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Project Title

A LiDAR-Based Approach to Quantitatively Assessing Streetscapes

University

University of Colorado Denver

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Research Needs

The existing research remains conflicted on the role that street trees, buildings, and other horizontal and vertical roadside features play in transportation safety (Zeigler 1986, Dumbaugh 2005, Wolf 2005, Wolf and Bratton 2006). Earlier work, for instance, concluded that street trees were unsafe (Turner and Mansfield 1989) and that reducing tree counts or spacing trees to create "safety gaps" would create safer driving environments (AASHTO 2004, Wolf 2005). More recent studies are challenging these results and showing that street trees may help reduce the speed at which crashes take place, the severity of those crashes, and even the overall number of crashes (Garder 2004, Dumbaugh 2005, Mok, Landphair et al. 2006, Jones and Jha 2009, Dumbaugh and Li 2011, Ukkusuri, Miranda-Moreno et al. 2012, Dumbaugh and Zhang 2013, Marshall, Coppola et al. 2018). Due to limitations about how we measure streets and the roadside environment, such studies cannot yet adequately explain what specific design features lead to safer or unsafe streets. For instance, the existing research rarely evaluated tree counts, canopy coverage, or utilized any sophisticated geospatial method to augment their analyses. When they did include variables such as tree counts, the manual and time-consuming nature of such counts limited most analyses to a few hand-picked streets or relatively small geographic areas. Though these more recent studies concluded that such features equate to safer streets, studying this topic with sophisticated GIS and remote sensing measuring tools covering a much larger and non-discriminative area may lead to more definitive results.

Research trying to understand the importance of streetscapes goes back more than a century. As early as 1889, Camillo Sitte made a forceful case that such principles should drive urban planning (Sitte 1889). In the early 1960s, Gordon Cullen expressed the importance of visual coherence and organization of urban design features such as buildings, streets, public spaces, and how they interact (Cullen 1971). Urban designer Donald Appleyard incorporated traffic exposure data and various physical characteristics of the built environment to help understand streets that are safe, livable, and desirable (Appleyard, Gerson et al. 1981). Rapoport then took a different approach in the 1980s with work differentiating between perceptual qualities for walkability verses driving in urban design (Rapoport 1990). Henry Arnold's works in the 1990s focused on trees and their interactions with streetscapes and urban environments (Arnold 1993).

Researchers eventually began to consolidate these ideas into methodologies for measuring and quantifying urban design characteristics (Purciel and Marrone 2006, Clifton, Smith et al. 2007, Ewing and Handy 2009, Purciel, Neckerman et al. 2009, Ewing and Clemente 2013). Ewing's work, for instance, combined the existing research with expert panels to determine the variables of interest (Ewing, Clemente et al. 2005, Ewing and Handy 2009, Ewing and Clemente 2013). The idea was then to send auditors into the field to collect this data, which was a staple of most methodologies (Brownson, Hoehner et al. 2009, Harvey, Aultman-Hall et al. 2015). Brownson reviewed twenty such audit methodologies and found a wide range in terms of the number of variables collected. Some collected less than 10 while others collected more than 100, with the Irvine-Minnesota Inventory (IMI) topping out at 176 variables (Boarnet, Day et al. 2006, Day, Boarnet et al. 2006, Brownson, Hoehner et al. 2009). Most fell into the 30 to 40 range such as the Pedestrian Environment Data Scan (PEDS) and the Systematic Pedestrian and Cycling Environmental Scan (SPACES) (Pikora, Giles-Corti et al. 2003, Clifton, Smith et al. 2007).

Audit-based approaches tend to be highly labor intensive. They initially require auditors to be recruited, trained, and deployed into the field. Collecting data for each street segment can then take 3 to 5 minutes, such as with the PEDS and SPACES methods, or up to 20 minutes per street segment with the IMI approach (Brownson, Hoehner et al. 2009). Collecting data for large areas or multiple cities is often beyond the resources of most organizations. Larger audits can also lead to subjectivity and issues of inter-observer reliability (Park 2008, Harvey and Aultman-Hall 2016). Another potential issue is that most of the existing audit-based approaches suggest a focus on walking, bicycling, and/or physical activity. This is not necessarily a detriment, but the outcomes may not be applicable in all policy situations.

Streetscape characteristics are now commonly considered to be far more important than just aesthetics and desirability. They can impact active transportation (Moniruzzaman and Paez 2012), public health (Giles-Corti and Donovan 2002, Badland, Schofield et al. 2009), traffic speed (Ewing and Dumbaugh 2009), road safety (Marshall, Coppola et al. 2018), livability (Forsyth, Jacobson et al. 2010), crime (Troy, Grove et al. 2012), mental health (Bell and Clark 1998, Seresinhe, Preis et al. 2019), as well as economic outcomes such as real estate prices (Gao and Asami 2007, Fullerton and Villalobos 2011) and economic activity (Montgomery 2013, Dover and Massengale 2014). But to truly understand these connections, we must do a better job of objectively measuring our streetscapes on a more consistent basis over larger areas.

Light Detection and Ranging (LiDAR) is a highly sophisticated Geographic Information Systems (GIS) and remote sensing technology. LiDAR is an accurate and precise mapping technology and surveying method that measures distance to a target by illuminating the target with pulsed laser light and measuring the reflected pulses with a sensor. When collected and analyzed properly, LiDAR is a much more efficient and objective method for measuring urban features then crude GIS or the manual, time-consuming, and possibly subjective approaches. In this project, we will evaluate aerial and mobile LiDAR collection methods for streetscape and transportation research. Over the last couple decades, GIS and related technologies have played a significant and often behind-the-scenes role in both basic transportation spatial database management uses and comprehensive transportation planning. LiDAR is now beginning to be used commonly for transportation purposes such as to guide autonomous cars. For example, researchers in LiDAR sensor technology are working towards better object-sensing to make the autonomous vehicles object detection capabilities more reliable (Funke, Brown et al. 2017). However, LiDAR has not yet been adapted for much in terms of more fundamental transportation research.

Research Objectives

This study will utilize LiDAR to measure and analyze urban streets and streetscape features. More specifically, the objectives of this study are to:

1. Conduct literature review
2. Investigate current LiDAR technologies
3. Gather conventional streetscape built environment data
4. Collect aerial Q1 LiDAR data
5. Develop and evaluate streetscape measures using Q1 LiDAR data
6. Collect mobile LiDAR data
7. Develop and evaluate streetscape measures using mobile LiDAR data
8. Create street enclosure measure
9. Advance knowledge by carrying out analyses to answer our research questions
10. Advance policy and practice with respect to objectively measuring cities
11. Advance education through the training of students
12. Build an evidence base by disseminating findings through publications and presentations

Research Methods

The United States Geological Survey (USGS), along with the support of other agencies, annually invests millions of dollars to acquire LiDAR throughout the U.S. as part of its National Elevation Enhancement Program (NEEP), or 3D Elevation program (3DEP), which launched around 2011. Their goal is to eventually have LiDAR acquired throughout the United States. Currently, over half of the U.S. is covered with some USGS-specified LiDAR standard. The USGS standards require that LiDAR be in one of four specified quality levels (QL). QL2 is most common and accounts for most of the U.S., followed by QL1. Specifications are as follows (Heidemann 2018):

- QL2 - Pulse density of 2 pulses/m2
- QL1 - Pulse density of 8 pulses/m2

Published applications of LiDAR are limited regarding its current applications to transportation research. The USGS lists flood risk management as the most important beneficiary of the NEEP program. However, infrastructure/construction management, natural resource conservation, agriculture and precision farming, water supply/quality, forest resource and wildfire mitigation, and aviation navigation/safety are all listed by USGS as business uses to benefit from the NEEP program (Snyder, Sugarbaker et al. 2013). Since NEEP LiDAR is publicly available and covering more area within the U.S. each year, we will first determine if LiDAR data collected at NEEP standards can play a pivotal role in transportation and urban planning/assessments. More specifically, we will attempt to assess 3D measurements of objects within streetscapes. If this is possible, then transportation and urban design analysts will have access to publicly available data that can assist with informed and objective decision making.

In MPC project #489 on street trees and safety, we completed a macro-scale streetscape analysis that utilized USGS QL2 data to understand what streetscape features can be collected and/or extracted from USGS QL2 LiDAR data. Our results suggested that QL2-level LiDAR data is useful for measuring buildings and trees in a streetscape – and gave us significantly different results than found with traditional 2D tree modeling – but not much more. In that work, we introduced the concept of mapping streetscape trees with voxels, which, in Geospatial terms, is a 3D volumetric pixel. Now, we intend to conduct a macro-scale streetscape analysis that utilizes USGS QL1 data to understand what streetscape features can be collected and/or extracted from such data. QL1 data is four times the density of QL2 data, so we anticipate a lot more streetscape information can be obtained from QL1 data versus QL2 data. We will then look at mobile-based LiDAR analysis of a streetscape to compare with the QL1 data. Mobile data is significantly denser then QL1 data. The intent is to collect mobile passes in areas where QL1 data was collected. This project will contrast with similar areas collected with QL1 specs to explain fundamental differences, advantages, and disadvantages between QL1 and mobile-based LiDAR streetscape mapping.

This project will build off MPC-489 and provide transportation and urban design analysts methods for quantifying streetscape features. Past researchers have often used macro-scale measures of urban form – such as population density or intersection density – as proxies for streetscape characteristics (Newman and Kentworthy 1989, Ewing, Schmid et al. 2003, Dumbaugh and Rae 2009). Urban designers are often interested in smaller scale spatial qualities that are difficult to assess at the macro level. These can include what Harvey et al. deem the meso-level characteristics that make up the "streetscape skeleton" such as buildings and trees (Harvey, Aultman-Hall et al. 2015, Harvey, Aultman-Hall et al. 2017). They can also include more micro-level street design elements (that Harvey et al. deem the "skin" of the streetscape skeleton) such as the number of lanes, the presence and type of bike facility, medians, sidewalks, and curbs. Beyond these engineering considerations, the micro-scale can also include benches, lighting, signage, awnings, bus stops, etc. This project seeks to understand what meso-scale and micro-scale street design features can be systematically and objectively collected using LiDAR technology.

We will first use high density, QL1 aerial LiDAR. Aerial LiDAR bounces off the first object it hits, generally off the top of the object. LiDAR will record a return on one of three types of objects:

1. A Hanging Object in Space: examples include the arms of light poles and powerlines
2. A Continuous Object: more specifically, an object that continues all the way to the ground such as a wall or light pole
3. Vegetation: a multi-point return object such as a tree

Hanging objects in space will be represented by where the point hits the voxel. Continuous object will also be represented by where the point hits the voxel, but the features will be captured and noted with a 3D-shapefile so that the entire feature is draped to the ground. For example with a hanging streetlight, we expect multiple points to hit the arm of the light. If that occurs at 20 feet in the air, the voxel zone at 20 feet will have those voxels classified as containing the object or lamp. With the help of Google Streetview, we can determine which voxels are at the base of the light on the sidewalk. A 3D-shapefile will capture those voxels so they can penetrate all voxel zones on the way to the ground. Continuous objects will utilize automated, multi-point return algorithms common to LiDAR processing software.

Little research exists regarding the use of voxel classification of data with urban features outside tree canopy assessments. When performing this assessment, the major question will be how to set the voxel size. With this, we will adhere to USGS standards for LiDAR data classification, which requires at least 1 LiDAR point per grid cell. QL1 data has nominal point spacing less than or equal to 0.35 meters, which translates to about 1.15 feet. A 1 foot grid cell would be too small, so we will likely utilize a 2 foot x 2 foot grid cell.

As for voxel height, that will depend on the average height of the free-hanging features. The continuous features will penetrate all voxel zones. However, the free hanging features will ideally interact with a single voxel zone. Unlike constraints related to occluded data, we see no reason to restrict the size of the voxel zone based on compromising the integrity of the LiDAR data. The ideal height of the voxel zone will then depend upon what we find when processing and classifying the LiDAR data. We think it is possible that 5 feet will be a well-represented height, thus each voxel would be 2' x 2' x 5'. However, we will make that determination after processing and classifying the LiDAR data.

After the LiDAR data is properly classified, a voxel processing application will be run on each classification. The GIS output will be a grid of each voxel zone height. The next step will be to run a GIS tool (such as ESRI's Intersect 3D feature with Surface tool) so the continuous objects are calculated and appended to all grid zones beneath the zone where the initial LiDAR data was captured. The ultimate result will be a street corridor polygon layer. Each record will be an individual street corridor. Each field will represent how much coverage that feature has at each voxel height zone.

A similar process can be used with high density mobile LiDAR data, but we will focus on comparing the results from the mobile LiDAR with similar roadways analyzed and processed with QL1 data. The voxels dimensions may be different, and we will have to address issues of how to deal with multiple classifications in a single voxel. However, the objective is to provide transportation and urban analysts with an understanding of how a streetscape can be quantifiably drawn up with mobile LiDAR point cloud data as well as to show what features can be extracted. We plan on displaying results that show how a streetscape is quantified and, more specifically, how much of each feature is covered in a streetscape. This will include side-by-side comparisons of mobile versus QL1 results from the same streets. We expect that smaller features, such as street furniture, may not be visible with QL1 LiDAR but can be extracted from mobile LiDAR data.

Though mobile LiDAR collection is still a relatively new product and concept, it is evolving quickly and becoming more popular due to its highly precise and accurate surveying capabilities, high density point clouds, and the ease of setting up such a system. The cost is also beginning to drop as compared to expensive aerial LiDAR. This project will be at the forefront of developing methods for objectively quantifying streetscape features and in terms of understanding what users can reasonably expect when trying to analyze streetscape features with mobile LiDAR.

Lastly, we will work to develop an objective method for defining street enclosure. Enclosure refers to the degree to which streets and other public spaces are visually defined by buildings, walls, trees, and other vertical elements (Ewing and Clemente 2013). It is considered theoretically important in terms of how people perceive and use a place (Lynch 1960, Cullen 1971, Alexander 1977, Jacobs 1993), but it has long been difficult to assess and measure (Harvey and Aultman-Hall 2016). A Harvey and Aultman-Hall study, for instance, used 2D LiDAR-derived polygons to address enclosure with respect to traffic safety in New York City (Harvey and Aultman-Hall 2015). This approach explains maximum height of the canopy and total canopy area; yet, enclosure includes many other important factors, particularly the heights of the multiple canopy sections that encroach upon a street. A follow-up study by Harvey et al. adds Boston and Baltimore but focuses on the streetscape skeleton as defined by buildings, without consideration of trees (Harvey, Aultman-Hall et al. 2017). Their novel approach collected 12 streetscape skeleton variables for more than 120,000 block-length segments using publicly available GIS data. Each GIS layer included 2D building footprint data along with an attribute table with information for the height of each building. Using a recursive GIS methodology, they were able to define a single building setback distance for each block face in a manner that tried to emulate human perception. Using cluster analysis, Harvey et al. then defined four streetscape skeleton classes – upright, compact, porous, and open – but were unable to differentiate between these cites based on streetscape skeleton nor between the functional classification of the street. The 3D voxel approach that we propose will build upon this strand of streetscape measurement research in order to help better define enclosure as a usable variable. Our methods will include both buildings and trees – as well as whatever other micro-scale elements can be gathered at each LiDAR quality level – and should function well in lower density spaces where building frontages are less prevalent.

Expected Outcomes

The LiDAR-based, quantitative approach to measuring urban streetscapes that we propose in this project can used in many strands of fundamental transportation research that we mention above, including research related to travel behavior, safety, health, livability, and economic outcomes. Incorporating voxel mapping to extract 3D characteristics of streetscapes with LiDAR filtering can significantly contribute to new measures, such as enclosure, and provide new insights into the role of enclosure in transportation research. It can also be used as an asset management tool for cities looking to inventory objects such as street trees, street lighting, bus stops, street furniture, and signage. The expected outcomes of this work will also include:

1. Findings with respect to the hypotheses and research questions
2. Manuscripts for presentation/publication at TRB and other peer-reviewed journals
3. Presentations to academic and policy audiences
4. A new module regarding LiDAR data extraction for a graduate-level GIS courses at the University of Colorado Denver

Relevance to Strategic Goals

This project primarily links to the FAST Act strategic goals of preserving the existing transportation system. It will also connect to promoting safety.

Educational Benefits

This study will provide opportunity for student research in terms of data collection, analysis, and paper writing. It will also be integrated into Dr. Marshall's GIS graduate-level course. The resulting data will be made available to students for use in term projects, master's reports, and PhD dissertation.

Technology Transfer

In terms of dissemination, the intent is to target both academic and practitioner audiences. For academic audiences, we will produce conference presentations and peer-reviewed journal papers. To share findings of this project with broader audiences in mind, we will make sure these results are disseminated via newsletter and/or popular press articles.

Work Plan

The proposed scope of work is scheduled for a one-year timeframe that will begin with a deeper look into the existing literature and historical approaches to measuring streetscapes. During this time, we will also be collecting and evaluating conventional streetscape and built environment data as well as Q1 LiDAR and mobile LiDAR data. In month 3, we will finalize our city selection. Months 6 through 9 will be dedicated to data analysis. We will then draft manuscripts and presentation materials in months 10 through 12. Over the course of the project, this work will be incorporated into lessons for a teaching module within graduate-level GIS course.

Task	Timeline
Literature review	Months 1 – 2
Data collection and evaluation	Months 2 – 5
Select cities for analysis	Month 3
Analyze data	Months 6 – 9
Incorporate lessons into classes	Months 7 – 10
Draft paper and presentation materials	Months 10 – 12

Project Cost

Total Project Costs:	$206,346.02
MPC Funds Requested:	$103,173.01
Matching Funds:	$103,173.01
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