrete, three-dimensional spaces that can experienced,

more or less, from a single vantage point within them. It is best suited to urban contexts where blocks are relatively short and straight, and buildings are sufficiently dense so that fields of view include multiple buildings, whose spatial relationships to one another define the shapes of outdoor spaces. The environments of rural roads, with more distance between intersections, more curvilinear paths, and little development along them, are more nebulous to define and more likely enclosed by trees rather than buildings. While rural and suburban settings offer a promising direction for development of further measurement techniques and research, the present study focuses on the high-density core and medium-density peripheral neighborhoods of major cities, where streetscapes are most intelligible as a unit of analysis.

3.3.1 Study Cities

Boston, New York, and Baltimore provided an opportunity to assess the regional consistency of streetscape skeletons using spatial data that were publicly available and of comparable quality (Figure 3.1). Each of the cities contains a variety of land uses and development densities within municipal boundaries. All three include downtown areas with many buildings upward of 100 meters tall, as well as outlying residential and commercial areas with smaller buildings and lower densities. The development histories of the three cities are similar, with 17th and 18th century settlement beginning in what are now downtown areas close to natural harbors. Development in the 19th and early 20th centuries greatly expanded each city's residential neighborhoods, while the late 20th century fostered continued expansion of medium-density development in peripheral areas along with high-rises and superblock development associated with "urban renewal" in

and around their downtowns. Redevelopment has been substantially more active in Boston and New York than in Baltimore, which has been losing population since its peak in the 1950s. All three cities have variously-sized gridiron street networks interspersed with more angular or curvilinear networks that predate the grids or were developed in the early 20th century.

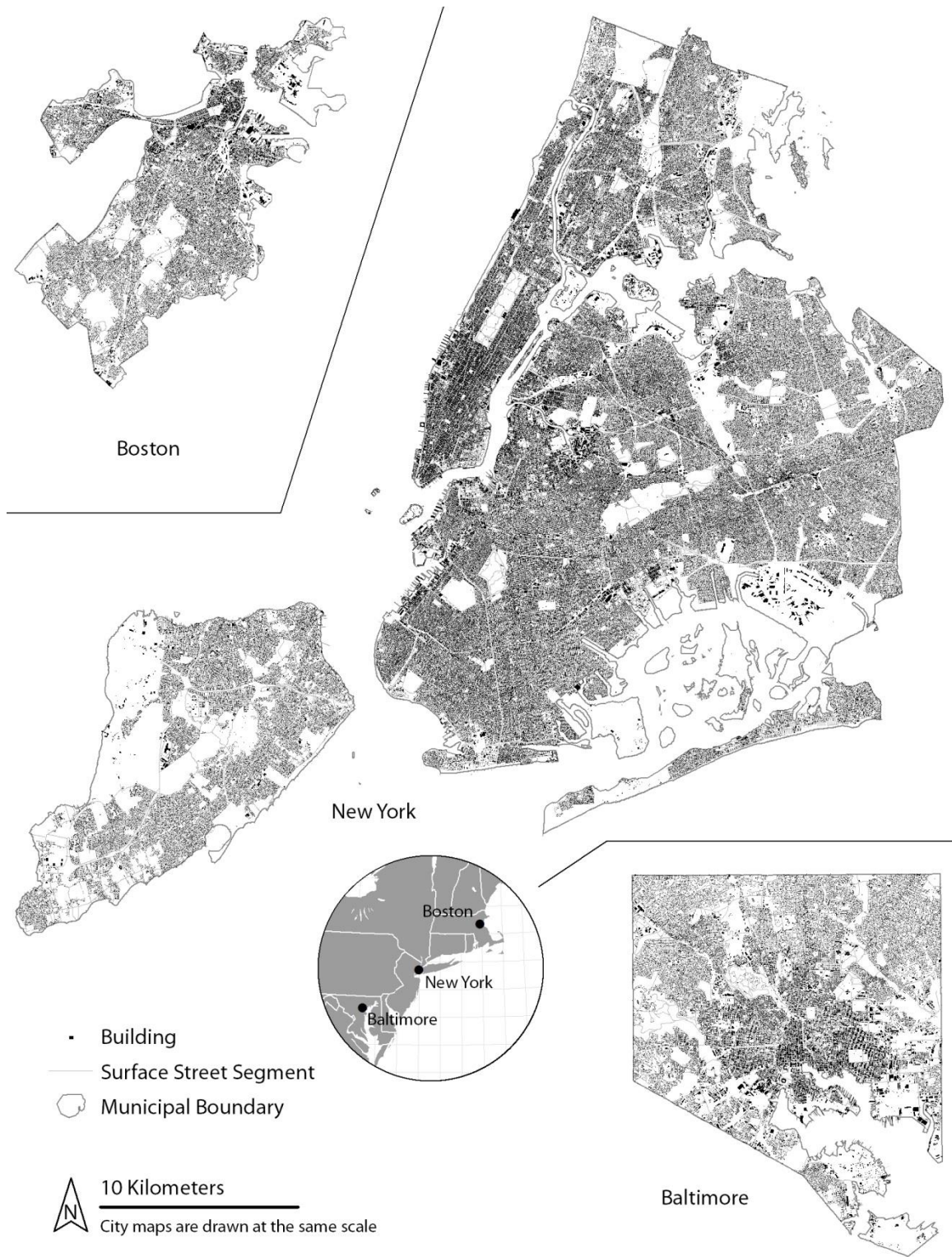


Figure 3.1: Study extents in Boston, New York, and Baltimore.

While the cities have similar development trajectories, they have enormously different spatial, population, and development scales (Table 3.2). New York is by far the largest, with a population roughly thirteen times that of Boston or Baltimore, and a land area several times larger. New York also has the densest development, with twenty percent of its land area covered by buildings compared with eighteen percent in Boston and fifteen in Baltimore. Lower and Midtown Manhattan, New York’s downtown core, are home to a large number of skyscrapers that form a signature skyline. Both Boston and Baltimore also have skyscrapers in their downtowns, though fewer and less extreme in height.

Table 3.2: Study city overview

City	Land Area sq km	Population	Population Density pop/sq km	Public Roadways km	Number of Buildings	Proportion of Land Area in Buildings	Buildings Over 100 Meters Tall
Boston	125	636,500	5,092	1,890	129,400	18%	107
New York	780	8,273,100	10,607	45,500	1,080,500	20%	640
Baltimore	210	621,300	2,959	3,672	258,775	15%	22

Importantly, this study included only streets and buildings within the municipal boundaries of each city, not adjacent municipalities that belong to their larger metropolitan areas. While further research should examine streetscapes in these suburban contexts, varying availability and precision of building geometry data made it prudent for this study to focus on the political boundaries where consistently high quality data were available for each city.

3.3.2 Data

Spatial data inputs for measurement of streetscape skeleton variables in all three cities were publicly-available through internet data portals or municipal agencies (Table 3.3; City of Baltimore, 2013; City of Boston, 2013; City of New York, 2013). Street centerlines from municipal sources, which were deemed to be the most geometrically precise of available options, were used as the geometric basis for street segments. Centerlines from ESRI StreetMap (ESRI, 2012), with associated Census Feature Class Codes (CFCCs), were used assign functional classes— *arterial*, *collector* or *local*—to municipal centerlines. StreetMap centerlines were joined to the nearest municipal centerline within twenty meters; municipal centerlines greater than twenty meters from an ESRI centerline were excluded from analysis. Original CFCC classifications were recoded so that primary highways with limited access (A1) and primary roads without limited access (A2) were considered *arterial*, secondary and connecting roads (A3) were considered *collector*, and local, neighborhood, and rural roads (A4) were considered *local* (Figure 3.2). Segments originally classified as vehicular trails (A5), roads with special characteristics (A6), and other roads (A7) were excluded from the analysis.

Table 3.3: Data sources

Role	City	Street Centerline		Building Footprint	
		Source	Year	Source	Year
Geometry	Boston	Boston DoIT	2011	Boston DoIT	2002
	New York	NYC Open Data	2012	NYC Open Data	2011
	Baltimore	Open Baltimore	2008	Open Baltimore	2008
Functional Class Attributes	All Cities	ESRI StreetMap	2012		

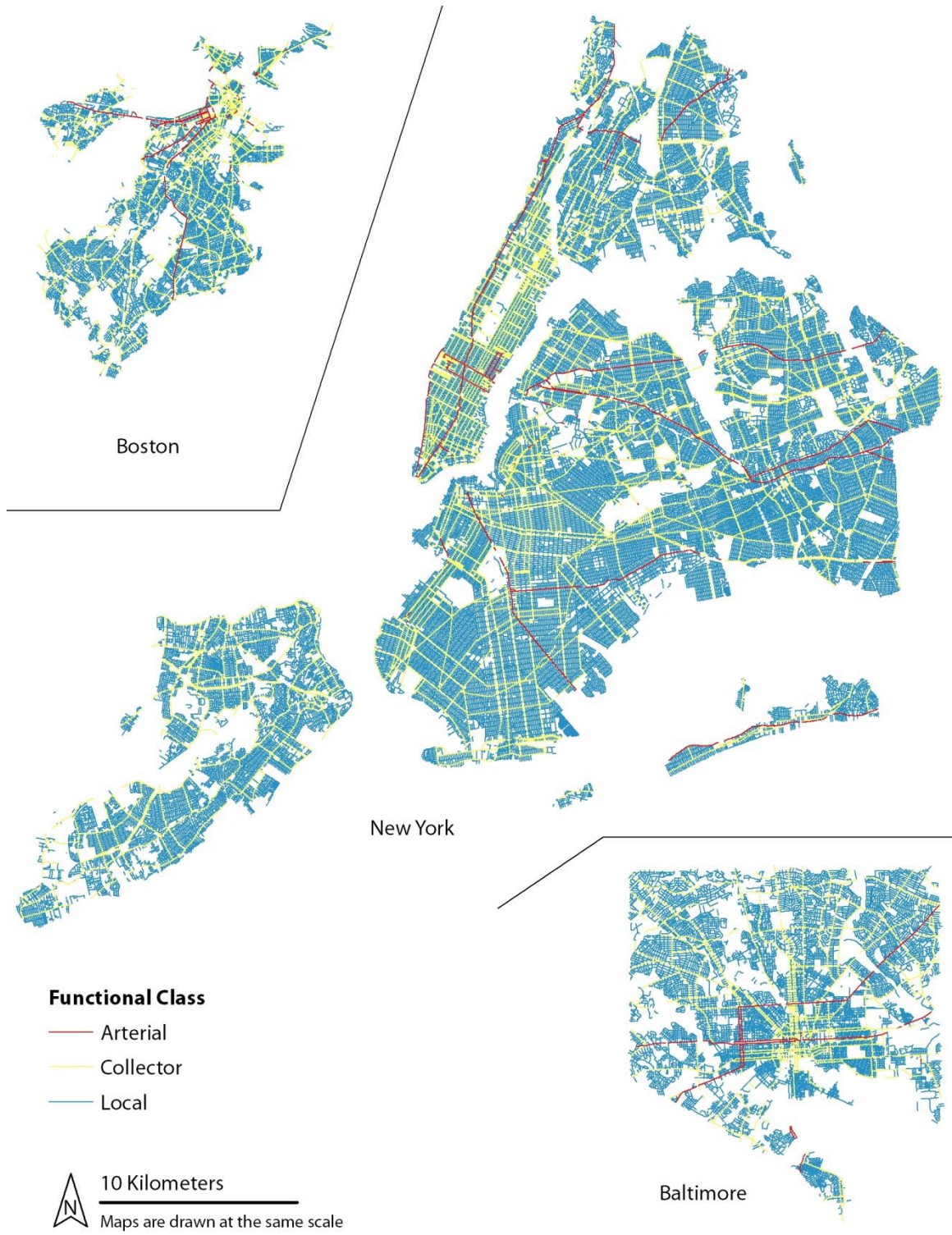


Figure 3.2: Spatial distribution of street segment functional classes in each study city.

Precise building footprints, originally derived through manual tracing of roof outlines from aerial photography and corrected to represent ground positions using stereoscopy, were publicly available from municipal sources in each city. The quality of building height estimates, which were included as a tabular attribute associated with each footprint, varied between cities based on the technology used to derive them. Height data for Boston were derived from LiDAR, while data for Baltimore and New York were derived primarily from stereoscopy.

Street centerline datasets, principally designed to facilitate transportation network analysis, included redundant centerlines along many divided-lane streets in order to model network flows more realistically. Complex intersections were often represented by many line segments tracing the potential paths of motor vehicle traffic. Because the method for measuring skeletal variables assessed the geometry of streetscapes, not their traffic function, centerline geometry were preprocessed to better approximate the assumption of a single, continuous centerline running parallel to the curb and in the approximate center of each street segment.

To produce centerline segments that were split at intersections, but continuous between them, original centerline data were dissolved by street name, removing mid-block splits. Intersections were identified wherever centerlines crossed or at least three centerlines converged. Because the GIS method used spatial extents to distinguish between segments, 0.5 meters were erased from the end of each segment to separate them slightly, yielding block-length centerline segments separated by at least one meter. Segments less than twenty meters long, which included most fragmented segments in and

around complex intersections, were excluded. Our visual inspection of segment geometry detected no areas where regular block spacing was less than twenty meters; thus, the basic structure of the street network was maintained. Segments greater than five hundred meters long, of which there were few, were also excluded on the basis of being unrepresentative of an urban setting and too long for users to interpret as a single, cohesive segment.

Attribute selection and a systematic visual inspection on an aerial photography base map were used to identify dual centerlines and alleys, ramps, and streets without names. Because naming conventions were often unreliable, as were type attributes associated with centerline datasets, segments on expressways, ramps, bridges, and tunnels were visually identified and excluded. Redundant centerlines—second, third, and fourth centerlines on a single right-of-way—were also excluded. In most cases the remaining centerline was not centered in the right-of-way. However, because the measurement method described below works independently on either side of a segment, this did not affect edge detection or overall street width measurement. All told, 12,111 kilometers of street centerline were prepared for analysis, constituting approximately 65% of all public roadway centerline distance across the three cities.

3.3.3 GIS-Based Streetscape Measurement

A geographic information system (GIS) provided an efficient and replicable approach for measuring streetscape skeleton variables. The measurement method developed for this study used a combination of GIS tools and database queries in a three-

stage sequence to (1) examine the distance of buildings to either side of a street centerline, (2) define edges which approximate the extent of a streetscape to either side, and (3) measure twelve skeleton variables within this extent (Table 3.4; Figure 3.3). Each variable was measured for each block-length street segment.

Table 3.4: Twelve streetscape skeleton variables based on building geometry

	Streetscape Skeleton Variable	Spatial Definition
1	Width	Distance between edges (building-to-building) across the street
2	Length	Centerline distance between intersections
	Height,	Average building height on the...
3	higher side	higher side of the street
4	lower side	lower side of the street
	Cross-sectional proportion,	Full width (building-to-building)/Height on the...
5	based on higher side	higher side of the street
6	based on lower side	lower side of the street
	Street wall continuity,	Proportion of edge intersecting buildings on the...
7	more continuous side	more continuous side of the street
8	less continuous side	less continuous side of the street
9	Buildings per length	Count of buildings on both sides/length
10	Variability in height	Standard deviation of average building height on both sides
11	Variability in width	Proportion of street area intersecting building area
12	Sinuosity	Centerline length/straight line distance between segment ends

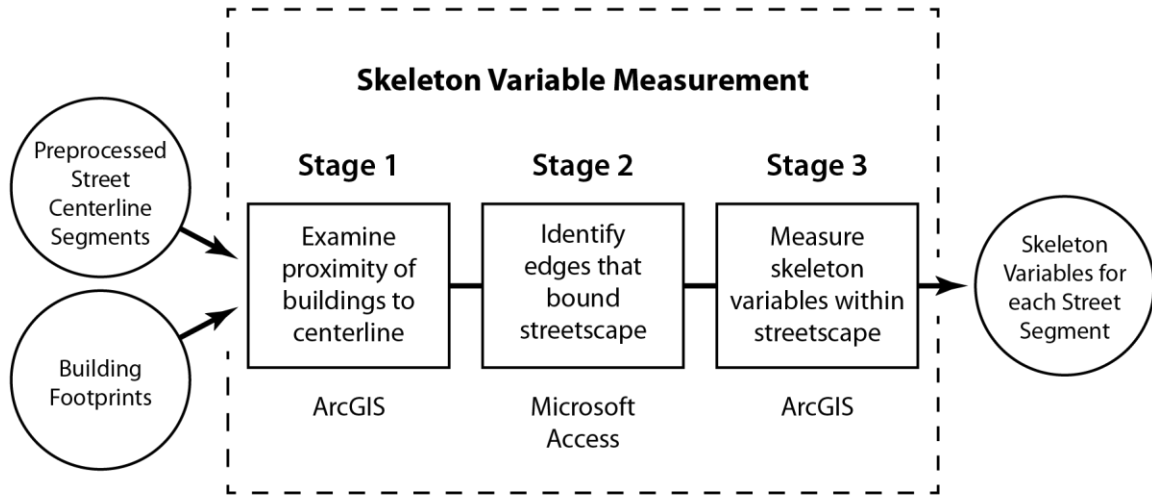
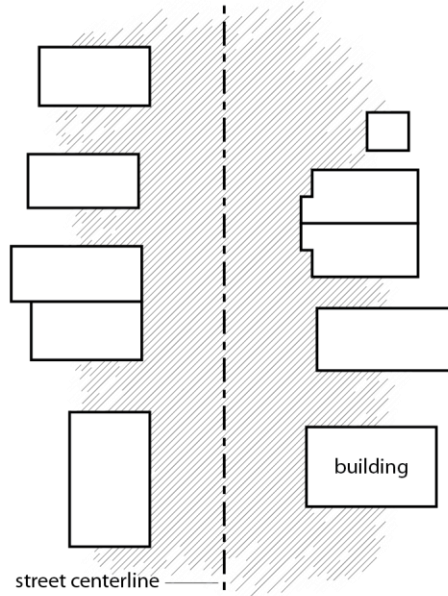


Figure 3.3: Multistage method for skeleton variable measurement.

Automatically identifying streetscape extents presented both a theoretical and technical challenge. Humans are efficient at interpreting complex geometric arrangements, such as streets lined by buildings with alleys, yards, and vacant lots between them, as discrete spaces with fuzzy edges (Stamps, 2009). Such fuzzy edges were difficult to identify algorithmically. Topological definitions of interiority were unusable because street walls may be riddled with gaps between buildings and at intersections (Figure 3.4, A). An automated method had to emulate edge detection from a street-level perspective, by identifying façade alignment at a predominant setback (Figure 3.4, B), to define crisp, albeit approximate, streetscape edges (Figure 3.4, C).

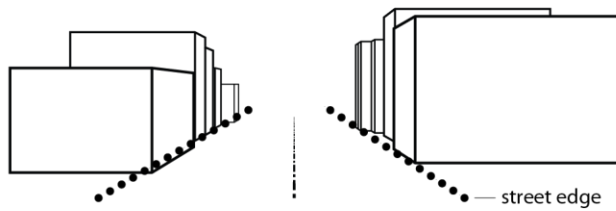


(A)

Overhead View

Streetscape edges may be difficult to define topologically.

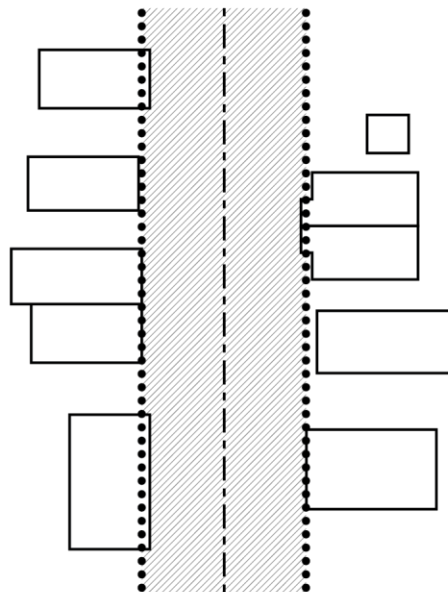
Variation in building setbacks and gaps between buildings can make the positions of edges imprecise.



(B)

Street-Level Perspective

Streetscape edges may be identified by alignment of building façades.



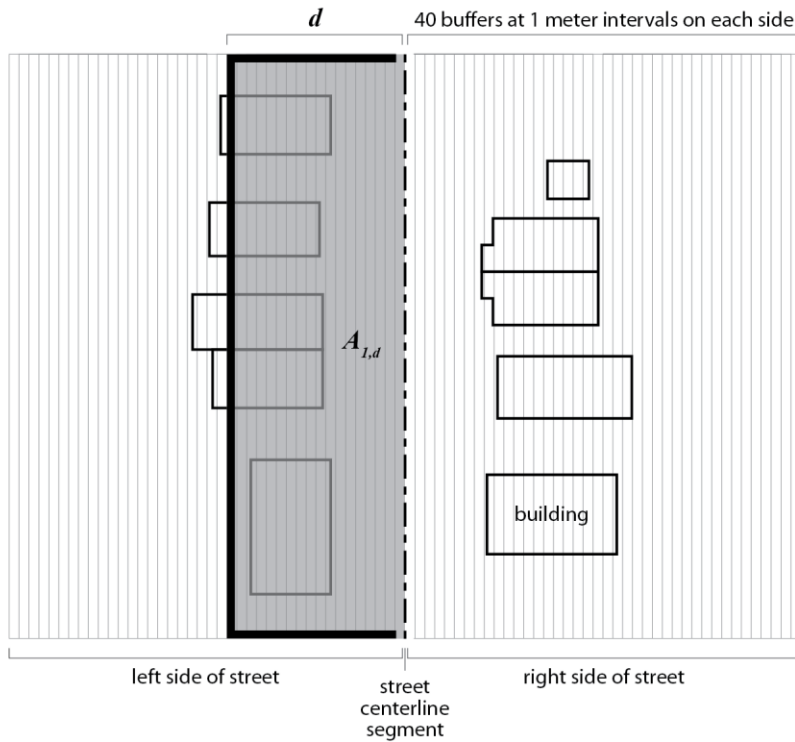
(C)

Overhead View

Streetscape edges were approximated by identifying consistency in building setbacks. Edges spanned gaps between buildings. The sizes of gaps were later assessed.

Figure 3.4: Edge detection from overhead and street-level perspectives.

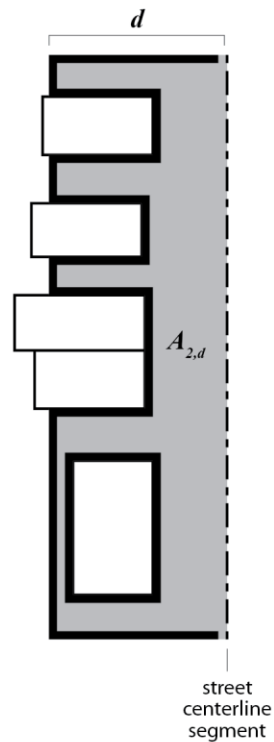
The GIS-based method identified edges along each side of each street centerline segment using an ArcGIS geoprocessing model and SQL queries in Microsoft Access. The GIS model drew flat-ended, single-sided buffers at a progressively larger distance (d), between one meter and forty meters at one-meter intervals, to either side of each centerline segment, calculating the area of each buffer, $A_{1,d}$ (Figure 3.5, A). Next, the model subtracted building footprints from the buffers and calculated the non-building areas, $A_{2,d}$ (Figure 3.5, B). The ratio $A_{1,d} : A_{2,d}$ was calculated for each buffer distance, along with the difference in area ratios between each buffer and its sequentially larger neighbor, $A_{1,d} : A_{2,d} - A_{1,d+1} : A_{2,d+1}$. A series of SQL queries identified where this ratio difference was maximized, indicating the distance, d , at which buildings most abruptly intersected the buffers and an edge would likely be perceived by street-level users (Figure 3.5, C).



(A)

Forty buffers were drawn to either side of each centerline at one meter intervals.

Areas, $A_{1,d}$, were calculated for each buffer.



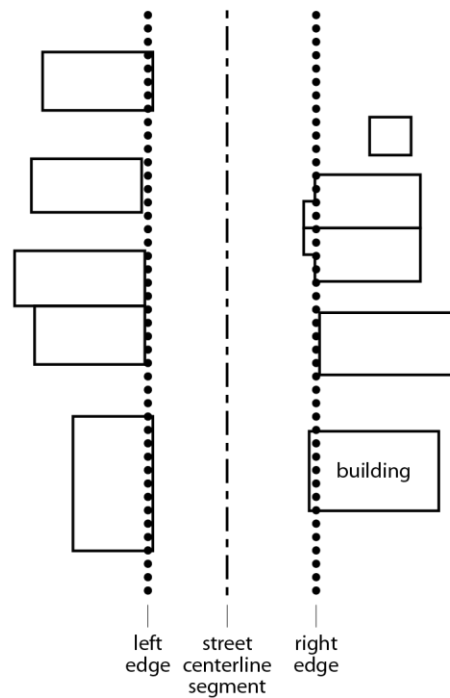
(B)

Building footprints were subtracted from each buffer.

Resulting areas, $A_{2,d}$, were calculated.

Ratios $A_{1,d} : A_{2,d}$ were calculated for all forty buffers on both sides of every street segment in the sample.

Figure 3.5: GIS-based streetscape edge detection using sequential buffers.
(Continued on next page)



(C)

Edges were identified where the differences between consecutive ratios, $A_{1,d} : A_{2,d}$ were maximized. This indicated where buildings most abruptly intersected the buffers.

Figure 3.5: (Continued from previous page)

The street width method could theoretically have drawn and assessed buffers *ad infinitum* to either side. A reasonable limit for analysis was forty meters from each centerline, resulting in eighty meters of total potential width. To our knowledge, the widest street corridor in the study cities that was lined by buildings with a consistent setback was Eastern Parkway in Brooklyn, New York, which has a building-to-building width of approximately eighty meters along twelve consecutive blocks. Assessing forty meters from each side of the centerline suitably described the Eastern Parkway street wall. Measuring width up to eighty meters also adequately distinguished between human-scale streets with a maximum width of approximately twenty meters, and those that were wider and likely dedicated to motor-vehicle movement (Alexander et al., 1977;

Blumenfeld, 1971; A. B. Jacobs, 1993). Finally, measuring forty meters to either side provided a reasonable balance of analysis extent, resolution, and processing efficiency, requiring approximately three hours for each batch of 10,000 street segments. Segments with no buildings within forty meters of the centerline were excluded from analysis.

Once streetscape edges were identified, streetscape skeleton variables were straightforwardly measured based on the geometry of centerlines, edges, and the buildings intersecting them. Because the GIS-based method identified edges only at one-meter intervals from the centerline, buildings were considered to intersect a street edge if they were up to one meter away. *Width* was the distance between opposing edges (Figure 3.6, A). *Length* was the centerline distance between segment ends (Figure 3.6, B). Because development along a street may have been biased to one side, such as a street along the edge of a park or water body, measurements based on height and street wall continuity were broken into two variables. *Height* was the average height of buildings along either edge, reported for both the *higher* and *lower* sides (Figure 3.6, C). *Cross-sectional proportion* was the ratio of average building height to overall width, reported based on the heights for both the *higher* and *lower* sides (Figure 3.6, D). *Street wall continuity* was the proportion of each edge that intersected a building, reported for both the *more continuous* and *less continuous* sides (Figure 3.6, E). *Buildings per length* was the count of buildings on both sides standardized by length (Figure 3.6, F). *Variability in height* is the standard deviation of heights among buildings along both edges (Figure 3.6, G). *Variability in width* was the proportion of area between edges occupied by buildings

protruding into it (Figure 3.6, H). *Sinuosity* was the ratio of centerline length to straight line distance between the ends of segment.

Streetscape skeleton variables were measured for a total of 122,216 street segments across the three study cities (Table 3.5). Fourteen batches consisting of no more than 10,000 segments each were measured on a desktop workstation over approximately thirty-five hours of total processing time. The resulting variables were all positive and continuous. Width, length, height, and variability in height, produced linear measurements with units in meters. All other variables were proportions. Width and the street wall continuity variables were the most normally distributed. Nine variables were skewed with tails to the right. Such distributions indicated a high degree of within-variable homogeneity. To best satisfy the assumption of normality implicit in cluster analysis, these variables were square root transformed prior to analysis. Square root transformations retained values of 0 and 1 that were helpful for interpretation of proportions.

Table 3.5: Skeleton variable descriptive statistics

City	Count	Width (meters)	Length (meters)	Height, higher side (meters)	Height, lower side (meters)	Cross- sectional proportion, based on higher side	Cross- sectional proportion, based on lower side	Street wall side	Street wall less cont. side	Buildings per length	Var. in height	Var. in width	Sinuosity
Mean (Standard Deviation)													
Boston	13,409	28.1 (14.5)	95.7 (65.5)	11.2 (9.5)	7.0 (5.1)	0.54 (0.70)	0.37 (0.46)	0.56 (0.19)	0.35 (0.22)	0.09 (0.05)	1.70 (3.05)	0.04 (0.03)	1.01 (0.11)
New York	83,195	33.7 (13.3)	106.3 (64.7)	13.7 (16.3)	8.2 (8.7)	0.47 (0.66)	0.31 (0.38)	0.60 (0.19)	0.38 (0.24)	0.10 (0.06)	1.87 (4.13)	0.04 (0.03)	1.00 (0.02)
Baltimore	25,612	31.8 (15.1)	77.4 (59.4)	10.0 (6.7)	6.7 (4.3)	0.42 (0.47)	0.30 (0.30)	0.59 (0.23)	0.37 (0.26)	0.13 (0.11)	0.56 (1.18)	0.03 (0.03)	1.00 (0.03)
All Cities	122,216	32.6 (13.9)	99.1 (64.8)	12.7 (14.2)	7.7 (7.6)	0.47 (0.63)	0.31 (0.38)	0.59 (0.20)	0.38 (0.24)	0.10 (0.08)	1.57 (3.63)	0.03 (0.03)	1.00 (0.04)

3.3.4 Cluster Analysis

Cluster analysis was used to identify multivariate patterns of similarity and difference among streetscapes and guide the development of streetscape skeleton types. A multistage process explored which variables were important to include in clustering, assessed the appropriate number of clusters, determined a final clustering result, assigned each street segment in the sample to a cluster, and interpreted the average characteristics of each cluster.

Following LaMondia & Aultman-Hall (2014) and Tkaczynski et al. (2010), I used a two-step cluster analysis implemented in IBM SPSS Statistics 21. The two-step method was ideally suited for a large dataset that would be prohibitively memory-intensive for traditional hierarchical algorithms and for which there were an unknown number of clusters. It pre-clustered records by sorting them sequentially into a tree structure based on similarity with other records. The initial branching divided records into groups of similar values for one variable. The next branching further divided into subgroups of similar values for the next variable. Because records were sorted sequentially, results were affected by record input order. Norusis (2008) recommended that records be randomized prior to analysis; multiple runs with randomized orders can be used to refine results.

Once branching was completed for all variables, the preclusters and their means for each variable were entered into a single linkage (nearest neighbor) hierarchical clustering algorithm that iteratively joined clusters to minimize distance within them and

maximize distance between them. Distance was defined as the log-likelihood of a joint cluster, defined as:

$$d(m, n) = \delta_m + \delta_n - \delta_{\langle m+n \rangle} \quad \text{Equation 3.1}$$

where $\langle m, n \rangle$ was the potential joint cluster consisting of clusters m and n .

The position of each cluster was calculated as:

$$\delta_v = -N_v \left(\sum_{k=1}^K \frac{1}{2} \log(\hat{\sigma}_k^2 + \hat{\sigma}_{vk}^2) \right) \quad \text{Equation 3.2}$$

where N_v was the number of records in cluster v , $\hat{\sigma}_k^2$ was the estimated variance of each variable k , and K was the number of variables (LaMondia & Aultman-Hall, 2014). The method assumed that variables were normally distributed and that both variables and records were independent from one another, though Norusis (2008) claimed that the method was reasonably effective when these assumptions were not satisfied.

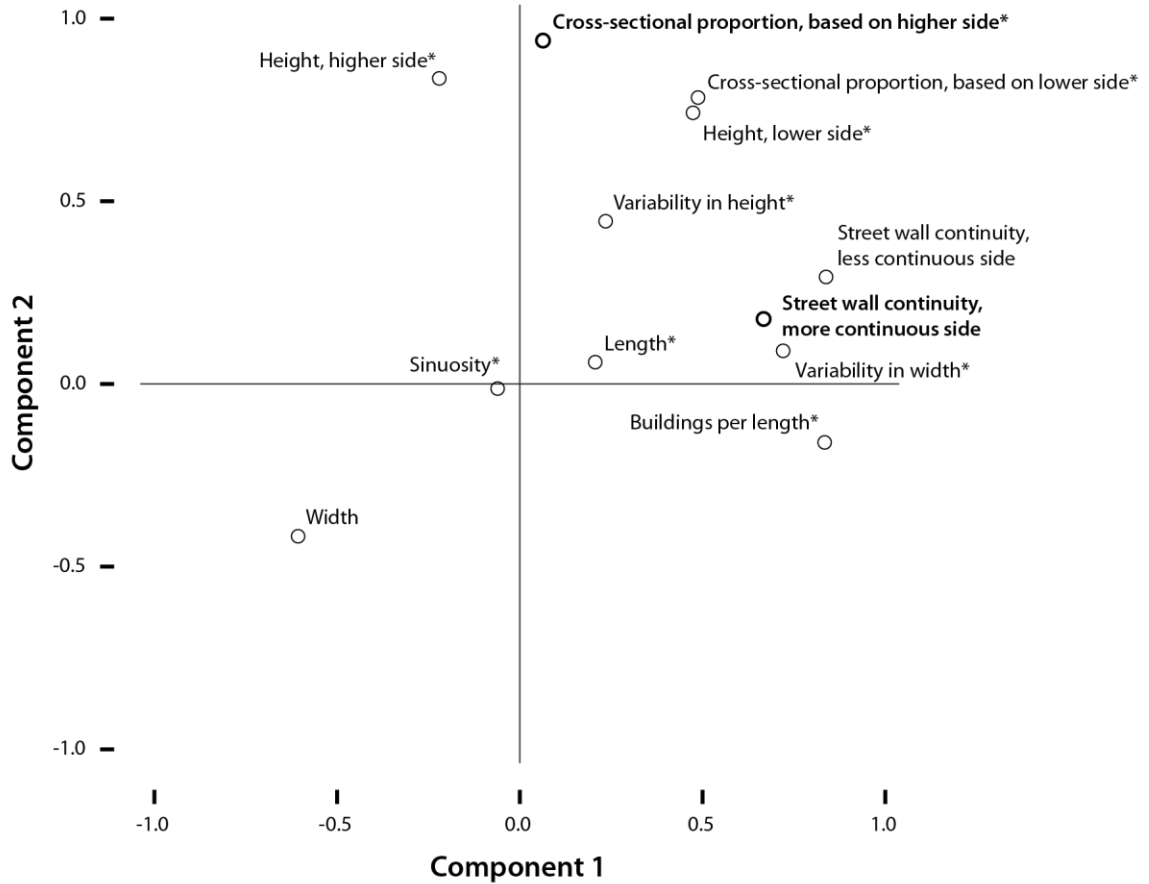
Two metrics were used to appraise clustering fit and the appropriate number of identifiable clusters. Clustering solutions were compared for fit using the Bayesian Information Criterion (BIC). Fraley & Raftery (1998) and Norusis (2008) recommend selecting the number of clusters at which the magnitude of BIC changes most dramatically to a small value, and where change is minimal thereafter—essentially, the inflection point of an exponentially diminishing curve. Because clusters in real-world data are rarely clearly defined, BIC comparison indicates only an approximation of the reasonable number of clusters and must be substantiated by theoretical meaningfulness.

Cluster fit was also assessed using the silhouette coefficient of cohesion and separation, which, for each record, evaluates the ratio of mean distance of points in the same cluster to the mean distance of points in the next closest cluster. The mean of silhouette coefficients among records summarized the overall cohesion, or similarity, of streetscape records within a clustering solution, and their separation, or difference, from the records in other clusters. The coefficient had a theoretical range from 0 to 1 (although negative values might have been achieved if there were no clustering tendencies within the data). Kaufman & Rousseeuw (1990) suggested that average silhouette coefficients between 0.5 and 1.0 indicated good cluster quality.

All streetscape skeleton variables were initially entered into the clustering algorithm. Variables were removed one at a time, and cluster fit was assessed for each of the results. The process demonstrated that clusters derived from two variables—cross-sectional proportion based on the higher side and street wall continuity on the more continuous side—were similar in size, number, and silhouette to those including additional variables. This finding was consistent with the assumption that clustering would be most effective when included variables were independent.

Principal component analysis (PCA) was used to visualize the relationships between variables and determine which were sufficiently independent to use for clustering (Figure 3.7). Cross-sectional proportion based on the high side and street wall continuity on the more continuous side were two of the most orthogonal in the first two principal components, indicating their relative independence. They were also two of the most heavily weighted. Additionally, cross-sectional proportion and street wall continuity

were composite variables, allowing them to represent the height, width, and length variables from which they were constructed.



* Square root transformed

Figure 3.7: Obliquely rotated principal component loadings of skeleton variables.

To assess the number of clusters appropriately identifiable among the data, ten clustering runs were examined for best-fit according to the BIC-based method described above. Each run used a randomly generated record order. Across the ten runs, the modal number of clusters for each city was four. The minimum number of clusters generated in

a given run was two and the maximum was ten. Silhouette coefficients for four-cluster solutions were consistently 0.5.

Joint distributions of cross-sectional proportion and street wall continuity were evaluated to confirm the validity and reasonableness of a generalized four-cluster solution (Figure 3.8). A large portion of records were located around the mean values for both variables, although closer inspection revealed a bimodal distribution in proportion of street wall resulting in two central clusters. Lower values of both variables formed a sparser third cluster. The long tail of cross-sectional proportion formed an even sparser fourth cluster that was identifiable based its separation from the density of other clusters rather than its internal cohesion.

To identify final clusters, and assign a cluster type to each street segment, two-step clustering was repeated using the same ten randomly generated record orders while specifying a four-cluster solution. Because the clusters were not output from the algorithm with consistent identifiers, their centroids were plotted to identify similarity in their positions across iterations (Figure 3.8). The plots revealed consistent centroid estimates across the cities, forming a general typology. Each street segment record was assigned the modal type identified by the ten clustering iterations. Mean variation ratios for cluster assignment, which indicated the proportion of assignments inconsistent with the mode, were 0.09 for Boston, 0.15 for New York, and 0.10 for Baltimore, demonstrating high consistency in cluster assignment across all three cities, but least consistency in New York. This was likely due to New York's relatively larger sample of streetscapes with less variability among skeleton measurements.

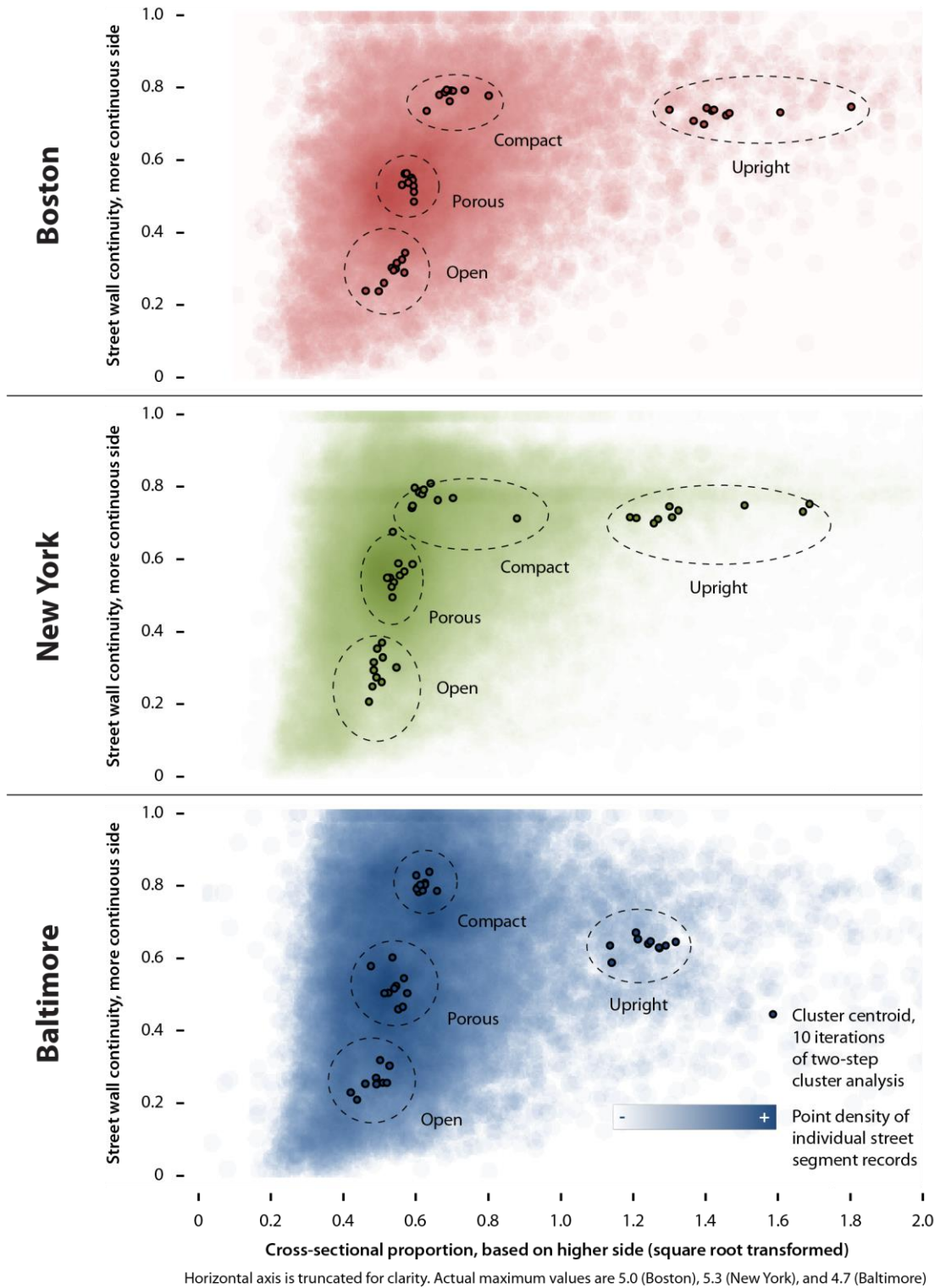


Figure 3.8: Joint distributions of cross-sectional proportion and street wall continuity.

Two sensitivity analyses were conducted to assess the stability of clustering results given alternate parameters. The first evaluated the effect on the number of identified clusters from incorporating a third variable, width, a measurement of streetscape scale rather than proportion. Three-variable clustering solutions had similar cross-sectional proportion and street wall continuity characteristics to those previously identified, with L-shaped distributions of cluster centroids similar to those in Figure 3.8. Three-variable clusters solutions were, however, less consistent across cities and less cohesive than those previously identified. The appropriate number of three-variable clusters, according to BIC values, was three in Baltimore and five in New York and Boston, with an average silhouette coefficient of 0.43. The addition of width did not substantially change the arrangement of clusters and produced slightly less definitive results than two-variable cluster solutions.

The second sensitivity analysis examined the effect of constraining two-variable clustering to either three or five clusters. When specifying three clusters, streetscapes with the lowest cross-sectional proportion and street wall continuity merged into a single cluster. The average silhouette coefficient was 0.49. Five-cluster solutions indicated a new, though inconsistently-centered cluster with square cross-sectional proportion—roughly equivalent height and width—moderate street wall continuity and an average silhouette coefficient of 0.44. Neither variation offered a superior silhouette or contrasting cluster arrangement to the four-cluster solution. Both sensitivity analyses indicated that clustering solutions were relatively stable to modifications in clustering parameters.

3.4 Results & Discussion

3.4.1 Four Streetscape Skeleton Types

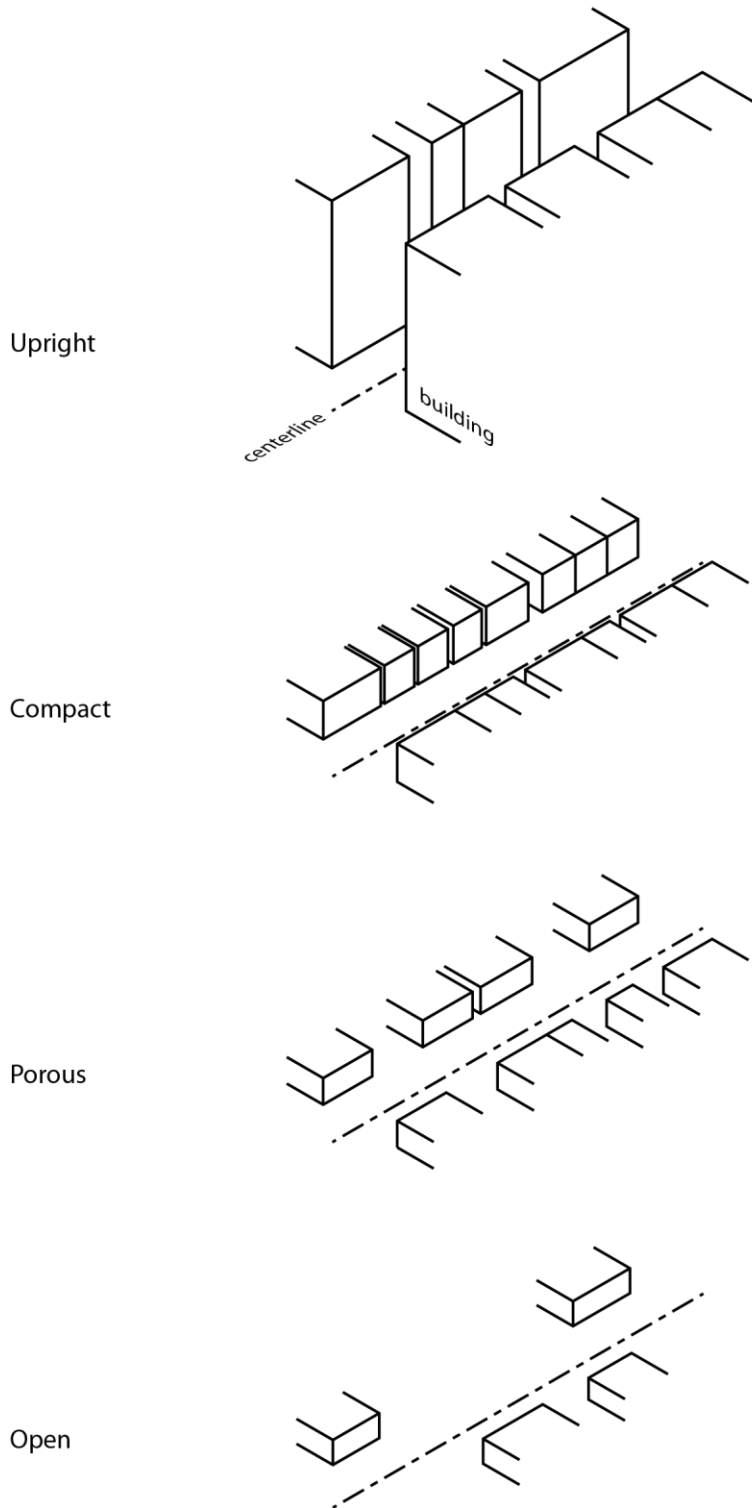
Four streetscape skeleton types, identified by separate cluster analyses of streetscape skeleton variables in Boston, New York, and Baltimore, describe a ranking of streetscape skeleton enclosure that is generalizable across the study cities (Table 3.6; Figure 3.9). I have assigned names to the types based simple descriptors of their geometry: *upright*, *compact*, *porous*, and *open*.

Table 3.6: Streetscape skeleton type descriptive statistics

Streetscape Skeleton Type	City	Count	N (% within city)	Cross-sectional proportion, based on higher side* [†]		Street wall continuity, more continuous side*		Width (meters)	Height, higher side [†] (meters)	Buildings per length [†] (per/100 meters)
				Mean	(Standard Deviation)	Mean	(Standard Deviation)			
Upright	Boston	1,081 (8.1%)	2.17 (1.61)	0.72 (0.15)	14.5 (9.2)	28.25 (23.5)	8.93 (5.95)			
	New York	7,299 (8.8%)	1.84 (1.63)	0.71 (0.14)	26.5 (11.3)	46.9 (38.2)	6.34 (4.01)			
	Baltimore	1,576 (6.2%)	1.62 (1.29)	0.65 (0.16)	13.7 (10.0)	21.0 (21.4)	9.59 (8.13)			
	All Cities	9,956 (8.1%)	1.84 (1.59)	0.70 (0.14)	23.1 (12.1)	40.8 (36.2)	7.14 (5.28)			
Compact	Boston	3,080 (23.0%)	0.51 (0.23)	0.79 (0.09)	28.3 (14.2)	12.5 (6.0)	11.44 (6.35)			
	New York	26,298 (31.6%)	0.42 (0.18)	0.78 (0.08)	31.2 (11.6)	12.1 (6.0)	13.48 (7.81)			
	Baltimore	9,811 (38.3%)	0.40 (0.17)	0.80 (0.10)	28.0 (12.2)	9.9 (3.3)	21.56 (12.58)			
	All Cities	39,189 (32.0%)	0.42 (0.18)	0.79 (0.09)	30.1 (12.0)	11.5 (5.5)	15.34 (9.84)			
Porous	Boston	6,441 (48.0%)	0.36 (0.17)	0.54 (0.07)	27.6 (11.7)	8.7 (3.2)	8.69 (3.07)			
	New York	36,949 (44.4%)	0.31 (0.13)	0.55 (0.07)	33.3 (11.3)	9.4 (4.0)	10.26 (4.82)			
	Baltimore	9,097 (35.5%)	0.31 (0.15)	0.52 (0.08)	33.9 (13.7)	9.1 (2.7)	8.72 (4.85)			
	All Cities	52,487 (42.9%)	0.31 (0.14)	0.54 (0.07)	32.7 (12.0)	9.3 (3.7)	9.80 (4.70)			
Open	Boston	2,807 (20.9%)	0.33 (0.22)	0.30 (0.10)	34.3 (18.0)	8.9 (4.8)	4.81 (2.52)			
	New York	12,649 (15.2%)	0.28 (0.19)	0.28 (0.11)	43.9 (16.9)	10.7 (8.6)	4.28 (2.72)			
	Baltimore	5,128 (20.0%)	0.26 (0.14)	0.26 (0.09)	40.6 (17.0)	8.8 (3.3)	4.15 (2.41)			
	All Cities	20,584 (16.8%)	0.28 (0.19)	0.28 (0.10)	41.8 (17.4)	10.0 (7.2)	4.32 (2.62)			

* Variables used to derive streetscape skeleton types

† Variables that were square root transformed for cluster analyses are reported here untransformed



Illustrations depict mean cross-sectional proportion, street wall continuity, and buildings per length for each streetscape skeleton type.

All illustrations are drawn with the same streetscape width. Differences in mean cross-sectional proportion are depicted by variation in building height.

Other variables, including variation in streetscape width due to building setback, are not represented.

Figure 3.9: Isometric illustrations of streetscape skeleton types.

Upright streetscapes are highly enclosed by nearly continuous street walls and cross-sectional proportions far larger than the other types. These streets are likely to be the narrowest in a city, have some of the tallest buildings, and have relatively few buildings per length. This type includes streets between high-rises, and also includes narrow lanes between shorter buildings which have similar cross-sectional proportions.

Compact describes streetscapes with enclosure derived from street wall continuity rather than cross-sectional proportion. They have the most continuous street walls of any type, and are also likely to have the greatest number of buildings per length. A block lined by rowhouses exemplifies the compact type.

Porous streets also derive enclosure from their street walls, but have less street wall continuity. Nonetheless, porous street walls may appear to be relatively continuous from a street-level perspective. Porous streets have fewer and shorter buildings than compact streets. They are typified by blocks lined by single-family homes.

Open streets are the least enclosed, widest, and are lined by the fewest buildings. They have stout cross-sectional proportions and have relatively discontinuous street walls, with buildings fronting roughly a quarter of the most continuous side. They are exemplified by commercial or industrial blocks with parking lots or other open space between buildings.

It is important to reiterate that the skeleton types, as defined here, are characterized by the most developed side of a streetscape—the side with the tallest buildings and most continuous street wall. A streetscape such as Central Park West in

Manhattan, New York, which has tall buildings along one side but open parkland along the other, is classified as *upright*. Classifying streets according to their most developed side emphasizes potential for even a single street wall to create partial enclosure. Differences in the degree of enclosure between one- and two-sided streetscapes are accounted for by contrasting widths and associated cross-sectional proportions. Without buildings to delineate an edge along one side, the width of a streetscape will be very large (the forty-meter maximum search distance to one side the centerline, plus any additional distance to the façade-based edge on the other side), resulting in a much smaller cross-sectional proportion than a comparable two-sided streetscape.

Streetscape skeleton types follow a consistent spatial pattern between cities (Figure 3.10). Upright segments, which are highly enclosed, are concentrated in downtown areas. Compact and porous segments are organized in concentric rings around the downtowns. The gradient between them may be either gradual or patchy, suggesting that they have similar land use and development roots. Some outlying neighborhoods are dominated by open streetscapes. For the most part, though, open streetscapes are distributed along specific corridors or in relatively undeveloped areas without rectilinear street grids. The overarching core-and-periphery pattern of the types indicates that they are a rough proxy for built environment density, which is broadly understood to follow a similar concentric gradient. Nonetheless, many areas dominated by a single type also include scattered anomalies. Such streetscape heterogeneity is potentially important to the experience of street users, but is left unrevealed by conventional density measures (Figure 3.11).

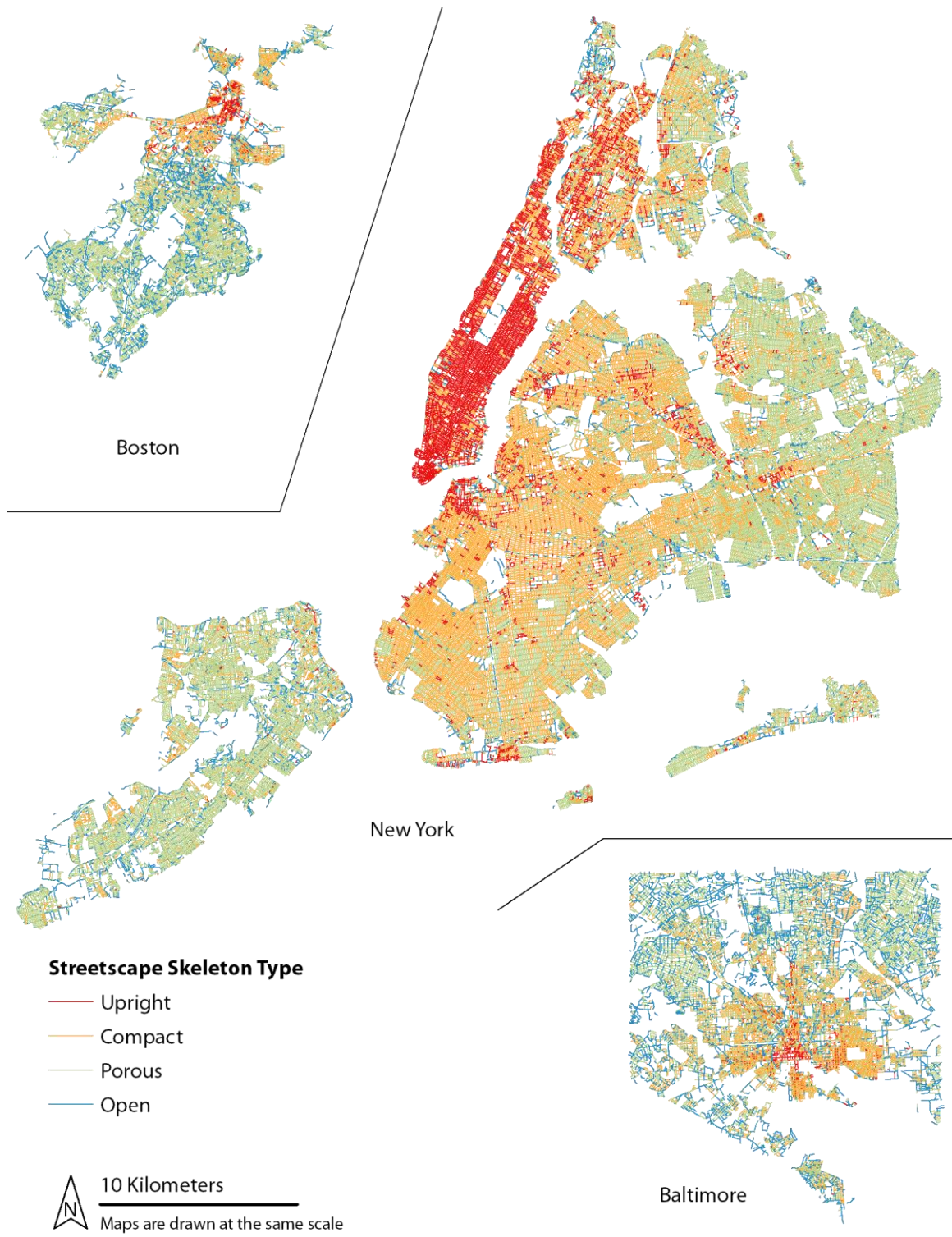
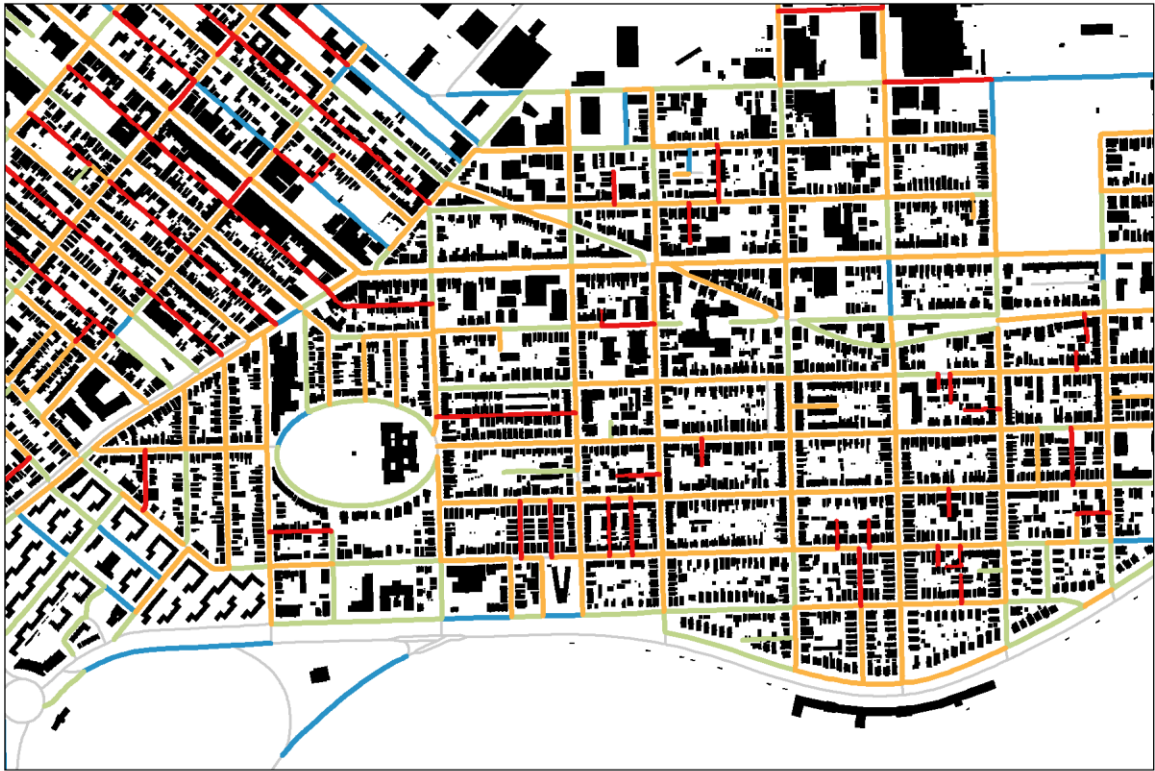


Figure 3.10: Spatial distribution of streetscape skeleton types within the study cities.



Centerline Segment by Streetscape Skeleton Type

- Upright
- Compact
- Porous
- Open
- Unmeasured
- Building Footprint

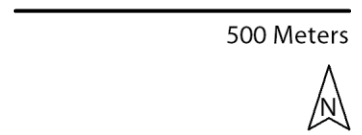


Figure 3.11: Heterogeneous streetscape skeleton types in Telegraph Hill, Boston.

The streetscape skeleton typology provides a framework for recognizing consistent patterns in the physical characteristics of block-level segments. While the four types do not account for streetscape design intricacies, they provide an accessible framework for identifying streetscapes in elemental terms.

3.4.2 Streetscape Skeleton \neq Roadway Function

At first thought, functional classes describing the design of roadways for motor vehicles may be equated to the design of streetscape skeletons. Arterial streets are often imagined to be wide and open, while local streets are narrower and lined by houses or shops. Cross tabulation of functional classes and streetscape skeleton types, however, reveals that they are poor proxies for one another (Table 3.7). Functional classes are distributed more-or-less evenly among streetscape skeleton types. Pearson Chi-Square and Gamma statistics indicate a 99.9% probability of nominal and ordinal independence for each city and for combined cities, except for the Gamma statistic in Baltimore, which indicates a 93.5% probability of ordinal independence.

Table 3.7: Cross tabulation of streetscape skeleton types and functional classes

Streetscape Skeleton Type	City	Functional Class			
		Arterial	Collector	Local	All
		Count (% within each city)			
Upright	Boston	27 (2.5%)	227 (21.0%)	827 (76.5%)	1081
	New York	275 (3.8%)	1,779 (24.4%)	5,245 (71.9%)	7,299
	Baltimore	12 (0.8%)	205 (13.0%)	1,359 (86.2%)	1,576
	All Cities	314 (3.2%)	2,211 (22.2%)	7,431 (74.6%)	9,956
Compact	Boston	162 (5.3%)	1,078 (35.0%)	1,840 (59.7%)	3,080
	New York	651 (2.5%)	6,069 (23.1%)	19,578 (74.4%)	26,298
	Baltimore	278 (2.8%)	1,307 (13.3%)	8,226 (83.8%)	9,811
	All Cities	1,091 (2.8%)	8,454 (21.6%)	29,644 (75.6%)	39,189
Porous	Boston	80 (1.2%)	1,187 (18.4%)	5,174 (80.3%)	6,441
	New York	353 (1.0%)	5,074 (13.7%)	31,522 (85.3%)	36,949
	Baltimore	147 (1.6%)	1,042 (11.5%)	7,908 (86.9%)	9,097
	All Cities	580 (1.1%)	7,303 (13.9%)	44,604 (85.0%)	52,487
Open	Boston	58 (2.1%)	832 (29.6%)	1,917 (68.3%)	2,807
	New York	325 (2.6%)	3,471 (27.4%)	8,853 (70.0%)	12,649
	Baltimore	103 (2.0%)	849 (16.6%)	41,76 (81.4%)	5,128
	All Cities	486 (2.4%)	5,152 (25.0%)	14,946 (72.6%)	20,584
All	Boston	327 (2.4%)	3,324 (24.8%)	9,758 (72.8%)	13,409
	New York	1,604 (1.9%)	16,393 (19.7%)	65,198 (78.4%)	83,195
	Baltimore	540 (2.1%)	3,403 (13.3%)	21,669 (84.6%)	25,612
	All Cities	2,471 (2.0%)	23,120 (18.9%)	96,625 (79.1%)	122,216

Independence between functional classes and skeleton types may be due to streetscape design patterns that are organized by neighborhoods instead corridors. While arterial streets often have design histories as major avenues and are somewhat wider than local streets, they have street wall continuity similar to their surrounding neighborhoods. Thus, arterial streets like Commonwealth Avenue in Boston, Broadway in Manhattan, and Orleans Street in Baltimore, have the streetscape skeletons similar to their local cross streets. The skeletons of collector streets may be even less distinguishable from those of local streets because they serve a mid-level functional role that is specific to the automobile age. Thus, streets that now serve as collectors may have originally been

planned and developed as local, low-traffic streets, and only recently retrofitted to accommodate heavier traffic loads. The result may be streets with contradictory streetscape and roadway design, such as those with high traffic and narrow setbacks in San Francisco, considered “unlivable” by Appleyard, et al. (1981).

Independence between streetscape skeleton types and functional classes may also be reinforced by block-by-block variability in streetscape design along corridors. Functional classification tends to be consistent along corridors over which it is feasible to install consistent roadway infrastructure, often under the guidance of a single transportation agency. Design of streetscapes, in contrast, is a piecemeal process directed by myriad public agencies, financial institutions, designers, and landowners. While there is a dominant streetscape skeleton type in most areas, heterogeneity is introduced by vacant lots, particularly tall buildings, or other development anomalies. There is far less linear consistency in streetscape skeletons than roadway functionality.

3.5 Conclusion

Streetscape skeletons contribute importantly to the utility of urban streets as public spaces, yet planners often simplistically assess streets by the functionality of their roadways. This paper demonstrates the potential for a complementary streetscape skeleton typology by using a GIS-based method to efficiently measure streetscape skeleton factors across more than one hundred thousand street segments in three cities, and applying cluster analysis to identify consistent patterns among key skeleton variables. The resulting types—upright, compact, porous, and open—provide an accessible

framework for discriminating between streetscapes on the basis of elemental geometry. Moreover, the types are categorically distinct from roadway functional classes, indicating the importance of interpreting streets as a combined function of roadway and streetscape design.

Measurement of streetscape skeletons using a GIS-based method is replicable and efficient compared with often-subjective and resource-intensive field auditing. The method is, to our knowledge, the first of its kind to define the boundaries of streetscapes based on consistency of building setbacks, approximating the way users interpret streetscapes from street-level perspectives. While field audits may permit nuanced interpretation of streetscape geometry and huge diversity of measurements, including microscale features such as materials and styling, they also allow for variability of interpretation and are resource-intensive to deploy. The GIS-based method evaluates segments consistently and efficiently. Minimal data inputs allow the method to be applied across multiple cities with comparable results. Skeletal variables, which are based on measurements widely understood and discussed by designers and planners, may also transfer directly into design specifications and policies. With objective terms for streetscape design that parallel the clarity of functional classes, planners will have greater capacity to plan streets that perform as public spaces as well as transportation conduits.

3.6 References

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CHAPTER 4: EFFECTS OF SKELETAL DESIGN ON STREETScape VISUAL APPEAL

4.1 Introduction

Planners and designers recommend countless strategies for improving the design quality of urban streetscapes. It is easy to get lost in the details. Ewing and Clemente (2013), for example, identify the importance of more than one hundred variables—windows, pavement condition, building colors, signage—contributing to the sensory experience of urban design. The National Association of City Transportation Officials (2013) present an extensive inventory of design strategies—cycle tracks, bus bulbs, bollards, pocket parks—to improve multimodal street safety and livability. Design details like these are undeniably important for optimizing the quality of streetscapes, but the skeleton of a streetscape, delineated by the massing of surrounding buildings and trees, provides spatial proportions that are elemental to perception of streetscapes as appealing public spaces. This study investigates the contribution of skeletal variables to visual perception of safety, an indicator of appeal, showing that the size and arrangement of buildings and trees within streetscapes provide baseline conditions contributing to a comfortable and inviting public realm.

The skeleton of a streetscape defines its three-dimensional space and introduces inherent visual complexity; both aspects contribute to visual appeal. Buildings are the most visually dominant objects framing streetscapes in an urban context. Aligned façades form walls along either side, providing enclosure that urban design theorists associate with sense of place and urban imageability (Alexander et al., 1977; Cullen, 1971; Lynch,

1960). Variations in the designs of façades foster repeating patterns and stylistic variation that provide visual interest in a streetscape. Trees, also visually dominant in many streetscapes, contribute additional enclosure and visual complexity (Arnold, 1993; A. B. Jacobs, 1993). Together, buildings and trees provide a skeleton (outlined in Figure 4.1) onto which a skin of design details—architectural styling, sidewalks, travel lanes, streetlights, and other fixtures—can be fitted to produce an extraordinary urban space. A well-proportioned skeleton may provide enduring bones for many generations of skin-level retrofit.

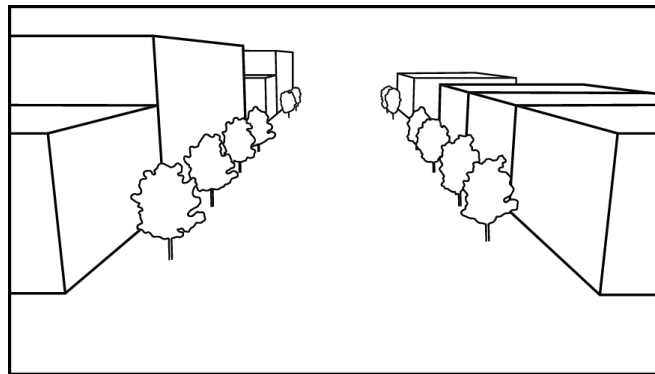


Figure 4.1: A streetscape skeleton defined by the massing of buildings and trees.

While the importance of skeletal factors for streetscape appeal is espoused by urban design theorists, the literature offers little direct empirical evidence of their relationship. Traditionally, it has been difficult to collect precise and consistent measurements of the built environment and human perceptions among a sample of streetscapes sufficiently large for making statistical inferences. Novel automated methods for measuring skeletal variables, and recording human perceptions in the same locations, now make it feasible to evaluate their relationships. This study applies a GIS-based

method to measure streetscape skeletons based on building and tree canopy geometry at the spatial resolution of city blocks. Skeletal variables are measured along more than six hundred New York City blocks where visual appeal measurements were previously collected using a crowdsourcing technique by researchers at the Massachusetts Institute of Technology (Salesses et al., 2013). Multivariate regression models demonstrate that a handful of skeleton measurements are powerful predictors of streetscape visual appeal, and those streetscapes more greatly enclosed by buildings and trees are more appealing spaces.

4.2 Background

Seminal urban design theorists draw concise logical arguments for how enclosure is important to the spatial definition and attractiveness of streetscapes, but offer little empirical evidence of these associations. Enclosure is what gives a streetscape a recognizable interior, allowing someone to be outside *it*, entering *it*, or in the middle of *it* (Cullen, 1971). Such spatial definition is important for sense of place within streets, making them spaces to *be* rather than vectors to pass *through*. Enclosing building façades form “street walls,” offering shade and protection from wind and rain, and a secure edge from which to observe goings on (A. B. Jacobs, 1993). Street walls delineate the extents of outdoor rooms, whose ceilings are defined by the height of aligned cornices of surrounding buildings (Alexander et al., 1977). Enclosure also contributes importantly to urban imageability, sense of spatial awareness and orientation, useful for distinguishing streets and neighborhoods from one another (Lynch, 1960). A person traveling the length of Manhattan, for example, may know where they are—the Financial District, Greenwich

Village, Midtown, Uptown, Harlem—simply by the shape and size of the streetscapes surrounding them.

Tree canopy provides additional enclosure by forming a partial roof while subdividing large streetscapes into more compact spaces. Trees may compensate for lack of enclosure where buildings are nonexistent or widely spaced (Arnold, 1993). Paris's tree-lined Champs-Élysées, parts of which are enormously wide between buildings, demonstrates how well-arranged trees can provide a degree of enclosure all on their own (A. B. Jacobs, 1993). Trees, especially large ones, also provide visual complexity in the organic structure of their branching, colors of their bark and leaves, filtered light and shadows they cast on surrounding surfaces, and their constant, subtle movement (Arnold, 1993). Street trees also substantially affect microclimate, which likely has an important effect on perception of streetscapes as appealing places. In an era when buildings are often planned with lifespans of 100 years or less, mature trees can play a similarly enduring role in shaping and adding visual character to streetscapes.

Social benefits of enclosed streetscapes may also contribute to their appeal, though arguments for these relationships are mostly logical and rhetorical rather than empirically tested. Alexander et al. (1977) suggest that smaller, more defined streetscapes will attract social and economic activity more readily than those that are large and ambiguously shaped. Wide setbacks, originally intended to provide streetscapes with light and air, also make them feel vast and discourage interaction between the public realm of the street and private land uses to either side (Dover & Massengale, 2013; Montgomery, 2013). Streetscapes designed to foster social vitality must be small and

enclosed enough to bring people together. Appleyard et al.'s (1981) seminal study of street livability focuses primarily on traffic volume, but the most socially active, livable streets he identifies in San Francisco are also relatively narrow. Jane Jacobs (1961) similarly identifies the social and safety advantages of narrow streetscapes lined by low-rise buildings in the Greenwich Village neighborhood of New York City, where neighbors and shopkeepers keep “eyes on the street” from their front windows. She critiques streetscapes amidst modern public housing projects as too tall and vast for social accountability. The structure of a community, Jacobs argues, is implicitly directed by its built environment. Alexander et al. (1977) suggest that buildings be no more than four stories tall to allow interaction between the uppermost floors and the street. Blumenfield (1971) proposes a limit on building-to-building streetscape width of 72 feet, the maximum distance at which faces are recognizable; 48 feet is recommended as the distance where expressions are detectable and communication is feasible with loud voices. Optimal dimensions, however, have not been tested against social outcomes using a rigorous methodology.

Recent planning and public health literature uses more empirical strategies to evaluate the appeal of streetscapes, mostly for walking. Several studies by Ewing identify a framework of urban design qualities important to pedestrians according to expert panels: imageability, enclosure, human scale, transparency, and complexity (Ewing et al., 2005; Ewing & Clemente, 2013; Ewing & Handy, 2009). These qualities are heavily affected by skeletal proportions, though Ewing and his colleagues measure them somewhat indirectly by estimating the length of sight lines and proportion of sky visible

ahead. They estimate other skeletal variables in more direct terms—building height, number of buildings and proportion of street wall along either side—inspiring several of the measurements operationalized in Chapter 3, and used to measure streetscapes in this study.

A handful of studies identify quantitative relationships between skeletal variables and walking behavior or pedestrian environment appeal. Moniruzzaman & Páez (2012) find that smaller setbacks and taller buildings are consistent with greater pedestrian mode share in Hamilton, Ontario. Nasar (1987) finds that lay pedestrians and design experts in Columbus, Ohio both rate street scenes more highly when they are more enclosed, have more unity of form, and are more vegetated. He recommends conversion of alleyways and other enclosed places to pedestrian use. Pikora et al. (2003) identify street trees and width as important variables of route preference for recreation, but not for transport. Skeletal streetscape design may not be imperative for walking, but it has potential to encourage it by improving enjoyment.

Macroscale built environment measures, such as density, are more commonly studied using quantitative methods. Saelens et al. (2003) review the consistent relationship between built environment density, street connectivity, and walking behavior identified by transportation, urban design, and planning literature. Ewing and Cervero (2010) similarly review how effects of the 5Ds—density, diversity, design, destination accessibility, and distance to transit—on vehicle use and travel distances are replicated by over 50 studies. While density and connectivity imprecisely represent the streetscapes of individual blocks, they generally translate into taller, narrower, and shorter streetscapes.

The dominance of macroscale data in built environment research demonstrates the challenges of acquiring reliable streetscape-scale measurements. Audit instruments are the most common strategy for recording skeletal data, often with subjective measures that are efficient for human auditors to judge. The Pedestrian Environment Data Scan (PEDS), for example, asks auditors to rate the enclosure of a streetscape as low, medium, or high (Clifton et al., 2007). Moniruzzaman & Páez (2012), using data collected with PEDS, make the incongruous conclusion that that smaller setbacks and taller buildings are consistent with greater walkability, while enclosure is not. Such results are likely affected by limitations in the specificity and consistency of audited data.

Some researchers question whether it is valuable to focus on the visual appeal of streetscapes in lieu of more practical concerns about safe infrastructure and destination accessibility. These arguments, however, may be largely founded on the relative convenience of quantifiably measuring infrastructure and accessibility. Alfonzo (2005) places walking environment “pleasurability” at the bottom of her hierarchy of walking needs, below feasibility, accessibility, safety, and comfort. Arguably, the boundaries between these needs are highly ambiguous and codependent on a number of built environment variables. Nonetheless, it is reasonable to assume that sidewalks and destinations are more elemental to a pedestrian’s decision making than attractive scenery. Boarnet et al. (2011) endorse this hierarchy, determining that availability of sidewalks, destinations, and safety from traffic significantly affect walking behavior among neighborhoods in Minneapolis and Saint Paul, Minnesota, while natural and architectural aesthetics do not. Southworth (2003) argues that, because practical infrastructure is

prioritized over aesthetic design, environmental satisfaction is often reserved for the elite. However, skeletal variables consistent with visual appeal, such as street trees and narrower width, may actually improve roadway safety in urban settings by lowering vehicle speeds (Ewing & Dumbaugh, 2009). Potential for skeleton aesthetics to provide co-benefits of safety should not be ignored. Walking will only be widely embraced when it is viewed as a safe and comfortable alternative to other modes.

With advancements in tools for measuring both the physical and perceived qualities of streetscapes, associations between skeletal design and human appeal are ripe for investigation. Block-level skeleton variables are now measureable with precision, replicability, and efficiency that was previously attainable only for macroscale built environment measures—density, grid connectivity, and destination accessibility. Moreover, crowdsourced judgments provide a replicable and large-sample approach for quantifying the appeal of streetscapes in aesthetic rather than practical terms (Salesses et al., 2013). Combining these measurements provides us with an opportunity to validate relationships between skeletal design and visual appeal with unprecedented spatial resolution, sample size, and objectivity.

4.3 Methods

4.3.1 Study Area

New York City, which offered a nexus of high resolution spatial and perceptual data, was an opportune study area for examining associations between streetscape skeletons and appeal. The City boasts more than 750 square kilometers of land area and

45,000 km of public roadways under the jurisdiction of a single municipal government which publishes high quality building, tree canopy, and street centerline geometry data, allowing us to measure streetscape skeleton variables throughout the entire extent of the city. Visual appeal scores of streetscape images, collected by researchers at the MIT Media Lab using an internet-based survey called Place Pulse, were available for more than six hundred sites throughout the city (Figure 4.2; Salesses et al., 2013). These data were merged to investigate how scores for the images were affected by skeleton design on the blocks where they were taken.

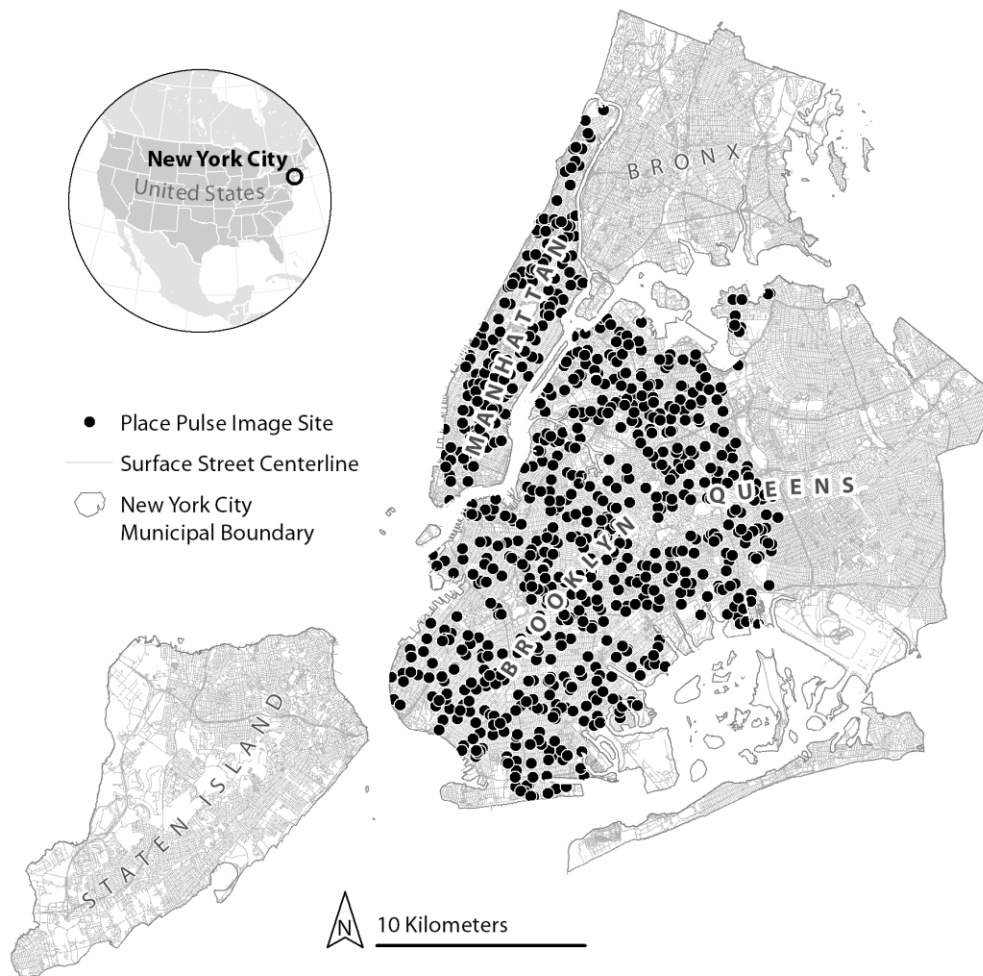


Figure 4.2: Place Pulse image sites in Manhattan, Brooklyn, and Queens, New York.

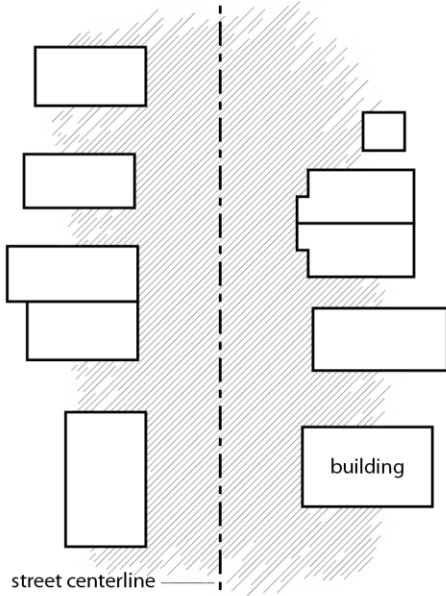
New York City is particularly conducive to examining the effects of streetscape design because it contains substantial built environment heterogeneity. Development ranges in style and density between residential areas dominated by one and two story detached homes, mixed use low-rise neighborhoods, and city blocks bounded by high-rises that are dozens of stories tall. Most parts of the City are platted on gridiron street networks with blocks longer in one dimension than the other, making the distribution of blocks lengths somewhat bimodal, though a broad range of other lengths and curvilinear networks are also represented. The City is divided into five boroughs, three of which are represented in this study. Manhattan, home to the oldest and densest development, with hundreds of high-rise buildings, is an elongated island along the northwestern side of the City. East of it are Brooklyn and Queens, which have dense downtown areas with high-rises on their western sides and large areas of low-rise residential and mixed use development to the east. Low-density industrial sites, airports, and natural areas line much of their southern shores. The broader Metropolitan New York City area includes outlying suburbs in New York, New Jersey, and Connecticut, and Pennsylvania with a population of more than 23 million and a combined area of nearly 7,000 square kilometers. New York City represents only its most urban portion. As such, this study does not account for the full range of suburban environments which have a unique set of design characteristics.

The built environment of New York City was heavily influenced by extensive early and mid-20th century development of low-rise mixed use blocks and high-rises in commercial centers. The city was an early and prolific adopter of the skyscraper, and is

now home to more than 600 buildings greater than 100 meters tall. Because much of New York City was developed before the widespread use of cars, it is dense and vertically oriented. As such, it is not representative of more recently developed cities, especially those in the southern and western United States, whose urban forms are more horizontal, or smaller cities that lack pressure for such density. Nonetheless, the diversity of the built environment across the City allows analogies to be drawn between its block-level streetscapes and those in many urban contexts.

4.3.2 Data

Skeletal streetscape measurements were derived from publicly available building footprint, tree canopy, and street centerline data processed using a GIS-based method presented in Chapter 3. The method evaluated skeletal dimensions of streetscapes along block-length street centerline segments. For each segment, the method first identified streetscape edges defined by alignment of building façades along either side. While some streets may be discretely bounded by continuous façades, streets may also be loosely bounded by buildings with a variety of setbacks and spaces between them. From an overhead view, the edges of such streets may be difficult to define precisely (Figure 4.3, A), but from a street-level perspective, edges may be readily perceived where façades align at predominant setbacks (Figure 4.3, B). To mimic street-level edge perception, the method used an iterative process to draw approximate edges at the setback distances where façades aligned most consistently along either side (Figure 4.3, C). These edges defined the horizontal extent of each streetscape, while the heights of adjacent buildings defined its vertical extent.

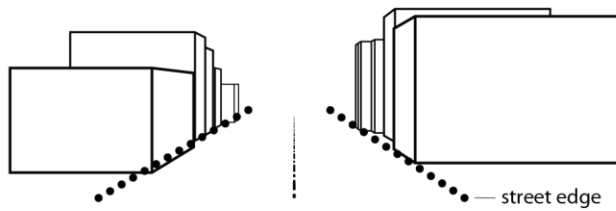


(A)

Overhead View

Streetscape edges may be difficult to define topologically.

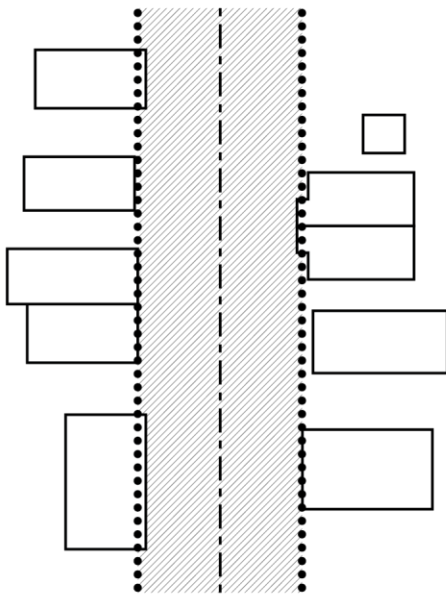
Variation in building setbacks and gaps between buildings can make the positions of edges imprecise.



(B)

Street-Level Perspective

Streetscape edges may be identified by alignment of building façades.



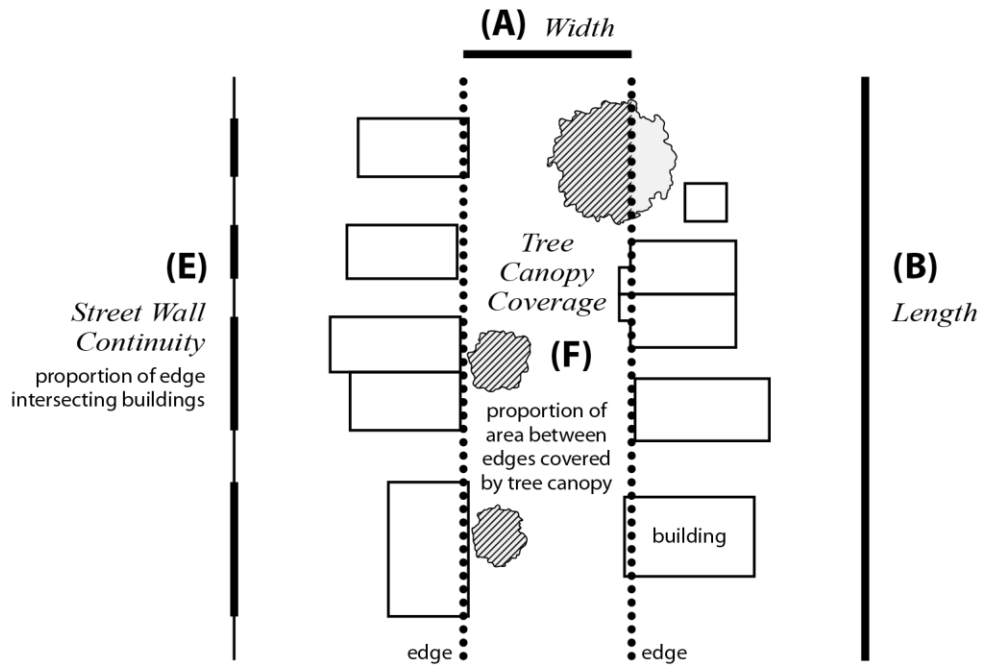
(C)

Overhead View

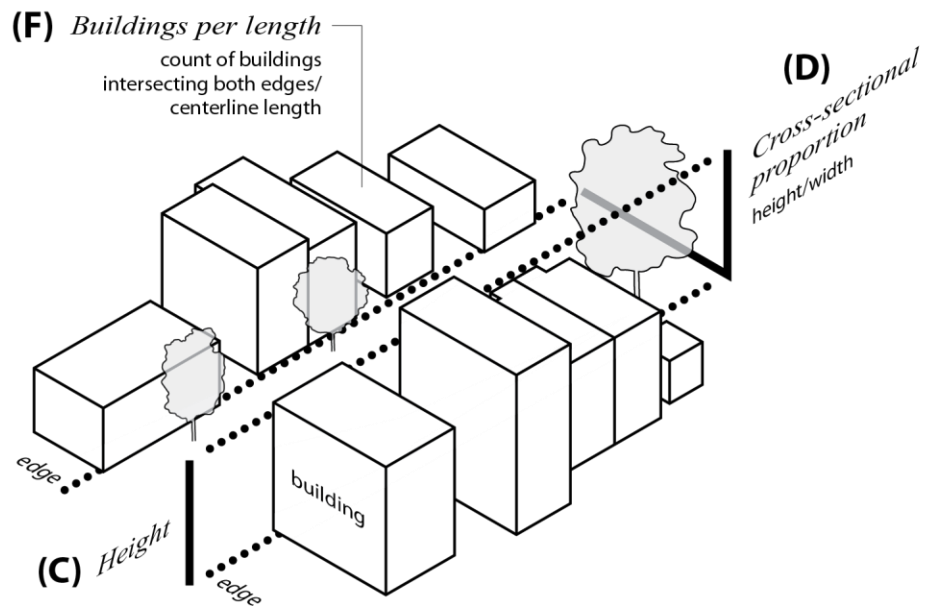
Streetscape edges were approximated by identifying consistency in building setbacks. Edges spanned gaps between buildings. The sizes of gaps were later assessed.

Figure 4.3: Streetscape edge detection from ground level and overhead perspectives.

Seven skeletal variables were measured for each sampled streetscape: *width*, *length*, *height*, *cross-sectional proportion*, *street wall continuity*, *buildings per length*, and *tree canopy coverage*. *Width* was the distance between opposing edges (Figure 4.4, A). In contrast with conventional width measures of the distance between curbs or right-of-way boundaries, width, in this study, was the distance between building façades on opposing sides of the street. This described the width of the space a street-level user would perceive. *Length* was the centerline distance between segment ends (Figure 4.4, B). *Height* was the average height of buildings along the single edge, out of the two edges along each segment, with the taller average height (Figure 4.4, C). *Cross-sectional proportion*, the quotient of height divided by width, described the interaction of these dimensions (Figure 4.4, D). Narrow streets lined by tall buildings had large cross-sectional proportions, creating upright and highly-enclosed streetscapes, while wide streets lined by short buildings had small cross-sectional proportions, manifesting in shallow streetscapes with minimal enclosure. *Street wall continuity* was the proportion of an edge that intersected a façade and thus formed a street wall (Figure 4.4, E). For each segment, street wall continuity was reported only for the more continuous of the two sides. *Buildings per length* was the count of buildings along both sides of a segment per length of centerline (Figure 4.4, D). *Tree canopy coverage* was the proportion of area between edges that was covered by tree canopy (Figure 4.4, F).



Overhead View



Orthographic View

Figure 4.4: Skeletal variable geometry.

Spatial data inputs for measuring skeletal variables were publicly available from the NYC Open Data web portal (City of New York, 2013) and were the most current available in November, 2013. Building footprint data were derived photogrammetrically from high resolution aerial photography, and included a building height attribute. High resolution tree canopy were derived by the University of Vermont Spatial Analysis Lab from aerial photography and aerial light detection and ranging (LiDAR) data using an automated method with manual quality control. The resulting tree canopy map, at one meter resolution, accurately represented the presence of even small street trees among tall buildings (Locke et al., 2010). Raw street centerline data were manually edited prior to analysis to remove dual centerlines along street segments with medians. Centerlines closest to the right-of-way center were maintained as the starting point for iterative edge detection to both sides of each segment.

Streetscape perception data were acquired from researchers at the MIT Media Lab who developed an online interface, *Place Pulse*, for gathering crowdsourced responses to questions about the visual appeal of streetscape images (Salesses et al., 2013; <http://pulse.media.mit.edu/>). The interface presented respondents with randomized pairs of images and asked them to indicate a preference according to one of three randomly displayed questions: “Which place looks safer?”, “Which place looks more upper class?”, and “Which place looks more unique?” (Figure 4.5). Each image was scored on a fixed scale according to its likelihood of being preferred in a random pairing. Images that were never preferred received a score of 0; those always preferred originally received a score of 10. These scores were rescaled between 0 and 1.

Among scores for each of the three Place Pulse questions, perceived safety was considered the best indicator of streetscape appeal. Scores for perceived safety were highly correlated with those for “upper classness” ($r = 0.89$). “Uniqueness” was relatively uncorrelated with both other scores ($r < 0.27$). Moreover, uniqueness does not necessarily imply sensory appeal, but rather contrast from the norm. Such contrast may be attractive in the best of cases, but detractive in many others. As such, perceived safety scores were used as a single proxy for streetscape visual appeal.

The full dataset included scores for 4,136 images collected at semi-randomly distributed points within the core cities of New York and Boston in the United States and Linz and Salzburg in Austria. A total of 208,738 decisions were collected, each expressing a positive vote for one image and negative vote for another. As such, each score was based on approximately 34 votes. A total of 7,872 unique respondents from 91 countries, geolocated by IP address, contributed to the sample. More than 97% of respondents self-reported age and gender, with 76% identifying as male and 21% as female; the median age was 28 years. Safety perceptions may have been biased by the largely young-adult male composition of the self-selected respondents. However, the sample may be considered reliable because perceived safety was judged in relative rather than absolute terms. For example, when asked which of two streetscapes looks safer, a young-adult man and an elderly woman may identify the same *safer* streetscape, yielding the same result, even if the former feels both would be safe enough to visit while the latter considers neither adequately safe. Moreover, because young-adult men may be less

sensitive to perceived risk than the general population, their judgments may be a conservative measure.

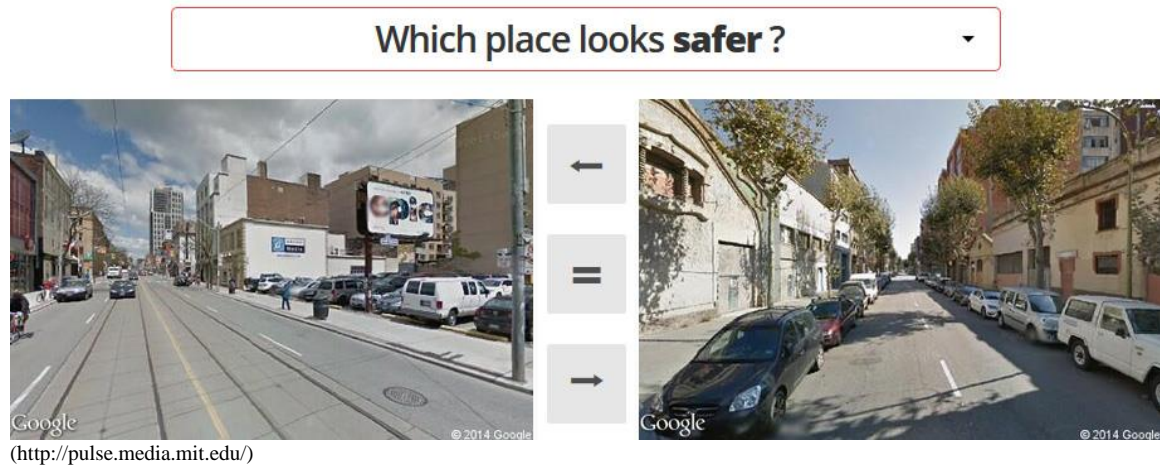


Figure 4.5: Screenshot of the Place Pulse website.

A subset of the Place Pulse dataset were evaluated, including scores for 1,222 streetscape images in the New York City boroughs of Manhattan, Brooklyn, and Queens. The average score among these images was 0.45 and the maximum was 0.8, out of a potential “perfect” score of 1. Each image site was geolocated by the latitude and longitude of its camera position. Many images shared approximately the same location, with two images taken in opposite different directions; in some cases more than one image was located along the same street segment. Image records within 20 meters of each other were combined into a single image site with an averaged perceptual score; approximately 91% of sites represented the average of two or more image scores. Sites were joined spatially to centerline segments, which included skeletal measurement attributes, within a 20-meter range. Images within 20 meters of more than one street segment, such as those at intersections, were omitted from analysis. This yielded a total

sample of 635 image sites paired with unique street segments on which skeletal variables were measured.

Two control variables were also joined to each image site to account for potential effects of local economic conditions and contextual urban form on visual appeal. Income statistics were calculated from five-year estimates for median annual household income by block group from the 2012 American Community Survey (U.S. Census Bureau, 2012). Because many image sites were located on streets that form boundaries between block groups, sites were assigned the average of median household incomes among block groups within 50 meters of their centroids. Walk Scores, which summarize the accessibility of retail, entertainment, natural, and other amenities within walking distance of a particular location, as well as the network connectivity of the surrounding street grid, were also collected for each image site. Walk Scores were obtained by manually entering latitude and longitude coordinates for the centroid of each image site into the search tool at the Walk Score website (www.walkscore.com). While the Walk Score algorithm is proprietary, scores have been validated by several independent studies as an effective metric for destination accessibility (Carr, Dunsiger, & Marcus, 2010; Duncan, Aldstadt, Whalen, Melly, & Gortmaker, 2011; Manaugh & El-Geneidy, 2011).

Descriptive statistics and bivariate correlations between perceived safety scores and both the skeletal and control variables, all of which are continuous, are presented in Table 4.1. Nearly all correlations were positive and significant at 99% probability, except the correlation with width, which was weakly negative, indicating that narrower streetscapes were perceived as safer, though the relationship was not statistically

significant. Tree canopy coverage had the strongest relationship with perceived safety (Figure 4.6). The strengths of relationships with other variables are well demonstrated by comparing them among sites with the highest and lowest safety scores. Figure 4.7 graphs these means and 95% confidence intervals across each variable, broken out by sites with safety scores in the top 20% (grey) and bottom 20% (white). Sites perceived as safest had significantly taller buildings, longer block length, larger cross-sectional proportions, more buildings, greater tree canopy, higher walk score, and greater income. Those perceived as safest also had marginally greater street wall continuity and were slightly narrower, though these differences were not statistically significant.

Table 4.1: Descriptive statistics and correlations with perceived safety scores

Variable	Min	Mean	Max	Standard Deviation	Correlation with Perceived Safety Score
Perceived safety score †	0.05	0.45	0.80	0.13	
Width (meters)	16	29	79	11	-0.05
Length (meters)	40	178	468	72	0.18*
Height (meters)	4	18	289	26	0.15*
Cross-sectional proportion	0.05	0.69	12.03	1.03	0.16*
Street wall continuity	0.02	0.70	1.00	0.16	0.12*
Buildings per 100 m length	0.0	2.1	11.4	2.1	0.26*
Tree canopy coverage	0.00	0.08	0.67	0.10	0.40*
Walk Score ‡	42	86	100	10	0.23*
Median household income	\$10,900	\$61,800	\$250,000	\$32,200	0.31*

* Correlation significant at 99% probability (2-tailed)

† Salesses et al., 2013

‡ www.walkscore.com

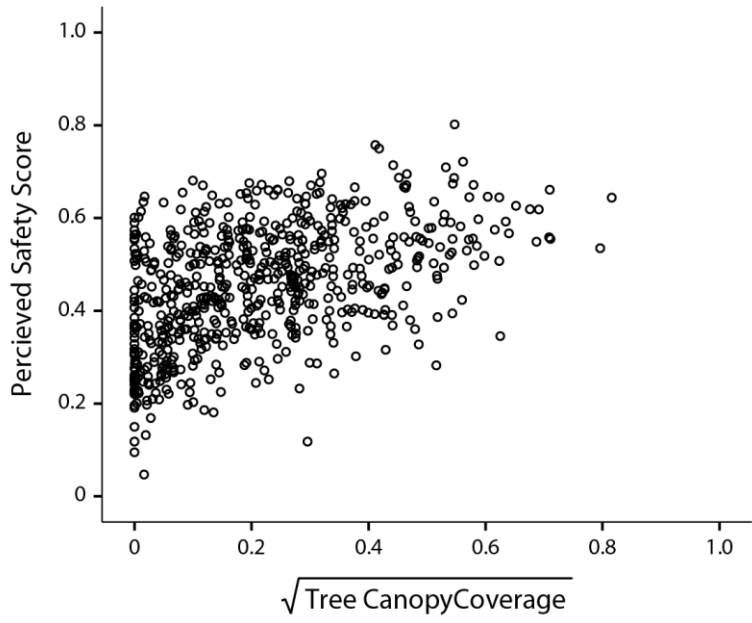


Figure 4.6: Relationship between tree canopy coverage and perceived safety score.

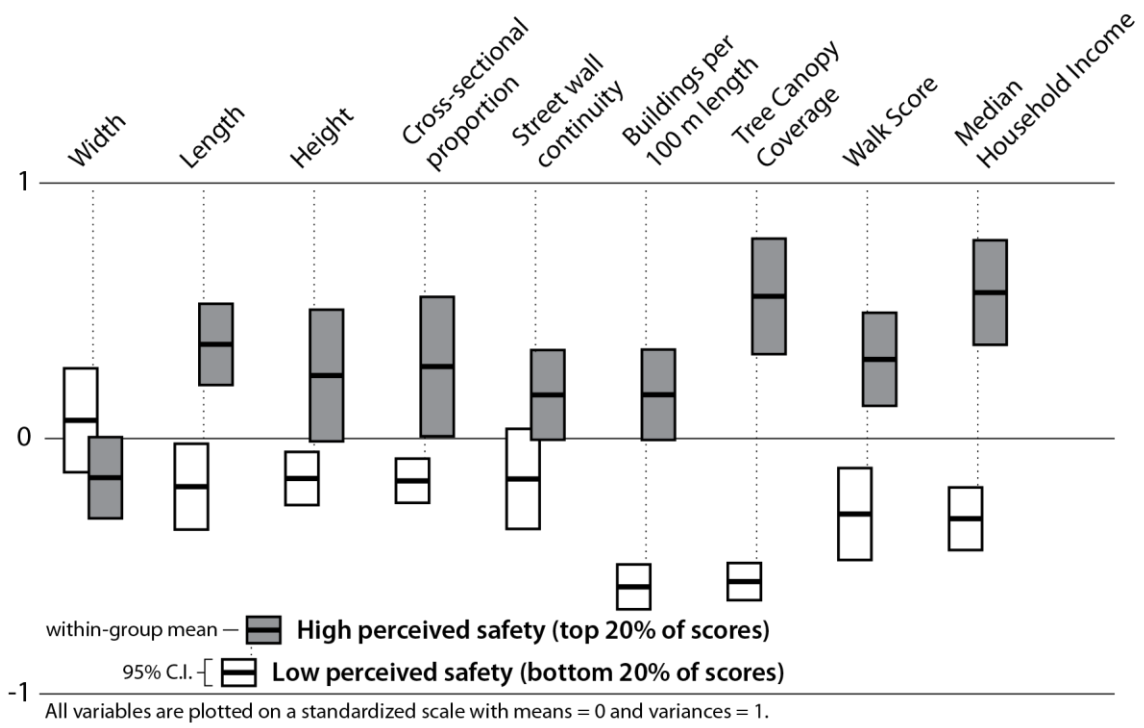


Figure 4.7: Response variable means among sites with high and low perceived safety.

4.3.3 Statistical Modeling

Both ordinary least squares (OLS) and logistic regression models were used to examine the multiple effects of streetscape skeletal measures on perceived safety while controlling for household income and Walk Scores. Results of ordinary least squares were more straightforward to interpret, but the bounded range of perceived safety scores between 0 and 1 violated the assumption of the response variables being infinitely continuous. In practice, OLS regression produced reasonable safety score estimates because the distribution of scores was highly normal, with 98% of records falling between 0.2 and 0.8. Following Grove et al. (2006) and Zhao, Chen, & Schaffner (2001), logistic regression was used to estimate an alternative model predicting the probability of fixed-range responses between 0 and 1. Similarity in parameter magnitudes and signs between the two types of models reinforced our confidence in their results.

Linear regressions were weighted to account for heteroskedasticity introduced by variety in the number of images contributing to averaged safety scores at each site. Because each image had approximately the same number of votes contributing to its score, the averages of two, three, or four images were based on larger samples of votes, theoretically resulting in less error compared to sites with only one image. As such, weights were applied according to the number of images contributing to a safety score. The weighted linear regression model was defined as:

$$y_i = w_i \left(\sum_{j=1}^K x_{ij} \cdot \beta_j + \varepsilon_i \right) \quad \text{Equation 4.1}$$

where y_i is the safety score of each site i , w_i is the number of contributing images, K is the count of predictor variables (with index j), and $x_{ij} \cdot \beta_j + \varepsilon_i$ is the linear combination of the predictor variable x , coefficient estimate β , and residual ε , for each modeled predictor. Coefficients were estimated by minimizing the sums of squared distances between observed and predicted safety scores using the Linear Regression tool in IBM SPSS Statistics Version 22.

Because safety scores represent the probability of each image being preferred in a random pairing, logistic regression was used to estimate the probability of such a preference. This was operationalized using a generalized linear model (GLM) with a binomial distribution and a logit link function. The effective response variable was the proportion of preference events to number of trials, but the SPSS GLM tool accepted only integer values for events and trials. Raw events and trials data were not made available by Salesses et al. (2013), so event counts were approximated by multiplying the safety score of each site, y_i , by the number of images contributing to it, w_i , and the average votes per image, 34. Trials were approximated as the product of images at each site and the average votes per image, 34. Both events and trials were rounded to the nearest integer prior to modeling. The general logistic regression model was defined as:

$$\frac{\|y_i \cdot w_i \cdot 34\|}{\|w_i \cdot 34\|} = \frac{e^{(\sum_{j=1}^K x_{ij} \cdot \beta_j + \varepsilon_i)}}{1 + e^{(\sum_{j=1}^K x_{ij} \cdot \beta_j + \varepsilon_i)}} \quad \text{Equation 4.2}$$

with variable definitions equivalent to those of the OLS model described above. Coefficients were estimated by maximizing the likelihood of agreement between observed and predicted event/trial proportions for each image site.

Skeletal variables with distributions skewed to the right were transformed prior to modeling to better approximate normal distributions. Height, cross-sectional proportion, and buildings per length included no zero values and were natural log transformed to correct for highly skewed distributions. Tree canopy coverage, which was comparatively less skewed and included zero values, was square root transformed.

Linear and logistic regression models were developed independently using an iterative process. Initially, all predictors were entered into each model; those with coefficients significant at less than 95% probability were sequentially removed until all coefficients were significant. The significance and sign of coefficients for the width variable, although never large in magnitude, fluctuated substantially based on the combination of predictors included in the model. Due to this inconsistency, width was excluded from both final models. Coefficients for height and street wall continuity were consistently insignificant in both models. The insignificance of height may be explained by its strong correlation with cross-sectional proportion ($r = 0.91$); the inclusion of both predictors would have challenged the assumption of predictor independence inherent in both OLS and logistic regression. Multicollinearity within the final models was not considered problematic; the maximum variance inflation factor (VIF) among predictor variables was 1.9. O'Brien (2007) cautions against VIF values greater than 10 in regression modeling.

4.4 Results and Discussion

Several skeletal variables were strongly related to streetscape visual appeal as measured by perceived safety. The full linear regression model, including controls for amenity accessibility and affluence, accounted for more than 46% of variability in perceived safety scores (Table 2). When only skeletal variables were modeled—length, cross-sectional proportion, buildings per unit length, and tree canopy coverage—they accounted for 42% of variability in perceived safety. Tree canopy alone accounted for approximately 22% of variability. These effects were similar in the full models (Table 4.2; Table 4.3). *Percentage* increases in cross-sectional proportion and buildings per length, due to their logarithmic transformation, were estimated to increase perceived safety scores by approximately 0.05 and 0.02 respectively according to the linear regression model. The same model estimates that every *square* increase in tree canopy coverage, due to its square root transformation, increased perceived safety by 0.34. Because the predictor variables had extremely different variances, however, their effects were most readily comparable by standardizing them with variances of one and means of zero. Across both models, standardized coefficients for tree canopy coverage had the greatest magnitude, followed by buildings per length and cross-sectional proportion.

The effects of Walk Score and median household income were relatively minor, although still significant contributors to perceived safety. Length had the least effect, which is unsurprising given the difficulty of judging block length from a street-level perspective. The effect of length may have been due largely to correlations, albeit weak, between length and other key predictors. Longer street segments tended to have more

buildings per length ($r = 0.16$) and greater tree canopy coverage ($r = 0.14$). Intersections, which may have been more visible from shorter blocks than longer ones, may have detracted from perceived safety by offering less enclosure and implying greater potential for vehicle interaction. In general, more enclosed streetscapes, with greater cross-sectional proportions and tree canopy creating a room-like space, were preferred.

More buildings per length may have also contributed to sense of enclosure by increasing diversity in height, setback, and architectural style that visually partitions streetscapes into distinct sub-spaces. The visual complexity of streetscapes with greater buildings per length and tree canopy may have also improved their appeal. The presence of numerous buildings increase potential for variation in style and mass that improves visual interest in a streetscape (Alexander et al., 1977; Cavalcante et al., 2014; Ewing & Handy, 2009). The important contribution of trees to perceptions of safety is consistent with the negative relationship between street trees and crime rates identified by Troy, Grove, & O'Neil-Dunne (2012). Trees may be an efficient strategy, relative to construction of new buildings, for providing an enclosed streetscape that is both perceptually and statistically safer.

Table 4.2: Final linear regression model

Response Variable: Perceived safety core †			
Predictor Variable	Coefficient	Standardized Coefficient	t-Value
Length	0.0001	0.074	2.475*
Cross-sectional proportion (LN)	0.045	0.258 ■	6.381*
Buildings per 100 m length (LN)	0.024	0.316 ■	9.932*
Tree Canopy Coverage (SQRT)	0.340	0.459 ■	15.024*
Walk Score	0.001	0.114 ■	3.138*
Median household income (in \$10,000s)	0.008	0.205 ■	6.592*
Constant	0.219		4.922*

N = 635
 $F(6, 628) = 89.9^*$
 $R^2 = 0.46$

* Significant at 99% probability
† Salesses et al., 2013

Table 4.3: Final logistic regression model

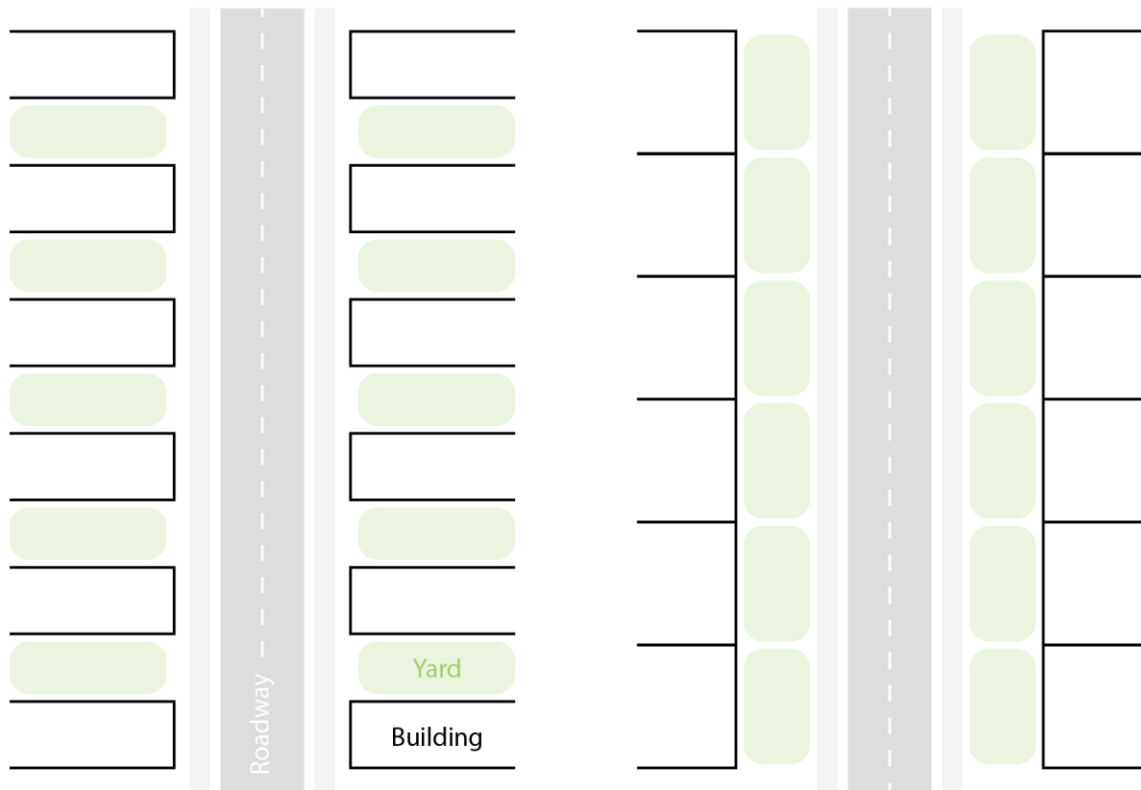
Response Variable: Perceived safety score †			
Predictor Variable	Coefficient	Standardized Coefficient	Wald Chi-Square
Length	0.001	0.039 ■	14.354*
Cross-sectional proportion (LN)	0.194	0.143 ■	105.934*
Buildings per 100 m length (LN)	0.103	0.178 ■	242.845*
Tree Canopy Coverage (SQRT)	1.413	0.242 ■	530.169*
Walk Score	0.006	0.063 ■	23.605*
Median household income (in \$10,000s)	0.033	0.105 ■	96.515*
Constant	-1.149		91.815*

N = 635
Log Likelihood = -2,210.419
McFadden Pseudo $R^2 = 0.22$

* Significant at 99.9% probability
† Salesses et al., 2013

A notably insignificant skeletal variable was street wall continuity, which theoretically contributes to enclosure. It had no significant effect when added to either

model (OLS: $P = 0.46$; Logistic: $P = 0.163$), though it was significantly correlated with perceived safety in a bivariate context ($r = 0.12$, $P < 0.01$). Streetscapes with more continuous street walls tended to have greater cross-sectional proportions ($r = 0.21$), buildings per length ($r = 0.35$) and Walk Scores ($r = 0.26$), so the effect of street wall continuity may have simply been accounted for by these other predictors. It may have also been insignificant if small street wall gaps were indistinguishable in images focused lengthwise along streetscapes (Figure 3, B). Only large, foreground gaps—empty lots, parking lots, gas stations—would have been detectable from this perspective. Street walls in the sample were largely continuous, with an average of 70% continuity over the length of a block, likely owing to high land values and development pressure in New York City. The insignificant effect of street wall continuity and the substantial positive effect cross-sectional proportion indicates that side yards in spaces between buildings may be favorable to front yards in large setbacks that widen streetscapes and reduce cross-sectional proportions (Figure 4.8). An extension of this study drawing on an expanded sample of streetscapes from other cities, ideally with greater heterogeneity in street wall continuity, would be useful for confirming its neutral effect.



(A) Yards between buildings

(B) Yards in front of buildings

Figure 4.8: Small setbacks with side yards versus large setbacks with front yards.

Neither model included width or height terms, indicating no difference in appeal among streetscapes based on scale. Because cross-sectional proportion is not dependent on scale, a tall, wide street with a large, upright cross-sectional proportion is likely to have the same appeal as a short, narrow street with a similar cross-section (Figure 4.9). However, because tall buildings are only economically feasible in the most central places, the vast majority of streets, which are lined by low buildings, must be narrow to maintain an appealingly upright cross-section. Allan Jacobs (1993) succinctly articulates this interaction, noting that “The wider a street gets, the more mass or height it takes to define

it, until at some point the width can be so great that real street definition ... stops, regardless of height” (p. 277).

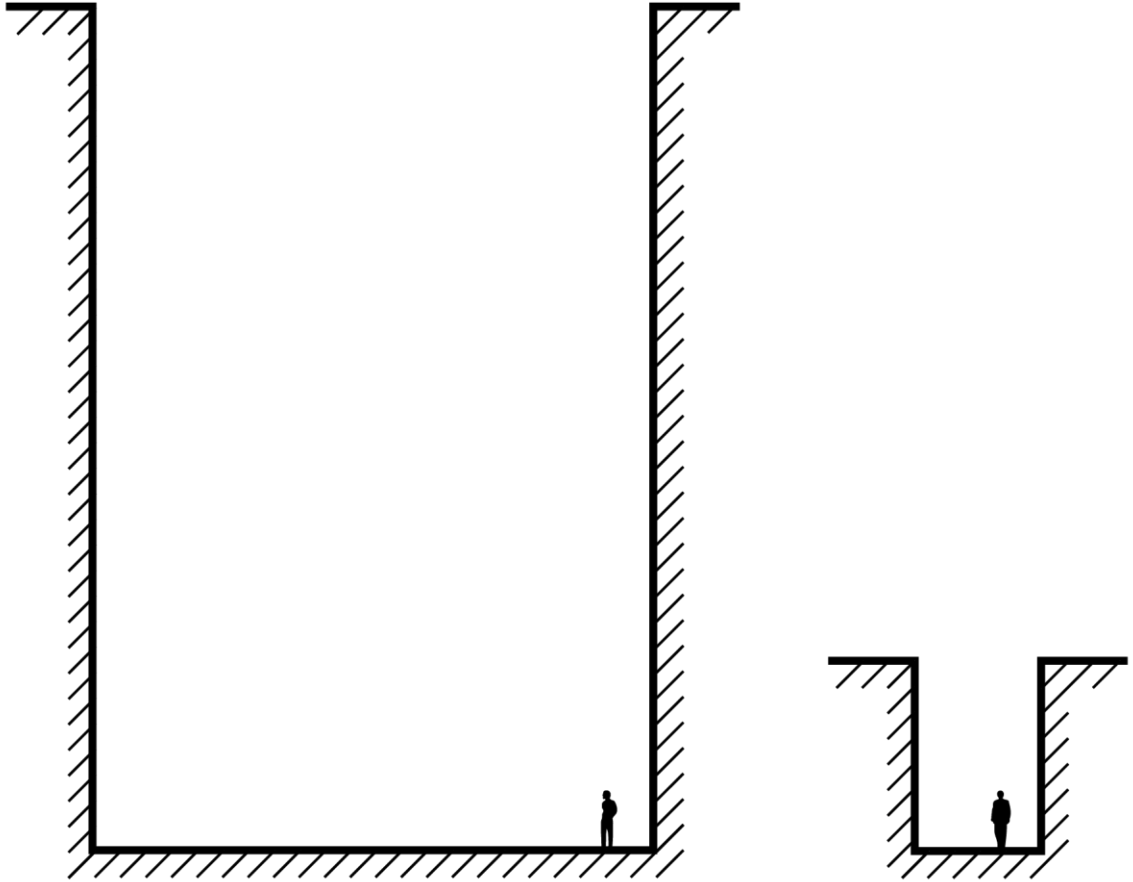


Figure 4.9: Contrasting streetscape scales with equivalent cross-sectional proportions.

While Jacobs insinuates a maximum streetscape scale at which spatial definition diminishes no matter what its proportions, this study revealed only linear relationships. Neither model produced better fit when terms were squared to allow parabolic association. Nonetheless, the existence of optimal streetscape scale or proportions seems logical. While New York City is a convenient setting for testing the extremes of height and cross-sectional proportion, it does not adequately represent extremely wide

streetscapes, like those on the fringe of sprawling cities such as Los Angeles and Atlanta, or extremely narrow streetscapes in historic European and Asian cities. Extending this study to sample more diverse built environments may demonstrate optimum points in skeletal variables, while also investigating how appeal varies by regional and international context. Streetscapes in northeastern U.S. cities may have very different optimums than those in the southwestern U.S., where certain architectural styles and vegetation might signal the appeal of wide, unenclosed streetscapes with minimal tree canopy.

Compared with skeletal variables, Walk Score and median household income had relatively small effects on streetscape appeal, notably indicating that destination accessibility and affluence play only partial roles in determining livability. Residential neighborhoods with few nearby commercial destinations may offer exceptionally appealing streetscapes, with well-proportioned cross-sections, many individual buildings, and abundant trees. Likewise, dense commercial clusters such as strip malls may offer high accessibility but poor aesthetic appeal. Accessibility and visual appeal are both important for livable communities, but they are distinct qualities.

The relatively weak effect of median household income suggests that skeletal proportions may have a greater effect on streetscape appeal than design details—building materials, fixtures, architectural styling— that may be more directly affected by affluence. It is also possible that subtle but important cues of affluence—brass door knobs or gas street lights, for example—were not detectable in the low resolution images judged by Place Pulse respondents. Whatever the cause, the relatively minor effect of

income indicates that streetscape skeletons, and associated visual appeal, may transcend socioeconomic barriers.

Statistical effects do not implicate causation, but it is reasonable to suggest, because of the temporal precedence of built environment construction, that observed variation in streetscape appeal is a consequence of skeletal variables rather than the inverse. Buildings and trees take decades, if not hundreds of years to develop. They have a durable presence in urban fabric. The appeal of a streetscape may certainly affect forthcoming design decisions; an esteemed streetscape may attract more investment, resulting in design improvements through time. However, the Place Pulse survey asked respondents to judge streets at a snapshot in time, from an outside perspective, with no awareness of the development trajectory or contextual setting, and in comparison to images from multiple cities in both the United States and Austria. Thus, the Place Pulse scores indicate the role of visual cues alone, rather than chronological or contextual knowledge, in perceiving streetscapes as appealing.

4.5 Conclusion

The skeletal proportions of streetscapes across New York City have an impressive effect on their appeal. In general, streetscapes with the greatest enclosure, fostered by substantial tree canopy, many individual buildings, and large cross-sectional proportions, are the most visually appealing (Figure 4.10). Tree canopy offers the strongest positive effect. Importantly, Walk Score is far less predictive of appealing streetscapes than skeletal variables, indicating a clear distinction between the block-scale design of

streetscapes and neighborhood-scale destination accessibility. Both are likely important to urban livability, but neither serves as an adequate proxy for the other. Neighborhood affluence also has a relatively minor effect on streetscape appeal. This suggests the aesthetic importance of skeletal variables, which are fairly consistent across low and high income areas, compared with design details—building materials, architectural ornamentation, fixtures—that may be higher quality in more affluent areas. Enclosing buildings and trees provide baseline visual appeal, even in less affluent places.

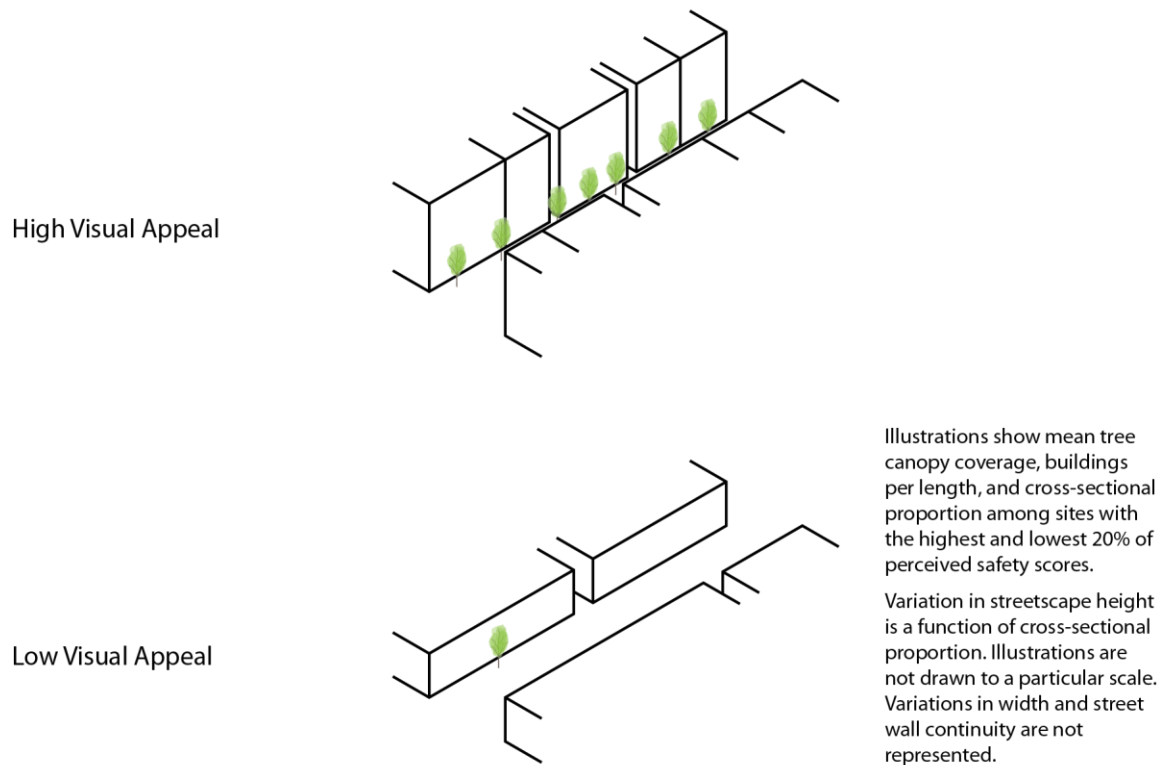


Figure 4.10: Illustrations of streetscapes with high and low visual appeal.

Appeal is not affected by several skeletal variables. Enclosure provided by street wall continuity has no significant effect on appeal when other variables are accounted for. Such neutrality suggests that spacing between buildings for side yards may be preferable

to setbacks for front yards that widen a streetscape and reduce its cross-sectional proportion. Streetscape width and height also do not have a substantial effect. However, since tall streetscapes are only economically feasible in the densest places, appeal of more narrow streetscapes is implied by appeal of larger cross-sectional proportions.

While skeletal enclosure provided by building massing and street trees is neither fast nor inexpensive to modify, it can be developed incrementally and incentivized by straightforward policy. Enhancing streetscape enclosure provides further rationale for existing tree planting agendas in many cities. Enclosure provided by buildings is also encouraged by market feedbacks in development. Infill improves both centrality and aesthetics, attracting additional infill. Many cities already incentivize such growth through strategies to strengthen downtown areas. Moreover, skeletal measures offer an intelligible language, akin to setback and building envelope regulations, for guiding productive development while allowing stylistic design freedom. Well-enclosed streetscape skeletons are a long-term investment, but may grow naturally over time into one of a city's most enduring assets.

Research on the social implications of built environments is accelerating quickly as the global population urbanizes and simultaneously aspires to higher quality of life. Nonetheless, methods for measuring the intricacies of urban design, human perceptions, and behavioral responses, remain in their infancy. This study demonstrates the application of novel strategies for capturing built environment measurements. GIS data and tools can be used for automated measurement of streetscape design. Perceptions of now-ubiquitous streetscape imagery can be efficiently drawn from thousands of

respondents using crowdsourcing technology. Such automated techniques for capturing both types of data represent a frontier of research that will draw on ever-larger and more diverse samples. Future studies should sample additional cities to investigate differences in streetscape design throughout the world and in variously sized cities. It will be particularly valuable to determine whether streetscape-appeal relationships are universal, or have cultural variability and should thus be designed and incentivized differently between cities. Finally, it will be important to investigate how roadway engineering contributes to streetscape appeal. This study has purposefully concentrated on the vertical design of streetscapes that surround roadways, but the horizontal layout of sidewalks, multimodal infrastructure, traffic lanes, and vehicular traffic itself, have an enormous effect on how streets are perceived and used (Appleyard et al., 1981). Research on the design of streetscapes and roadways must be merged to design whole streets that are comfortable and attractive. Nonetheless, researchers should strive to provide frameworks that are not overly comprehensive, leaving details to the discretion of architects, urban designers, and transportation engineers who can make context-sensitive choices. A single detailed recipe for livable streets would be overwhelmingly complex, stifling creativity in detailed design that contributes importantly to appeal of streets as subtly unique places.

4.6 References

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