

Space Syntax and Walkability Analysis in Support of Urban Design Decisions

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ABSTRACT: This research presents an application of the space syntax method to examine physical behavior in three urban neighborhoods – a compact downtown and two variations of sprawl development – in order to explore the link between environmental factors and physical activity. The environmental factors analyzed here include improved street connectivity, density, and mixed-use development. As a novel addition, this work also considered access to open spaces, parks, and trailheads, aspects unique to the study area. The first part of this research examined how compact urban areas, as compared to urban sprawl, influenced healthy behavior. The space syntax method was applied to explicate the morphological logic of the urban grid and quantify the built environment in relation to physical activity, including the street network characteristics of connectivity, integration, and depth. Second, this study addressed the comparative health and socio-cultural benefits of urban forms through measures of neighborhood completeness. This quantitative methodology was used to measure the level of density and amount of mixed-use in terms of walkability. As space syntax argues that more integrated streets are more likely to attract movement and visitors, the third part of this work evaluated the roles of various open spaces, parks, and trailheads within the mixed-use, dense development of a downtown, and how their respective locations might promote healthy behavior. Finally, this research concludes that increased residential density and retention of public open spaces of an existing single-use commercial downtown core, as well as easy access to parks and trailheads, could complement a walkable community design and suggest a healthy urban form. This work is relevant to existing urban neighborhoods and small urban communities looking to identify new development paradigms with regards to improved walkability and health promotive urban form.

KEYWORDS: Community Health, Connectivity, Mixed-use Development, Urban Density, Urban Form

1.0 INTRODUCTION

The Center for Disease Control (CDC) has reported that during the past 20 years, there has been a dramatic increase in obesity in the United States, with 35.7% of adults and 17% of children and adolescents reported as obese. Obesity, as well as diabetes, heart disease, and some cancers, often develops from the sedentary lifestyle and poor dietary choices frequently seen today. According to the CDC, these chronic diseases are the leading cause of death and disability in the United States. They cannot be cured, but they can be controlled; moreover, they are largely preventable through measures such as access to healthy food and exercise. After decades of designing spaces that discourage physical activity and promote chronic disease (primarily through increased auto-oriented development), the time has come to reevaluate community design and integrate new opportunities for healthier habits. Providing environments that make walking, biking, and using public transit more convenient and desirable will not only improve resident health, but might also lead to other positive outcomes such as reduced vehicular traffic congestion, environmental pollution, and social isolation.

As the rate of chronic disease has increased, architects and city planners throughout the United States have begun addressing the need for built environments that promote a healthy and active lifestyle, neighborhoods that are conducive to walking and other physical activities. In 2010, New York City officials produced the *Active Design Guidelines* as a reference for urban planners, designers, and architects, which address health concerns such as obesity and diabetes through intelligent design (New York City, 2010). Their compilation of research demonstrated that "a diverse mix of land uses, a well-connected street system and a good public transit system all tend to increase physical activity among city residents." Seattle is also embracing the future through a health-promoting EcoDistrict that offers healthier buildings, better mobility, improved access to fresh foods, and more social equity (Rainwater, 2012). Overall, the neighborhood form has a powerful influence on how people inhabit and traverse their environment during their daily activities. Urban design and planning strategies are known to motivate users to choose healthier options and strengthening a sense of community.

Walking is one of the most common types of aerobic physical activity. The National Household Travel Survey found that at the distance of one mile, 60% of people walked for social or recreational reasons, 46% walked to school or church, 40% walked to shops, and 35% walked to work (USDOT, 2017). However, such frequency, according to recent studies, may depend on the environmental dimensions present. With a focus on making walking an attractive and more viable option, researchers have identified five "d" variables that are necessary for analyzing the relationship between the urban environment and travel patterns: *density*, *diversity*, *design*, *destination accessibility*, and *distance to transit* (Cervero & Kockelman, 1997). *Density* includes the

concentration of people and jobs within a given zone, and *diversity* involves gauging the number, variety, and balance of land uses (i.e., residential, commercial, institutional, etc.) within that zone. *Design* refers to the street system and its connectivity and integration. *Destination accessibility* considers the ease of travel for pedestrians, and *distance to transit* measures the average distance from a destination to transit stops.

Providing an environment in which residents are encouraged to walk at least 1.24 miles per day will help them to reach the public health goal of at least 30 minutes of moderate activity daily, and lower their chance of obesity and other chronic diseases (Frank et al., 2004). Researchers have demonstrated that people walk and bike more often when they live in neighborhoods with higher street connectivity, greater population density, and more mixed-use development (Frank et al., 2005). Studies have also suggested that the workplace is the main base for walking trips in urban settings, and that people will walk more often if they have local destinations such as their homes, dining, shopping, or transit within 0.25 to 0.5 miles of their workplace (Zimring et al., 2005). Having a substantial mix of destinations or land uses within the 0.25 to 0.5-mile radius has been proven to be a significant and meaningful variable for walkability. One study on the relationships among obesity, community design, and physical activity found that each quartile increase in land use mix was associated with a 12.2% reduction in the odds of being obese (Frank et al., 2004).

Having a wide variety of well-connected destinations in close proximity provides an environment conducive to walking and biking. However, public open spaces such as parks and trailheads have also been shown to offer health benefits to city residents, and should be integrated into urban neighborhoods in order to increase the possibility of physical activity (Koohsari et al., 2014). These open spaces provide more than just an environment conducive to various forms of recreation; they also add ecological, social, and aesthetic value to a community (Pikora et al., 2003). As urban environments can often deprive people of access to nature, open green spaces would provide attractive neighborhoods that would contribute to a positive attitude and increase social activity. Strong street connectivity to such recreational spaces would, in turn, increase the likelihood of people accessing these locations as part of their daily or weekly routines (Thompson, 2013). Out of necessity, cities were previously planned with dense, walkable, mixed-use neighborhoods, but with the advent of the automobile, a sprawling auto-oriented infrastructure led to the way cities have been built for the past 100 years (Rainwater, 2013). Departing from the car-centric way many towns and neighborhoods are planned today, promoting livable development patterns in closer proximity to a variety of desirable and necessary destinations would provide a comprehensive solution to the obesity epidemic and result in healthier cities. This research focuses on existing urban neighborhoods in Bozeman, Montana, as a means of exploring design strategies that could promote a higher level of health and wellness despite urban sprawl.

1.1 The study area

Over the past twenty years, the city of Bozeman has worked to maintain a healthy and vibrant downtown, establishing ten city blocks along Main Street that benefit from a wide array of local shops, services, and restaurants. The city anticipates a large population boom in the next 20 years, with a growth rate of 3.8% per year. Concerned by this growth and its possible ramifications, the city has adopted a community plan that addresses issues of development and change while protecting public health, safety, and welfare. Sprawl is defined as a pattern of development that includes low population density, underutilized areas, and forced reliance on individual automobile transportation to satisfy basic needs. To retain and enhance the qualities that make Bozeman a desirable place to live, work, and play, the city has taken note of an emerging urban planning and development paradigm that signals a return to the development pattern that promoted walking, cycling, and public transport. Thus, this downtown site provides an excellent example of a prosperous, lively, and appealing community. In terms of traveling to work, 9% of the working population walk, 6% bike, and 1% use public transportation. This is remarkable compared to the other dense, pedestrian-friendly cities such as New York City and Seattle have comparable numbers, with 10% from New York City and 9% from Seattle walking to work, and 3% and 4% biking, respectively (FindtheBest, 2014). The CDC reported that from 2009 to 2010, Bozeman had a diabetes rate of 3.9% and an obesity rate of 17.4%; this compares favorably to the national diabetes rate of 11.9% and obesity rate of 35.9%. Despite having these relatively low rates, the city of Bozeman is focused on further improving community health. Consequently, this research maps out the existing urban form to both illustrate its effectiveness and provide areas where it might continue to improve.

1.2 Research questions

While environmental factors are associated with improved physical activity levels in urban neighborhoods, their suitability for existing urban environments is not assured, and stakeholders continue to struggle with balancing economic, environmental, and social cohesion concerns. This paper investigates the suitability of Bozeman's existing urban form for furthering health benefits. Answers to the following questions are pursued: As compared to urban sprawl, how do existing compact urban forms influence walkability? What role mixed-use, dense developments play as compared to single-use, sprawl developments, particularly with regards to

walkability? How can the locations of open spaces, parks, and trailheads within a mixed-use, dense development impact physical health?



Figure 1: (a) Bozeman area map with outlying neighborhoods circled (source: Downtown Bozeman Improvement Plan, 2009). (b) Downtown plan area with 10 blocks highlighted (source: Downtown Bozeman Improvement Plan, 2009).

2.0 METHODS

This study employed measures of space syntax and neighborhood completeness and objectively analyzed several of the city's environmental characteristics. The first step involved comparing the compact urban forms and urban sprawl with regards to physical activity, using space syntax to measure the street network connectivity, depth, and integration of three locations. Secondly, to define and measure the health benefits of density and mixed land use, neighborhood completeness was calculated and walkable destinations and opportunities for densification were identified. As space syntax theory argues that more integrated streets are more likely to attract movement and visitors, the third part of this study evaluated the positioning of various open spaces, parks, and trailheads within the mixed-use, dense development. Although it was predicted that the urban form was already quite dense, diverse, and accessible as compared to the nearby sprawling residential neighborhoods, the ten blocks along Main Street that made up the downtown core lacked one vital component: housing. Therefore, the discussion below supplies suggestions for integrating more housing into the existing downtown fabric.

2.1 Compact urban form vs. urban sprawl

Introduced in 1984 by Hillier and Hanson, space syntax is "a set of techniques for the representation, quantification, and interpretation of spatial configuration in buildings and settlements." By developing an "axial map" comprised of the longest and fewest lines that can cover all of the spaces in a given layout and connect them with one another, the spatial layout of a street network can be quantified. The axial lines that make up the map represent sight lines for people moving within the spatial network, including streets, roads, and pedestrian paths (e.g., lines of movement or physical routes). These lines are then transformed into vertices on a graph in which each line has a value of *connectivity* that relates to the number of intersections along its length. Space syntax also involves the concept of *depth*, which measures the network distance or steps of adjacency between network components. For example, to travel to a space that has a depth of 3, one has to make three turns from a root space (e.g., Main Street). A third quantitative measure that can be derived using space syntax is *integration*. This is "a function of the mean depth (number of connections that must be traversed) if one were to move from every space (node) to every other space (node). The higher the integration value of the node, the less its depth." Thus, a shallow graph is highly integrated, whereas a deep graph includes segregated spaces (e.g., a cul-de-sac).

The configuration of a network is considered to be the "primary generator of pedestrian movement." The more a space is integrated, the more likely it is to be densely occupied by moving people (Hillier et al., 1993). Because space syntax can be used to link street network connectivity and integration with pedestrian movement, this research used space syntax measures to determine the extent to which the downtown area of Bozeman, MT, was highly integrated and pedestrian-friendly as compared to the totality of its residential neighborhoods. A street network is a connected web of thoroughfares that forms blocks (a system of logical sites for private development) and provides multiple routes for walking, biking, and driving (Marshall, 2006). Small blocks and frequent intersections are necessary to encourage walking and biking, as people then have a variety of routes from which to choose. In terms of scale, the "maximum average block perimeter to achieve an integrated network is 1,500 feet with a maximum uninterrupted block face of ideally 450 feet, with streets at intervals no greater than 600 feet apart along any one single stretch" (Farr, 2007, p. 129). In order to illustrate how a compact urban form (as compared to an area of sprawl) provides a more pedestrian-friendly environment based on street connectivity, the ten blocks of downtown along Main Street were compared to

two nearby residential neighborhoods representing areas of urban sprawl (see Figure 2). In all three cases, the main route networks in each area were been made bold, for clarity.



Figure 2: The three environments assessed using space syntax, all shown on the same scale. (a) Map of the main study area, the 10 blocks of downtown Bozeman (17 lines). (b) Map of an adjacent residential neighborhood (13 lines). (c) Map of a second residential neighborhood located in the city's primary area of sprawl (17 lines) (source: Google Maps).

2.2 Mixed-use and dense development

Research has revealed a strong relationship between neighborhood design and the length and share of trips people will willingly make on foot. The essential element in encouraging such behavior is having more walk-to destinations clustered as closely together as possible (Farr, 2007). In other words, a strong mixed-use, dense development is key to promoting a healthy, walkable community. Questions raised by this concept include how many destinations are needed, and how close together they need to be to encourage consistent pedestrian behavior. Neighborhood completeness, a quantitative methodology presented by Criterion Partners and Farr Associates (Farr, 2007, p. 133), was used to evaluate the existing downtown community of Bozeman, and measure its levels of density and mixed-use in terms of walkability. It was then further employed to “identify opportunities for densification and economic development.” The first step in calculating a neighborhood’s completeness is listing all of the possible pedestrian destinations, such as banks, hardware stores, supermarkets, and places of worship (see Figure 3). The resulting number of destinations is then multiplied by the proportional area balance of all pedestrian destinations in the pedestrian shed, in order to determine the level of neighborhood completeness. Neighborhood completeness, then, equals the number of pedestrian destinations within a quarter-mile pedestrian shed multiplied by the proportional area balance of all pedestrian destinations in the pedestrian shed (use balance).

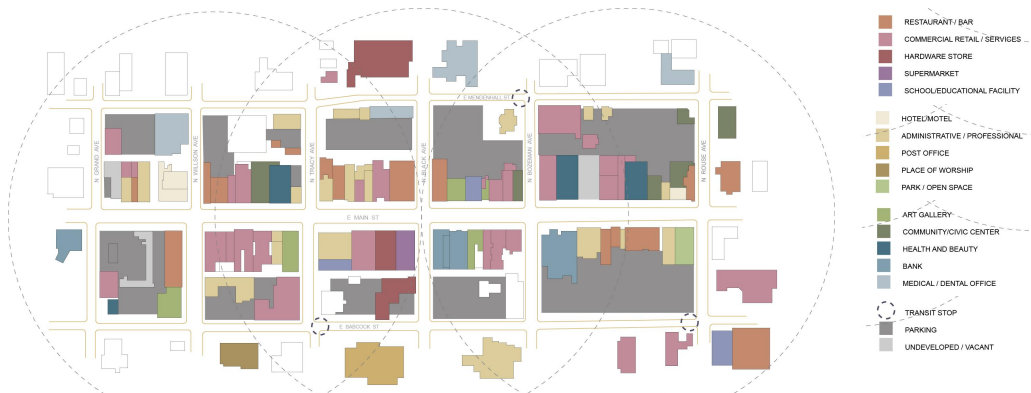


Figure 3: Downtown Bozeman land-use map showing 16 different pedestrian destinations in the neighborhood.

Neighborhoods should be suitable for walking, with all of the necessary amenities within a one-quarter to one-half mile radius. Most people will walk this distance before turning back. Longer distances will result in them opting to drive or ride a bicycle rather than walk. Therefore, the first value for finding the neighborhood completeness of these 10 urban blocks (see Figure 3) was calculated by finding the number of pedestrian destinations within a quarter-mile vicinity (critical mass); this made up the walking catchment area. Since the 10 blocks consisted of several quarter-mile radii, as seen in Figure 3, the overall neighborhood completeness was an average of these three radii calculations. The second value in the neighborhood completeness equation, the proportional area balance or use balance score, was found by multiplying the number of destinations in each land-use area; that number was then divided by the overall pedestrian catchment area. Next, the resulting value was compared to the neighborhood completeness indicator, which rates values as poor, minimal, satisfactory, or excellent.

2.3 Parks, open spaces, and trailheads

Public open spaces, parks, and trailheads are key locations within neighborhoods that can be both destinations for walking trips and settings for recreational physical activities; moreover, they can be enjoyed by people from a range of sociodemographic backgrounds. Although many studies have focused on proximity to determine its influence on physical activity, such as by measuring the shortest distance from home to the nearest park or open space, Hillier and Lida (2005) argued that people perceive and navigate urban spatial layouts in topographical rather than metric terms (Koohsari et al., 2014). In other words, the perceived distance to a destination such as a park or trailhead may be influenced more by the number of changes in direction that a person must make to arrive there. The more intersections, turns, and barriers that the journey to the location includes, the less comfortable people feel making that journey. Accordingly, space syntax was used to determine the ease of accessing public open spaces within the street network of downtown Bozeman. Figure 4a shows, the open space in the downtown area was rather lacking, despite the surrounding area having several large outdoor recreation destinations. In the 2009 Downtown Improvement Plan (Figure 4b), city planners and officials made courtyards and plazas a priority for new development, and improved Bozeman Creek to be a “centerpiece of a downtown open space system.” Their goal was to provide more functional open spaces that could be used and enjoyed, day and night, by nearby residents, visitors, and workers.



Figure 4: (a) Map of downtown Bozeman showing existing open spaces. Although the surrounding area includes several parks and open areas, the downtown itself has very few. (b) Proposed network of open spaces for the ten-block downtown neighborhood (Downtown Improvement Plan, 2009).

3.0 RESULTS AND ANALYSIS

3.1 Neighborhood connectivity and integration

In order to illustrate how the compact downtown urban form provided a more pedestrian-friendly environment than the two nearby residential neighborhoods (see Figure 2), measures of street network connectivity, depth, and integration were calculated. The street network connectivity, which consisted of the number of intersections along a chosen path, helped to identify how many routes a pedestrian in Bozeman might travel. In each of the three axial maps (see Figure 5), which include (a) Downtown Bozeman, (c) Sprawling Neighborhood 1, and (e) Sprawling Neighborhood 2, the layouts demonstrate a comparable amount of axial lines (i.e., movement paths).

With Node 1 in each resulting graph (b, d, and f) representing the primary route (e.g., Main St.), the results were as follows: Node 1b had 12 intersections, Node 1d had two intersections, and Node 1f had three intersections. From these results, it was concluded that Downtown Bozeman had a much higher level of connectivity than the other residential neighborhoods, at least in terms of access to the major road in each area. The importance of strong connectivity is that these main roads are occupied by important destinations, such as food, work, and retail services, and the likelihood of traveling to these destinations by foot decreases as the connectivity level decreases.

In terms of depth, which is a measure of the steps of adjacency between network components (i.e., the number of turns), Graph b shows an overall depth of 2, Graph d a depth of 3, and Graph f a depth of 6. What this means is that anywhere a pedestrian might be within the downtown core environment, they would only have to turn twice to reach Main Street (see Line 1). A pedestrian would have to turn three times in the case of Sprawl Neighborhood 1 (see Figure 5c) to reach the main road, and six times in Neighborhood 2 (see figure 5e). As previously mentioned, people perceive and navigate urban spatial layouts more in terms of changes in direction than overall distance (Hillier, 2005). Thus, even if the route taken is longer in terms of distance, a pedestrian will likely be more comfortable walking it if the route has fewer turns.

The third quantitative measure, integration, shows the mean depth if one were to move from every space in the area to every other space. The downtown core had an integration level of 3.18, meaning that the average number of connections that must be traversed throughout the whole area was around three. Comparatively, Neighborhood 1 had an integration value of 4.08 and Neighborhood 2 had 5.06.

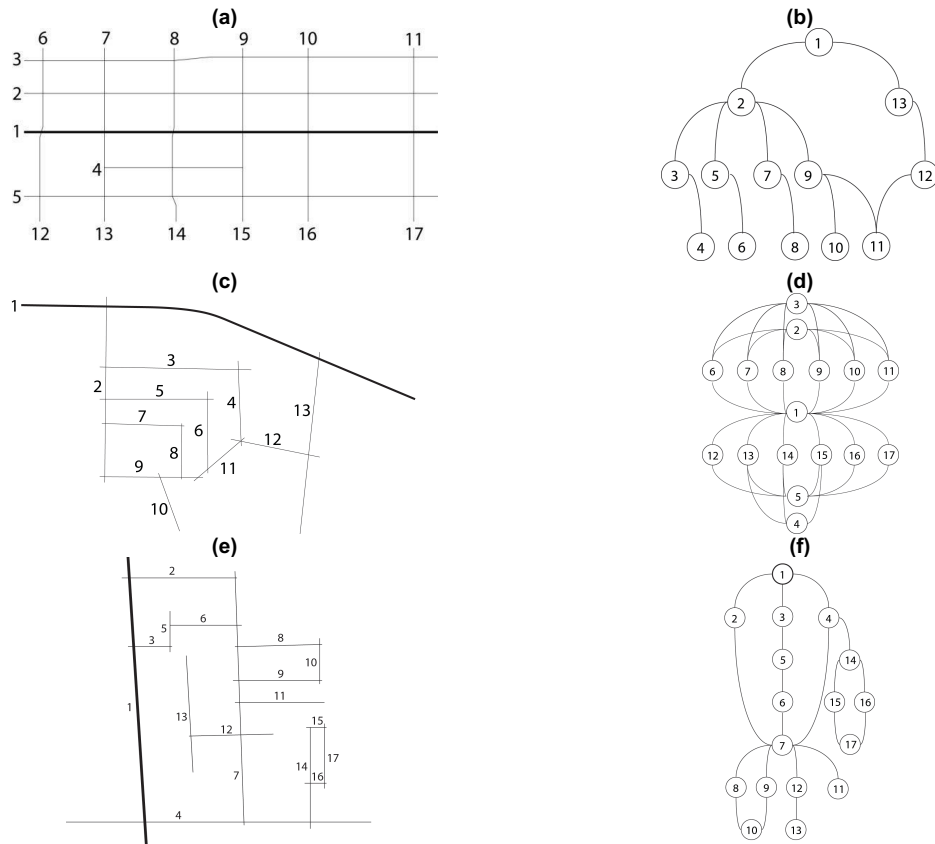


Figure 5: Using space syntax to assess the three environments. **(a)** Axial map of the downtown core (17 lines). **(b)** Downtown core graph. **(c)** Axial map of sprawl Neighborhood 1 (13 lines). **(d)** Graph of sprawl Neighborhood 1. **(e)** Axial map of sprawl Neighborhood 2 (17 lines). **(f)** Graph of sprawl Neighborhood 2.

As a recent study has pointed out, people living in neighborhoods that are better connected to the rest of the city tend to report higher levels of physical activity than those whose neighborhoods have lower connectivity. As shown in Table 1, the space syntax results indicate that the downtown core had a consistently stronger spatial configuration than the other two sprawling neighborhoods, and therefore provided an environment that supported a higher level of physical activity.

	Number of Axial Lines	Connectivity (node 1 intersections)	Depth (# of turns)	Integration (mean depth)
Downtown Core	17	12	2	3.18
Sprawl Neighborhood 1	13	2	3	4.08
Sprawl Neighborhood 2	17	3	6	5.06

Table 1: Comparison of the compact urban form of the downtown and two outlying neighborhoods in terms of connectivity, depth, and level of integration.

3.2 Density and mixed-use development

Since the 10 blocks consisted of several quarter-mile radii, the overall neighborhood completeness was calculated by averaging the three radii calculations. From the list of 16 amenities in the neighborhood (see Figure 3), it was determined that Area 1 had a critical mass of 11 pedestrian destinations within a quarter mile from one another; this made up the walking catchment area. Likewise, Area 2 had 10 destinations and Area 3 had nine destinations. The use balance, the second value in the neighborhood completeness equation, was calculated by multiplying the number of destinations per land-use area and dividing that number by the overall pedestrian catchment area. For Area 1, the proportional area balance equaled 0.73, for Area 2 it was 0.60, and for Area 3 it was 0.43.

By multiplying these values together (i.e., critical mass and use balance), the resulting neighborhood completeness values were determined to be as follows: Area 1 was 8.03, Area 2 was 6.00, and Area 3 was 3.87. In order to capture the overall neighborhood completeness, these three area calculations were averaged,

with the result equaling 5.97 (see Table 2). According to the “Neighborhood Completeness Indicator,” the resulting neighborhood completeness for Downtown Bozeman was categorized as “satisfactory.” In order to improve this rating to “excellent,” the city should enhance the density and mixed use of the downtown core by increasing the number of unique pedestrian destinations by seven. The other two residential neighborhoods were determined to have “poor” levels of completeness. Improving this score is outside the scope of this research, as it would require significant changes in zoning and a substantial financial investment.

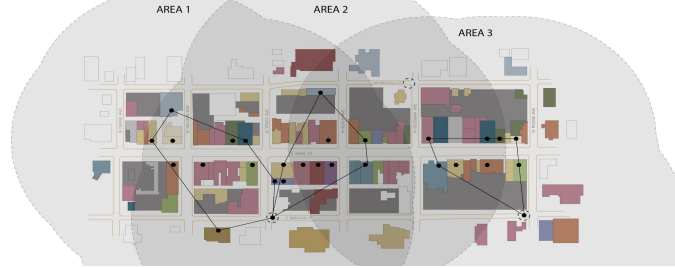


Figure 6: Downtown Bozeman land-use map showing three critical masses clustered no more than a quarter mile apart.

As the city of Bozeman anticipates population increase, the need for more housing is imminent. Furthermore, the potential threat of urban sprawl is rising, a situation the community desires to minimize. Previous space syntax data identified the downtown area as better connected, shallower, and more integrated than the more sprawling residential neighborhoods, which are positive factors in promoting physical activity. However, the downtown does not have the housing area that the sprawl neighborhoods possess. Table 2 categorizes the downtown neighborhood completeness as merely average, but there is room to improve this by providing a larger variety of pedestrian destinations in close proximity to one another.

	Critical Mass (# of Ped. Destinations)	x	Use Balance	=	Neighborhood Completeness	Neighborhood Completeness Indicator	
Area 1	11	x	0.73	=	8.03	Excellent 10 to 20	
Area 2	10	x	0.60	=	6.00	Satisfactory 5 to 10	
Area 3	9	x	0.43	=	3.87	Minimal 3 to 5	
Averaged Neighborhood Completeness					=	5.97	Poor Less than 3

Table 2: Neighborhood completeness calculations, with the indicator chart from Criterion Partners (Farr, 2007, p. 133).

In order to provide a truly walkable, livable environment, the downtown housing ratio and building density can be increased; this would be possible by building upon the existing infrastructure. In a proposal by Bhiwapurkar (2013), it was argued that the development density could be increased by adding mixed-use development above the existing two-story structures and employing a solar envelope design approach. Two options provided for growth are the addition of three residential floors or two commercial/retail structures, each with three residential floors above. The overlaying functions of multistory buildings will require further investigation using space syntax, as argued by Ratti (2004), in order to fully understand physical activities it will generate.

3.3 Parks, open spaces, and trailheads

Visiting a park, trail, or open space is usually voluntary unless the park is between the traveler and another go-to destination such as shops. This condition exists in Bozeman’s downtown. Space syntax argues that well-integrated streets are more likely to attract visitors, even nonregular ones (Koohsari et al., 2014). Figure 4(b) shows locations of six public spaces within the downtown street network. Location A, a large public space, located on a well-integrated Main Street is expected to have higher utilization, which may cause it to attract even more visitation. Conversely, Location F is on a street that is less integrated, and therefore less likely to be utilized. However, user behavior contradicts such prediction as spaces like Location F are being used by downtown visitors who park their cars nearby, as well as residents south of the downtown walk through these areas to get to Main Street. Also, this space connects with a trail frequently used by the majority of residents located on the east side of downtown, behind the new library. In addition to walkability, there are a number of physical and mental health benefits from urban greenery that have been reported in the literature; however, discussing them is beyond the scope of the present research. As the city moves forward with their downtown improvement plan, considering how these public spaces intersect with the overall street network will provide more convenient access. This point warrants further testing, as no study has yet examined whether public spaces located on more integrated streets are, in fact, frequented more often (Koohsari et al., 2014).

CONCLUSION

By exploring street connectivity, urban density, and mixed-use development, as well as easy access to public open space, parks, and trailheads, this research provides new insights into improving physical activity within
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the urban community of Bozeman, MT, as well as a development framework for other urban communities. Access to parks and trailheads from the downtown core is a newly added feature to improve physical activity and it is unique to the study area. The existing downtown core in Bozeman has strong street network connectivity, density, and integration as compared to the outlying sprawling residential neighborhoods. The density and mixed-use development of the single use downtown could be improved by adding to the existing infrastructure. Downtown residential housing could also be added to provide a truly walkable, livable environment. By doing so, the neighborhood completeness would be increased, allowing residents to meet their daily needs on foot, once more walk-to destinations begin to cluster together. By explaining how urban form impacts pedestrian activity, this study shows how to mitigate the increasing rate of obesity and associated chronic diseases, and positively impact the way communities grow. Future behavioral research, however, is suggested to test the walkability predictions made by the space syntax method in a mixed-use dense environment.

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Quantified Comparison of Landscape Urbanism and New Urbanism: Applying Mean Depth and Connectivity Measures in Space Syntax to Two Toronto Case Studies

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ABSTRACT: Landscape Urbanism and New Urbanism are two of the most recent and most relevant paradigms in contemporary urbanism. The two offer some major differences (such as density and approach towards urban sprawl, transportation mode choice, urban block size and arrangement, etc.) as well as some similarities (such as ecological sensibility, natural resource preservation, and connectivity of the urban fabric), causing them to become interested in similar urban contexts (such as post-industrial and brownfield sites), and making them comparable. Recently, there has been a lot of discussion around the conceived ideological, theoretical, and physical differences of these two paradigms, where proponents of each have brought forth arguments aimed at proving the superiority of their side and refuting the other. Despite the extent of these arguments, no quantitative comparison has been offered. To this date, the majority of these discussions have remained quite superficial. This paper proposes the use of Space Syntax as a methodology that can help fill this literature gap for meaningful quantitative comparison between the two paradigms. For the purpose of this study, a comparable Landscape Urbanist and a New Urbanist project were selected. The Lower Don Lands (Landscape Urbanist) and the West Don Lands (New Urbanist) projects are both located in downtown Toronto, Canada. They are both very recent projects and are of comparable sizes.

A common claim between Landscape Urbanism and New Urbanism, and a relevant issue in contemporary urbanism, is the connectivity of the urban fabric. This characteristic was selected to be quantitatively compared between the two case studies through measures of the Space Syntax methodology. As such, the two case studies were compared using “connectivity” and “mean depth” measures. Results were then assessed to determine which project performed more successfully in making a connection between its site and the surrounding urban fabric.

KEYWORDS: Landscape Urbanism, New Urbanism, Space Syntax, Integration, Mean Depth

INTRODUCTION

This study seeks to provide a quantitative method through Landscape Urbanist and New Urbanist projects can be compared and contrasted. To achieve this goal, first a methodological study of the two paradigms was performed where key claims of each were highlighted and further demonstrated and strengthened through case studies. Then, two urban cases were selected, one from each of the two paradigms. Then, according to the physical and quantifiable characteristics representing certain claims studied previously, Space Syntax was selected as the method through which those claims would quantifiably be put to the test and compared. Bafna offers holistic description of Space Syntax in his 2003 article:

Space syntax is best described as a research program that investigates the relationship between human societies and space from the perspective of a general theory of the structure of inhabited space in all its diverse forms: buildings, settlements, cities, or even landscapes. (Bafna 2003)

As such, the cases were compared using “connectivity” and “mean depth” measures from the Space Syntax methodology. The intent of this study is to fill the gap in the existing literature, where comparison between Landscape Urbanism and New Urbanism lacked quantifiable evidence.

1.0 BACKGROUND

Landscape Urbanism and New Urbanism remain two of the most relevant urbanism paradigms in contemporary urbanism. Without a detailed study and to the untrained ear, most of what each of these two opposing sides in the world of urbanism claim to be after sounds logical and beneficial solutions to the maladies and issues of contemporary cities. Looking more closely, one can detect both stark differences, and obvious similarities as there are aspects where both paradigms correctly, albeit through different approaches, detect urban issues.

Extensively discussed throughout existing literature, from one perspective, Landscape Urbanism and New Urbanism's fundamentally different approach to the medium responsible for ordering of urban spaces appears to be primarily responsible for ensuing differences between the two. The subject of much heated debate is that Landscape Urbanism takes "landscape" as its medium, whereas New Urbanism takes the "building". One of the most famous quotes upon which Landscape Urbanism bases this choice is that of Stan Allen:

landscape has traditionally been defined as the art of organizing horizontal surfaces... by paying close attention to these surface conditions – not only configuration, but also materiality and performance – designers can activate space and produce urban effects without the weighty apparatus of traditional space making. (Allen 2001)

This also boils down to the classic question of whether architects or landscape architects should be the dominating profession in urban design. On this issue, Waldheim calls for "architecture as a tool of instrumentality, not autonomy." (Waldheim 2016) For Landscape Urbanists, as Waldheim discusses, their pick of landscape as the major medium of urbanism sees its roots built on the canon of regional environmental planning such as Patrick Geddes, Benton McKay, Lewis Mumford, and even Ian McHarg. Waldheim also strengthens his stance on picking landscape as the Landscape Urbanist's medium of urbanism by stating that, landscape is a medium uniquely capable of... temporal change... adaptation... [and] contemporary processes of urbanization... [It] is suited to open-endedness, indeterminacy, [and] change. (Waldheim 2016)

These are some of the major keywords appearing in any Landscape Urbanist discussion. This divergence between Landscape Urbanism and New Urbanism also extends into the discussion of the importance of streets and space definition through edge conditions, both of which are essential to New Urbanists as components of good urbanism. Douglas Kelbaugh explains this distinction between Landscape Urbanism and New Urbanism and the importance of the treatment of the street and space definition through buildings best:

What [Landscape Urbanism] doesn't agree about is the "street," especially the "room-like plaza," or street wall of buildings, which is bed rock to New Urbanism. (Duany and Talen 2013)

This leads us to one of the more widely known differences between Landscape Urbanism and New Urbanism, namely the former's not only tolerance, but in some sense, encouragement of pseudo-suburban and low density urban conditions, and the latter's despise for such setups. Landscape Urbanism is an admirer of horizontality, and of surfaces, whereas New Urbanism advocates verticality and higher density. In the Charter of the New Urbanism, New Urbanists decry sprawl and the suburbia by stating that New Urbanism is disinterested in "[the] spread of placeless sprawl... [we] stand for... [the] reconfiguration of sprawling suburb." (Talen 2013) They even go as far as to declare New Urbanism's mission as "the reform of suburban sprawl." (Talen 2013) However, Waldheim believes that urban conditions such as low-density suburbia are part of the urban reality that we must deal with. On this subject, he asserts that,

New Urbanism is unable to deal with the automobile-based horizontal character of contemporary urbanism. (Waldheim 2016)

Landscape Urbanism takes the "systems approach" rather than a "design guided by intention" approach as its method. Landscape Urbanists base many of their design concepts on ideas such as dynamic processes, temporal change, adaptation, indeterminacy, and flux, and deploy processes and systems through which constant change and morphogenesis is directed towards achieving such goals as ecological performance and wildlife habitat improvement. One of the projects where we can see such process design is the Lower Don Lands project in Toronto, Canada, which, as seen later, is one of the subjects of study in this paper. Waldheim describes the project as one that is after

opening of the site to... the vicissitudes of tide and time... [and] activating dormant or redundant ecologies. (Waldheim 2016)

He declares that,

Stoss's proposal begins with... opening of hydraulic processes... [in this proposal], emergent, submergent, and submerged habitat are multiplied. Stoss's project proposes a five-fold increase in surface area and watercourses devoted to open-ended and self-regulating fluvial processes. (Waldheim 2016)

On New Urbanism's side of the story, probably the following quote from the Charter of New Urbanism suffices to explain their take on the issue: "We are not relativists." For New Urbanists, it is all about a determined end product—Duany and Talen clarify and elaborate the idea professing that,

New Urbanism is limited and pre-occupied. It is about certainty and a determined state versus Landscape Urbanism which is about indeterminacy, flux, and open-endedness. (Duany and Talen 2013)

All that being said, Landscape Urbanism and New Urbanism showcase some remarkable similarities as well as stark differences discussed above. One such commonality is both theories' claim on aiming for providing urbanism with optimal ecological performance and environmental friendliness. However, each of the two employ different methods and techniques to achieve this goal. Landscape urbanism, largely concerns itself with the issues of natural and ecological processes, watersheds, storm water and flood management, and wildlife habitats. New Urbanism, approaches the issue by building compact, which preserves as much land and natural resources as possible, as well as parks that provide fresh and clean air.

Another major common issue of concern claimed by both Landscape Urbanism and New Urbanism is the connectivity of the urban fabric. We can see numerous examples in the form of urban infill projects all over the world such the Hellinikon airport redevelopment project in Athens, Greece on the Landscape Urbanism

side. On the importance of what this project, as a means to stitch back the urban fabric, sets out to achieve, Waldheim states that the winning scheme for the project "...[reconnects] the higher elevation neighborhoods above with the coast below." (Waldheim 2016) Another example, this time on the New Urbanists' side is the Georgetown Safeway in Washington, D.C, a project which is described by Daniel Solomon as one which "...[mends] the hole in the neighborhood's urban fabric" (Charter 2013) Although the common theme in reaching the goal of connectivity seems to be the street network, it must be noted that Landscape Urbanism and New Urbanism, because of their inherent formal characteristics, have vastly different looks to streets. Andres Duany and Emily Talen explain that,

New Urbanism focuses on importance of streets defined by disciplined frontages... believing them to be an essential component of walkability... Landscape Urbanism is more concerned with maintaining a high profile of green space, irrelevant of its effect on street life. (Duany and Talen 2013)

Therefore, as Both Landscape Urbanism and New Urbanism claim to preserve and enhance urban networks, developing an approach to analyzing these claims is a central concern of this paper. This characteristic, as explained in more detail in the "Method" section of this paper is the urbanism theme explored quantitatively in this study.

Despite no lack of comparative literature considering the relatively young debate, there is an obvious absence of considerable literature regarding quantified studies. As such, and considering the quantitative analysis capabilities provided by Space Syntax, this study deals with quantifying Landscape Urbanism and New Urbanism in two case studies in downtown Toronto, Canada to assess how each of these projects perform regarding their success in creating connectivity and the stitching of the urban fabric.

2.0 METHOD

The Landscape Urbanist "Lower Don Lands", located in Toronto, and the New Urbanist "West Don Lands", located also in Toronto, just north of the Lower Don Lands project, were selected for the purposes of this study. These projects were studied and analyzed within an urban context three times as large as their cumulative sizes on each planar dimension.



Figure 1: Lower Don Lands. Source: (Google Earth)



Figure 2: West Don Lands. Source: (Google Earth)



Figure 3: Lower and West Don Lands within context (Axial map)

The Lower Don Lands is an infrastructure waterfront project designed by the Landscape Urbanist firm, Stoss LU in 2007. The site consists of 121 hectares of land on the Toronto waterfront, formerly and majorly consisting of, as per Stoss LU's statement,

a tangle of transportation infrastructure, a channelized and deadened river, and large territories of underutilized brownfields and former industrial port lands.

Stoss LU's proposal seeks to revive the Don river by paying special attention to both flood protection as well as the river's ecology and hydrology through its restoration as a wildlife habitat. Stoss LU describes another major goal of the project as

[establishing] a comprehensive urban design framework that integrates new development, bold and image-able transportation infrastructures, dynamic new open spaces, and robust, multi-modal circulation networks (Stoss LU website).

Just north of the Lower Don Lands project and few years earlier in 2004, Urban Design Associates in collaboration with DTAH designed the West Don Lands project, a 32-hectare piece of formerly brownfield lands east of downtown Toronto, now reimagined as "6000 residential units and a wide range of live/work, commercial, retail, and employment space". This project includes the design of a major park with flood control devices which also, like the Lower Don Lands project, considers itself to be a "critical component of the restoration of the Don River".

As stated above, the question tackled in this study is, how can one make meaningful and analytical comparison of Landscape Urbanism and New Urbanism using a quantitative method? To answer this question, one must first look for a proven systematic method that equips researchers with measures that can successfully relate to variables that describes issues of study in a case. In this case, Space Syntax provides us with measures such as "mean depth" and "connectivity" that, in a quantified manner, provide a description of integration and connectivity of the urban fabric. There are numerous publications verifying Space Syntax and its capability for assessing integration of the urban fabric. As with the relationship between the street network and block structure being integral, Lim et al. (2015) that the question of how block patterns and street patterns relate is one often asked in the context of Space Syntax. Also, from a morphological standpoint, their assessment that,

enriching the interface between classic Space Syntax measures and other morphological descriptors of urban form is a research aim which is being pursued with renewed intensity by many scholars in different centers of Space Syntax research (Lim et al. 2015)

seems right on cue and relevant to the question at hand in this study. The use of this method is further verified by Bafna, where he describes the aim of Space Syntax to be

to develop strategies of description for configured, inhabited spaces (of buildings, settlements, or built complexes) in such a way that their underlying social logic can be enunciated. (Bafna 2003)

Bafna also offers definitions and descriptions of different measures of Space Syntax such as connectivity and mean depth, the two measures used for the purpose of this study.

One local property that is often used is called connectivity. It is also defined for each spatial unit and is the number of spatial units directly connected to it. (Bafna 2003)

Bafna's description of depth and its relationship with integration and therefore connectivity of the urban fabric is also of note:

integration represents the average depth of the spatial unit from all other spatial units within a given system, and hence its value is affected by the entire spatial configuration. (Bafna 2003)

These descriptions help justify their use in the current study. As such, a comparison of the two aforementioned Space Syntax measures in each of the two projects mentioned above should provide us with a means to compare how each project performs regarding this characteristic which is one claimed by both Landscape Urbanism and New Urbanism.

3.0 RESULTS AND DISCUSSION

Apart from “mean depth” and “connectivity” measures in Space Syntax, there are several more measures and tools that might help describe and better understand the two Don Lands projects, especially regarding their perceived characteristics that are associated with the specific urbanism paradigm each of them are born from. What with the nature of this study having to do with street networks, all aspects of urbanism pertaining to street networks may prove relevant. For example, total street length per area represents the street density, a simple measure showing whether New Urbanism, with its much stronger emphasis on the importance of streets, holds true to its promise. This measure is 138.14 meters per hectare for the Lower Don Lands project and 308.57 meters per hectare for the West Don Lands project. With the New Urbanist measure turning out to be over twice as much as its Landscape Urbanist counterpart, we can conclude that the preliminary assertion regarding higher street density for New Urbanism holds true.

Table 1: Quantified Measures

	Lower Don Lands	West Don Lands	Urban Context
Total Street Length/Area	138.14 m/ha	308.57 m/ha	-
Average Block Area	2.52 ha	1.22 ha	-
Number of Blocks/Area	0.4 /ha	0.82 /ha	-
Average Connectivity	3.18	3.99	2.55
Average Depth	8.12	7.47	7.06
Average Integration	1.05	1.17	1.1

Another couple of measures identify with blocks, their number per area, and their average area. Here, it is imperative to provide a valid definition of blocks, as the Lower Don Lands project being a waterfront project, thus proving to be somewhat of an anomaly for the regular block definition. Jennifer Dill offers a fitting definition.

[Census] blocks are typically defined as the smallest fully enclosed polygon bounded by features such as roads or streams on all sides. (Dill 2004)

Based on this definition, Lower Don Lands has 48 blocks and West Don Lands has 27 blocks, which, according to their respective areas, yields 2.52 and 1.22 hectares as their average block area measures. This could be looked at as another fortifying point for the New Urbanist project as its value of less than half as much as that of the Landscape Urbanist one can be interpreted as more easily handled blocks that have more street frontages. It is also worth noting that nearly all West Don Lands blocks were reasonably close to the average block size of their corresponding project, whereas this number for the Landscape Urbanist project varied significantly more. This can be read as a proof of New Urbanism’s tendency towards more regulated block network system and its conservative nature versus Landscape Urbanism’s more free and rebellious approach in this regard.

Another measured compared regarding blocks was the number of blocks per area. For the Lower Don Lands project, this measure turned out to be 0.4 per hectare and for the West Don Lands project, it was 0.82. Again, the significance difference bears meaningful interpretation. Number of blocks per area can represent number of street segments and subsequently be an account of intersection density which increases choice and speed of access to destinations.

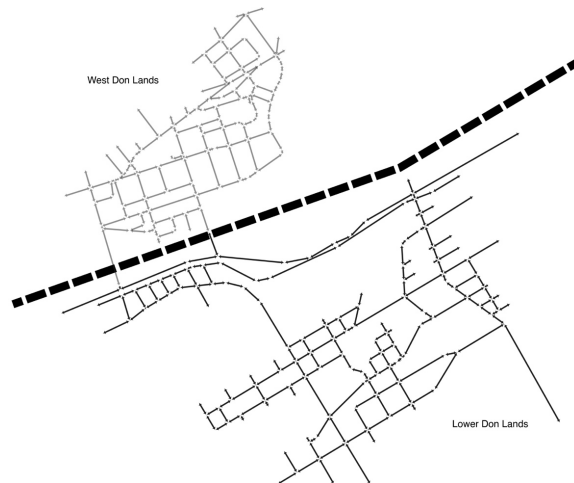


Figure 4: Line Segments

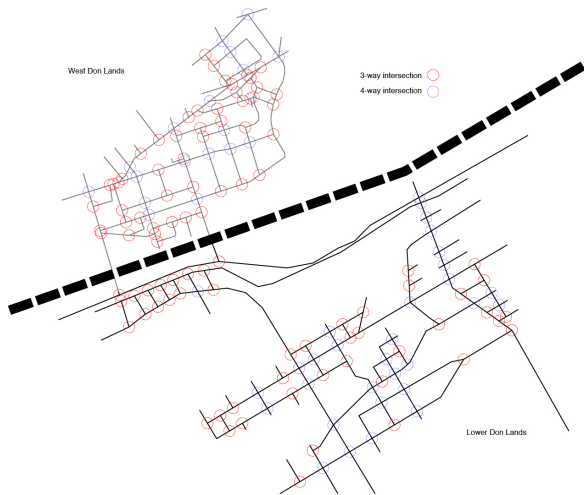


Figure 5: Intersections

To extract the “connectivity” and “mean depth” measures for Space Syntax analysis, the axial map of the context was used to input into the software “DepthmapX-0.50”. Each measure was extracted for the Landscape Urbanist project, the New Urbanist project, and the whole context, and then compared.

It is first appropriate to describe the meaning and significance of each of the two measures in question. Bafna (2003) accurately provides all definitions and applications needed in this study. According to him,

Depth of one space from another can be directly measured by counting the intervening number of spaces between two spaces. (Bafna 2003)

Based on this definition and considering the purpose of studying our two syntactic measures, the lower the depth, the more an urban condition is successful stitching itself to the surrounding context and achieving connectivity of the urban fabric. That is to say that the lower the depth, there will be less intervening spaces between two spaces, which leads to depth providing a measure that interprets into indirect visibility. According to Table 1, the average depth for the axial line segments representing streets in the Lower Don Lands project is 8.12 and for the West Don Lands project, this number is 7.47, which is a little smaller than the Landscape Urbanist Project, but not so much to meaningfully make a difference. Compared to the whole urban context (7.06), both the Landscape Urbanist and the New Urbanist project offer a higher average depth, which, if taken to mean anything, it means that they possess less connectivity. However, one must consider other parameters such as the fact that a large portion of that urban context on the west side is comprised of downtown Toronto, where there is higher density of intersections and street density. However, if that can directly be translated into intelligibility in terms of way finding is quite a different story.

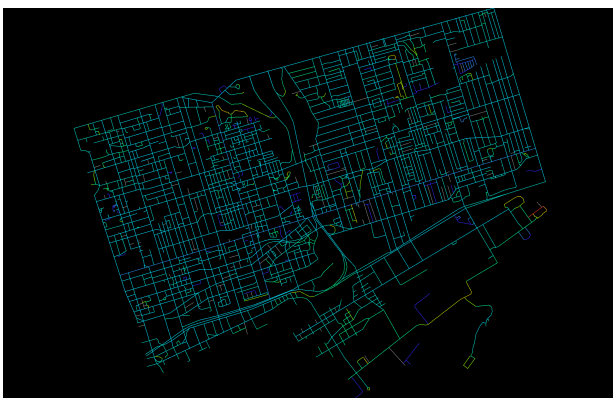


Figure 6: Mean Depth (Axial Map)

Bafna describes the local property of “connectivity” thus:

[connectivity is] defined for each spatial unit and is the number of spatial units directly connected to it (which is simply the number of convex spaces directly accessible from a given convex space or the number of axial lines intersecting an axial line). (Bafna 2003)

This means that, contrary to the case with the connectivity measure, the depth value translates to direct visibility, and as such, makes an urban condition more connected to its context, the higher its average depth value. According to Table 1, the average connectivity of the Lower Don Lands project is 3.18 and that of the West Don Lands is 3.99. Again, this is not a large margin of difference, but judging solely on the numbers, one can say that also in this regard, the New Urbanist project is more successful at connecting the urban fabric.

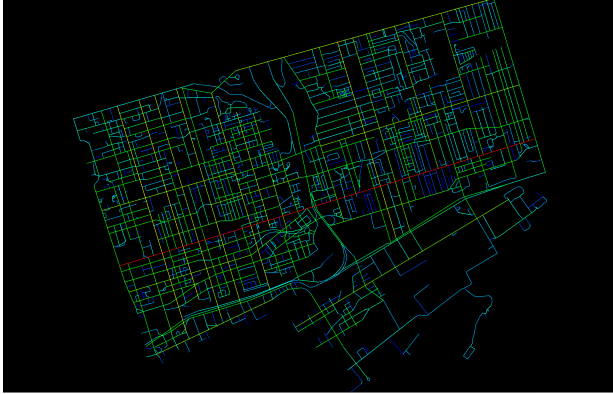


Figure 7: Connectivity (Axial Map)

On the relationship between connectivity, integration, and intelligibility, Bafna asserts that,

The degree of correlation between connectivity and integration values can be used as a measure of the predictability built into the entire environment and therefore of its intelligibility. (Bafna 2003)

He states that,

[intelligibility] predicts that a small town whose street network is arranged such that streets that have a high degree of integration connect to more streets on an average, and those streets that are globally segregated connect to fewer streets directly, will be an intelligible town on the whole. (Bafna 2003)

According to Bafna, intelligibility is defined as

the property of the space that allows a situated or immersed observer to understand it in such a way as to be able to find his or her way around in it, (Bafna 2003)

therefore making it directly related to wayfinding, which is an important cognitive factor of the connectivity of urban fabrics. By looking at the correlation between integration and connectivity in our area of study, one can deduce that overall, this is an intelligible urban condition:

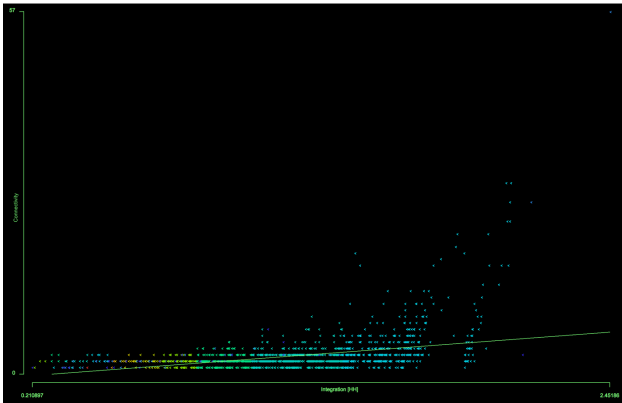


Figure 8: Correlation between Integration and Connectivity

Also, based on Table 1 and considering the integration values of Lower Don Lands and West Don Lands (1.05 and 1.17 respectively) individually in correlation with their corresponding connectivity values yield s almost similar results in terms of intelligibility, with not much of a meaningful difference for the purpose of comparison.

4.0 CONCLUSION

There is still a long way to go to successfully and meaningfully compare Landscape Urbanism and New Urbanism quantitatively. This study aims to try only one of many ways this gap in existing literature can be

started to fill and as such, is simply here presented to be an experimentation of the application of one available method – with a quantitative definition of connectivity and integration as one of the many urban themes inherent to the two paradigms- to a comparative analysis of Landscape Urbanism and New Urbanism. Admittedly, there are several shortcomings and limitations to the Space Syntax Method as well as the conditions under which this study has been performed. One such limitation is the individual context under which each of the two projects in this study fall under. When considering connectivity of street networks, it is crucial to have as much of a similar street network context for both projects as possible. The Lower Don Lands project falls under an entirely different urban network context, what with the project sharing boundaries with water on the south and west, a major highway on the north, and not much urbanism on the east. The described condition makes this project an extremely isolated site and therefore more difficult than its New Urbanist counterpart to establish reviving connections with its surrounding context. Further, it should be noted that comparing two broad urbanism agendas like Landscape Urbanism and New Urbanism could never be called comprehensive and definitive by simply comparing two projects representing principles of each, as none of these projects fully represent their respective paradigms.

Another issue that limits the viability and validity of such studies is the lack of available built Landscape Urbanist projects, as this is still a young urbanism paradigm. Also, Landscape Urbanism's nature and purpose significantly differs from that of New Urbanist projects that are more geared towards the built environment and higher density.

As the current literature also suggests, there are serious limitations to the Space Syntax method as well. For example, Vinicius Netto (2016) points to limits of this method regarding the relationship between society and space, which is an inherent and underlying theme to everything that has to do with urbanism. Space Syntax, as with many other methods, also falls prey to heavy reductionism on many fronts, thus making it not comprehensive, and not reliable as a singular method, when drawing conclusions regarding multi-layered, far-reaching themes such as integration and connectivity. Mihai Racu (2016) also points out several inconsistencies within the Space Syntax Methodology that prevent it from being an effective and reliable means for meaningful assessment of urban issues. One issue that has to do with the actual application of the method has to do with the representation of the axial map, which was also used in this study. According to Racu,

[the representation] process is based on drawing the map using the longest lines and the smallest number of lines, [and] this possibly [leads] to arbitrary results." (Racu 2016)

Therefore, although numbers might suggest that overall, the New Urbanist project is more successful at connecting the urban fabric, the fact that there is not much of a meaningful margin of difference between the numbers that yielded such a conclusion means that the said conclusion must be taken with a grain of salt. The above limitations are all elements that need to be carefully considered when drawing conclusions based on numbers that normally do not have the ability to take these adverse conditions into account.

However, none of this is to say that these types of studies are failed attempts. Quite to the contrary, it is to say that more studies and analyses are to be performed to find the right conditions, measures, and methods to make meaningful comparisons between Landscape Urbanism and New Urbanism and draw valid conclusions.

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Can Environmental Design and Street Lights' Retrofit Affect Crime Incidents in San Antonio?

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ABSTRACT: The neighborhood planning and street design are two major contributors to the physical environment's implications on safety measures. Natural surveillance, including glazing, lighting, and positioning of non-private areas and access paths inside and outside of buildings, has been studied ever since Oscar Newman and Jane Jacobs writings on successful design of streets with community spaces and observer's control of outside spaces. Various methods and data processing tools are used in the literatures to examine the location's capacity for natural surveillance as a major player in Crime Prevention Through Environmental Design [CPTED] and criteria such as space formation, nighttime lighting and its intensity, and visibility are used to identify crime hotspots. This paper is part of a broader project that examines environmental variables acting as crime generators at the public realm in the City of San Antonio [CoSA], and it focuses on drug, property, and violent [DPV] crimes reported for the period from 2012 to 2016. The study area is comprised of ten-neighborhood alongside the historic corridor of Fredericksburg Rd. Using geoprocessing tools of Geographic Information Systems, the method included univariate analysis of five environmental design variables: land use, street network, major transportation corridors, public spaces (parks and bus stops buffers), and street lights. Variables were triangulated with crime hotspots and the results showed that two neighborhoods (Gardendale and Five Points) have endured perseverance of crime hotspots from 2012 to 2016 in areas where multiple variables non-grid street network, parks, highway underpass, and a mix of commercial, industrial and multifamily land use were detected. When these variables exist in one location, they acted as crime-generators and created situational crime areas with intensity of crimes in public open space. The study provides a pathway for further examining -through qualitative data and micro scale analysis- to intervene in policy and design of public space in order to mitigate the likelihood of crime occurrence and endurance.

KEYWORDS: Crime, Environmental Design, Land Use, Street Network, and Street lights

INTRODUCTION

The neighborhood planning and street design are two major contributors to the physical environment's implications on safety measures. The modern interpretation of crime prevention through environmental design [CPTED] has been discussed in published scholarly work in the fields of urban and environmental design, criminology, and social theory (Ekblom, 2011; Cozens and Love, 2015; Sakip et al., 2012; Minnery and Lim, 2005; Marzbali et al., 2012; Lee et al., 2016). In most literature, elements defining CPTED stemmed from the Jane Jacobs' narrative on what made a city safe including high pedestrianism and clear public private distinction, and from Oscar Newman's defensible space which suggests different urban design tools for leveraging crime prevention. Some studies (Lee et al., 2016 and Marzbali et al., 2012) defined several elements of the CPTED that would significantly reduce perception of fear of crime including: access control, surveillance, maintenance, parks and community centers, and territoriality. According to the National Guidelines for CPTED of New Zealand's Ministry of Justice (2005), there are seven qualities that characterize well designed and safe places. These qualities are: 1) access through safe movement and connections; 2) surveillance and sightlines; 3) layout: clear and logical orientation; 4) activity mix; 5) sense of ownership through caring for the place; 6) well-designed environments; and 7) physical protection using active security measure.

In urban planning and design, territoriality has been applied by Jacobs, and then by Newman to places with close social networks can develop voluntary community guardianship. According to Newman, residents' territorial attitude could deter potential crimes because of the theory of natural surveillance. Newman's concept also addressed that semi-public community space surrounded by residential buildings would be important for

developing territoriality through increased visibility of public spaces. His concept is that spaces controlled by its own residents with the sense of community are more effective in maintaining safe neighborhood than police enforcement. Natural surveillance, including glazing, lighting, and positioning of non-private areas and access paths inside and outside of buildings, has been thoroughly studied ever since Newman and Jacobs writings.

The literature also discussed another, equally important, contributor to crime prevention attributes, which is land use. Researchers have also warned that the unplanned growth without studying the implications of land use may increase crime rates. The works of Hirschfield (2008), Ludin et al. (2013), Sypion-Dutkowska (2017), and Loukaitou-Sideris et al. (2001) have also discussed land use as a factor that could influence crime opportunity, and some studies suggested that policy-makers should examine potential areas of growth using GIS technology to strategically plan for future growth. Hirschfield (2008) also discussed the need to study the areas with ease of accessibility as they increase crime opportunities, and thus act as crime generators. These areas encompass the following elements: bus stations, road junctions, and the edges of urban areas according to crime pattern theory (Hirschfield, 2008). Changes in these elements are referred to as situational crime prevention approach, which is defined by Clarke (1997) as a strategy that focuses on crime settings, rather than those committing the crimes. It is therefore an approach that seeks to anticipate the occurrence of crime based on the analysis of environmental design elements, and thus can make the environment less appealing to offenders.

Beside CPTED physical components, sociologists have discussed social development theory, which support the role of urban lighting in providing a milieu for human interaction and feelings of safety at night time. During night time, street lights has a greater weight in natural surveillance measures and therefore it could impact the sense of safety and contribute to crime prevention endeavors. Kytta et al. (2013) studied the impact of both the social qualities and design characteristics of the neighborhood on perceived safety of residents as well as perceived levels of crime. The study concluded that, because of their density and design qualities, and access to smaller open spaces, urban infills could help change distressed development by increasing the level of perceived safety.

Improvement of street lighting has been a popular strategy for improving community safety and reducing the fear of crime. This reflects a shift towards situational crime prevention using environmental improvements to reduce the fear and eliminate opportunities for crime. Nonetheless, studies by Gilling (1997), Koskela and Pain (2000), and Walklate (1989) criticized this approach by indicating that it evades the deeper implications of socio-economic causes of crime, yet it can reduce crime and fear in certain areas (Clarke, 1992; Oc and Tiesdell, 1997). Other studies argued that improvements of street lights is resulted in both day-time and night-time crime reductions, which might not be due to deterrence, but because of an increased sense of ownership and community pride (Pease, 1999). This argument is supported by other findings as Farrington and Welsh (2002) explained that street lights normally work best in stable and well-maintained communities.

Improvement of street lights was incorporated in the UK as a nationwide initiative that involved six cities, where the effect of retrofitting lighting sources was examined for its potential effect on crime and sense of safety. Herbert and Davidson's (1994) research focused on two of these six cities, Hull and Cardiff, where in both the type of light sources and location of the street lighting poles increased the sense of safety in the two areas of study. In the same study, the authors divided the types of social problems into four categories: incivilities, crimes, insecurities, and services, where the effect of street lights changes was measured.

In San Antonio, a crime rate of 56 per one thousand residents (82,784 total crimes) made the city one of the highest crime rates in America compared to all communities of all sizes - from the smallest towns to the very largest cities (Neighborhood Scout, 2017). One's chance of becoming a victim of either violent or property crime in San Antonio is one in 18, which is higher than 96% of communities across Texas.

This paper is part of a broader project that looks into the changes in reported crime incidents in the inner city and urban corridors of the (City of San Antonio CoSA, Texas. Nonetheless, it focuses on crimes reported between 2012 and 2016. The paper focuses on a geographic area along one of the historic corridors, named Fredericksburg Road. To determine the study variables, a thorough review of the literature discussing crime prevention through/and association with environmental design variables was conducted. 20 papers were reviewed in this process, which resulted in two approaches of analyzing nighttime street lights. While in one approach adopted by several authors (i.e. Katyal, 2002 and Loukaitou-Sideris et al., 2001), street light was a component of environmental design variables, other authors (i.e. Shaw, 2014 and Steinbach et al., 2015) separated street light from other environmental design variables. It is worth mentioning that this disparity is due to the complexity of nighttime street lights impacts on crime.

In the first approach, street lights were considered with regard to the physical domain of light poles and their characteristics (i.e. location, height, source type, wattage, etc.), all of which are physically-measurable attributes through the utility companies or the municipalities and, thus, were part of the environmental design variables. In the second approach, street lights were considered a factor contributing to the sense of safety and reduced fear of crime, and therefore they were separated from environmental design variables. In this paper, physical attributes of street lights (i.e. location and wattage) are integral part of environmental design variables. With this decision, the approach of Ostrom (1976), Lee et al. (2016), Marzbali et al. (2012), Kim and Park (2017), Herbert and Davidson (1994), and Kytta et al. (2013) was adopted.

1.0 METHOD

There are various methods and tools to examine the location's capacity for natural surveillance as a major player in crime prevention through environmental design. Both quantitative and qualitative methods including surveys and interviews were used to assess environmental design of the context of crime locations, and various criteria pertaining to space configuration, nighttime lighting intensity and light source type, and building and street configurations comprise primary features contributing to the creation of crime hotspots in specific locales. The geographic scope of the inner city of San Antonio, where most of older developments and variations of transit corridors exist, was selected to examine the impact of retrofitting street lighting and other environmental design facets on crime incidents. The new LED for street lights were installed in San Antonio throughout 2013, and thus for examining the impact of street light transitions, 2013 data was excluded from the analysis. Crime data CoSA was obtained from the year of 2012 through 2016 and were split into two categories: 1) crimes occurred before installation date of LED source, and 2) crimes occurred after installation.

1.1. Study Area

This paper focuses on the selected neighborhoods representing the geographic scope of 16 neighborhoods along the Fredericksburg Road. Selection criteria for the pilot neighborhoods were based on built environment attributes deemed associated with situational crime theory discussed in the literature. These attributes include: 1) availability of data on street lights by installation dates; 2) balance between mix of non-residential uses within the residential-only areas; 3) proximity to major transportation corridor (i.e. Interstate-10 or Interstate-410); and 4) proximity to areas with concentration of night life activities.

1.2. Study Variables

In their studies of the association of built environment variables including land use, Canter (1999), Ludin et al. (2013), and Syption-Dutkowska and Leitner (2017) have praised the importance of using reliable data sources and tools that can identify patterns and spatial distributions of crimes. These three studies utilized Geographic Information Systems (GIS). Canter (1999) also discussed how the careful analysis of crime pattern, situation, and trend can be utilized to support policy decision making and allocate resources to determine the effectiveness of crime deterring strategies. Several spatial analysis models were also used in crime analysis.

Five themes comprising all variables discussed in more than 20 studies were concluded. The five themes are: 1) land use and zoning, 2) transportation and transit routes, 3) urban form and territoriality, 4) surveillance and crime generators, 5) socio-economic status, and 6) nighttime lighting. With the exception of the socio-economic status, selected variables in each of these themes, as shown in figure 2, were selected for this paper and were mapped using GIS. Socio-economic status was considered controlled variables for this paper, leaving only selected CPTED variables to be examined. In future, the authors will be integrating socio-economic variables as dependent variables. Variables used in this study encompassed the following:

Independent Variables

- 1) Land use: residential, commercial, industrials, etc.;
- 2) Street network: grid vs. non-grid/diagonal
- 3) Territoriality and major transportation corridors: interstates/highways;
- 4) Public open spaces: community parks, and bus stops buffers;
- 5) Natural surveillance: street lights (type of source and pole location)

Dependent Variable

Crime incidents that are likely to take place in the public view. Thus, only reported drug, property, and violent crimes [DPV] were selected for this analysis. Areas with low -and no- counts of DPV crimes were omitted from the geographic scope of the 16 neighborhoods, which yielded only ten neighborhoods identified as the pilot study area (see Figure 1).



Figure1: Fredericksburg corridor and the ten selected neighborhoods for the study area in San Antonio, TX.

1.3. GIS for mapping variables and crime hotspots

All selected variables were mapped individually using ArcGIS 10.5.1 (ESRI, 2017) and a univariate analysis was conducted for each variable: land use, street network, bus stops buffers, parks buffers, highways buffers, street lights, and DPV crime incidents for 2012, 2014, 2015, and 2016. The analysis encompassed the following tools and measures, which are also illustrated in the workflow shown in Figure 2:

- A vector polygon layer of land use was analyzed by using ordinal measures of the standard Land-Based Classification Standards (LBCS) developed by the American Planning Association.
- A vector line layer of street network was classified using ordinal scale- into three categories: 1) grid, grid-edge, 2) non-grid intersection, 3) non-grid edges.
- Vector point layer of bus stops and polygon layer of parks were analyzed using geoprocessing tools of GIS. A 250 m (820 ft) buffer for parks and a 100 m (328 ft) buffer for bus stops were created to examine likelihood of crime occurrence in the vicinity of these features as public open spaces.
- Highways (transportation corridors with high traffic volume) were analyzed using a 250 m (820 ft) buffer around the two major highways adjacent to the study area: Interstate 10 (IH-10) Interstate 410 (Loop 410).
- Street lights' vector point layer was analyzed to create a heat map using kernel-density spatial analyst tool, and a seven-class categorical raster output was created. Kernel analyst was chosen for this analysis because its use of algorithm that allows for better weighting of highly dense points and its associated smoother outputs.
- Vector point layers of the DPV crime incidents reported in 2012, 2014, 2015, and 2016 were analyzed to create a heat map using kernel-density spatial analyst tool. Only crimes occurred during nighttime, between 6:00 pm to 6:00 am, were included, and crimes reported outside of this time were excluded. Seven-class categorical raster output was created. 2013 data was removed from the analysis due to the major LED lights retrofit that took place during 2013.

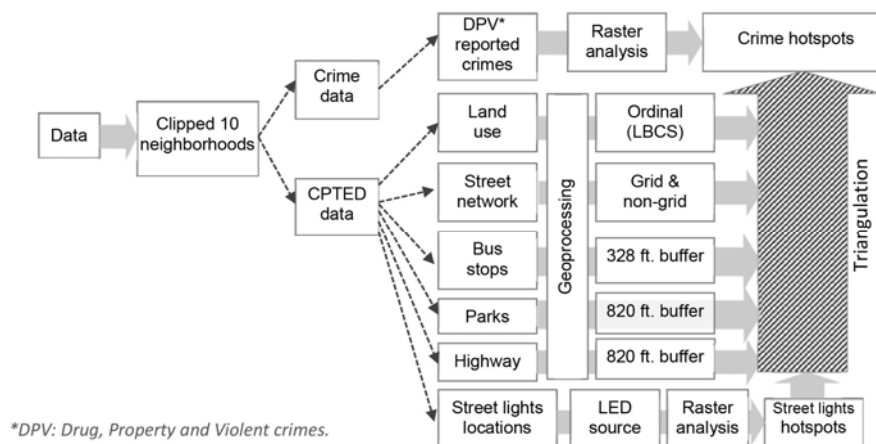


Figure 2: Workflow of the analysis and processing models of environmental design and DPV crime incident variables.

Following the univariate analysis using vector and raster data processing tools, cross examinations of the environmental design variables (land use, street network, highways, parks and bus stops/buffers) with the

heat map of crime incidents was conducted. To assess the relationship between LED street lights and the location of crime hotspots, we cross-examined compared the crime heat maps of 2012 (pre-LED retrofit) with crime heat maps of 2014, 2015, and 2016. With this triangulation, it was possible to observe patterns, including perseverance and shifts, of some locations of crime hotspots as well as their relationships with different environmental design variables including nighttime street lights as discussed in the following section.

2.0 RESULTS AND DISCUSSIONS

2.1. Univariate Analysis

The univariate analysis of the selected environmental design variables revealed the following characteristics of the study area (see Figure 3). Univariate analyses were cross-examined with the raster outputs of DPV crime hotspots:

Land use: A concentration of commercial land uses is evident on both sides of Fredericksburg Road. along Maverick, Los Angeles Heights, Montecillo Park, Keystone, and Gefferson neighborhoods. Other areas where commercial activities are concentrated are: 1) south side of Alta Vita neighborhood, 2) North-west portion of Five Points neighborhood, where commercial and mixed land-use dominates land uses, 3) around Interstate 10 in Gardendale neighborhood, 4) intersection of Gefferson, Woodland Lake, and Monticello Park neighborhoods, and 5) west side of Gardendale neighborhood, and 5) north and east edges of Beacon Hill and Alta Vista neighborhoods respectively.

Street network and Highways: Most of residential blocks of the study area are stemmed from a grid network, however, in Five Points and Maverick neighborhoods, non-grid system represented the majority of street network. These two neighborhoods are located in the north and south sides of the study area. At Gardendale's east side as well as the intersection of Keystone, Monticello Park, and Woodlawn Park neighborhoods, street network was also based on non-grid system. The latter had a big box structure of the local grocery store, known as HEB.

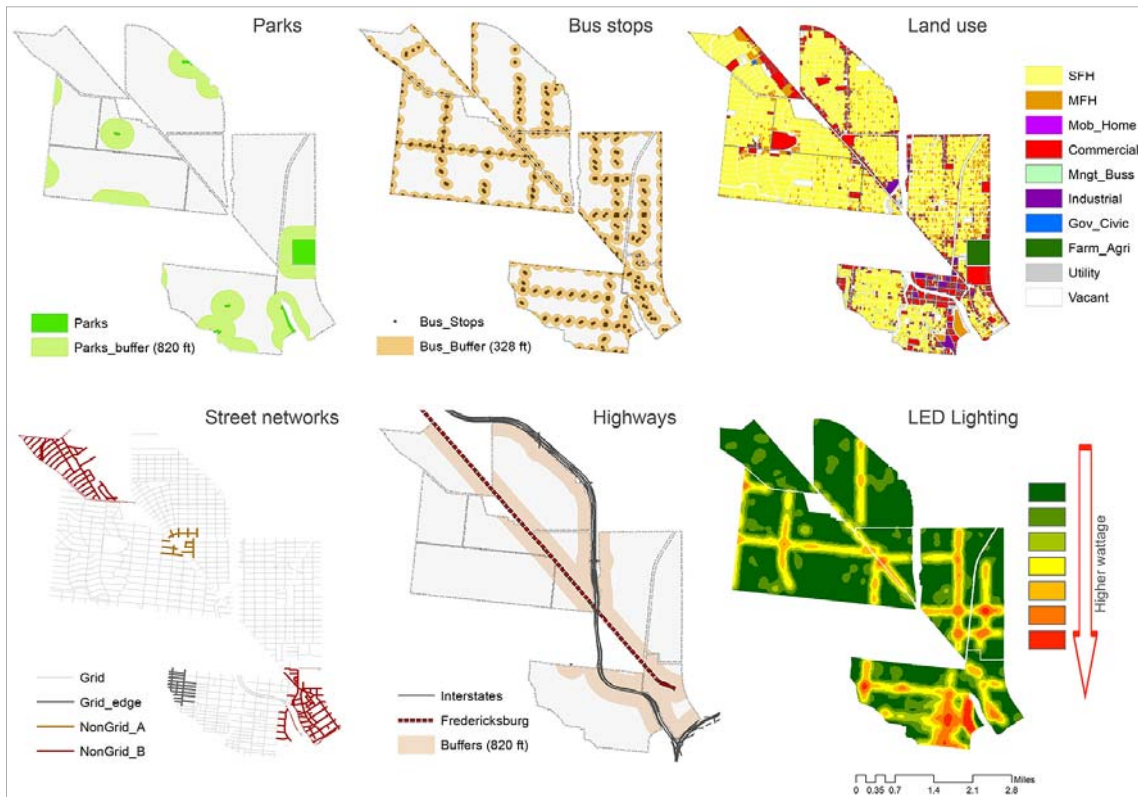


Figure 3: Univariate spatial analysis results for CPTED and street lights around Fredericksburg Corridor

Public open spaces: There are three parks inside the study area, and six parks on its edge. A 250 m (820 ft.) buffer around parks and a 100 m (328 ft.) buffer around bus stops was also created using ArcGIS geoprocessing tools (see Figure 3). Based on Anderson et al. (2013), these buffers normally act as crime generators, and thus create a situational crime opportunity as discussed in the introduction section of this paper. Therefore, the buffers were cross-examined with DPV crime hotspots and the results are discussed in the data triangulation section.

Interstates: There are two interstates, IH-10 and IH-410, pass-by and intersect with the study area. A 250 m (820 ft.) buffer around each was created using ArcGIS geoprocessing tools.

Street lights: Focusing on the watt-value of each LED street light source, a raster dot kernel-density analysis was performed on street lights layer. Figure 3 shows the aster output of this analysis including an overview of the concentration of LED lamps along main commercial and mixed-use streets, with higher wattage detected in the commercial areas, west of IH 10 in Gardendale as well as along the commercial corridor in Beacon Hill neighbourhood. It's worth mentioning that LED lamps was ranging from 100 to 400 watts. LED raster output was cross-examined with crime heat maps as discussed in the triangulation section.

2.2. Crime Hotspots

Using GIS spatial analyst tools, kernel-density analysis was performed on the point data of the DPV crimes (for 2012, 2014, 2015, and 2016) to create crime heat maps using seven-class scale to show areas with least crime concentration to areas with maximum concentration of crimes. In Figure 4, crime heat maps show a scale ranges from green to red, where red indicates the highest crime concentration in a cell size of 50 ft, and dark green is designated for the least concentration of crime incidents for the same cell size. The maps present a location-based profiling for areas with tenacious DPV crimes, which are indicated in red and orange- within the study area.

By comparing the location and intensity of crime hotspots across the study area from 2012 to 2016, an overall decline in the magnitude of DPV crimes reported at the intersection of Montecillo, Los Angeles Heights, and Keystone was evident. It is also noticed that both south portion of Five Points and south-east sides of Gardendale are obstinate with relatively high crime magnitude despite the drop in severity of crime concentration (from red to orange according to the crime concentration scale). Area located on the northwest portion of Gardendale showed a persistence of crime concentration, despite a slight drop in 2015. Along different segments of Fredericksburg Road, it was clear that a low to moderate crime magnitude was evident, and a drop in severe hotspots was detected particularly in 2014 and 2015.

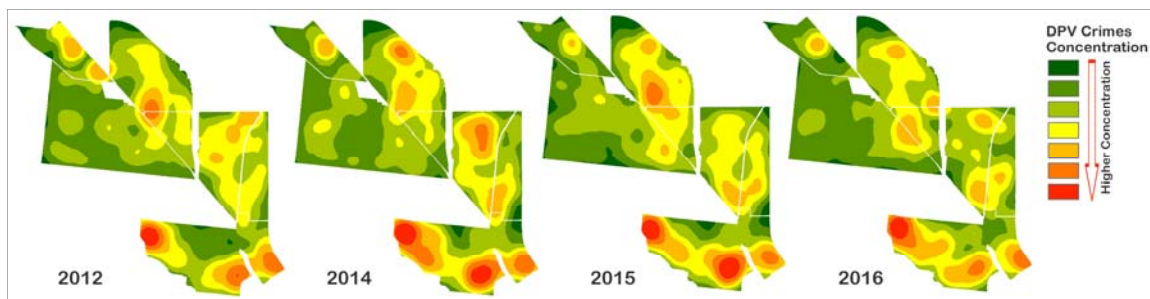


Figure 4: Heat maps of DPV crimes in the study area around Fredericksburg Corridor.

2.3. Data Triangulation

The univariate analysis maps were cross-examined with the raster output of DPV crimes hotspots. Each univariate map was separately examined for association with severe to moderate hotspots (shown in Figure 4 in red, orange and yellow respectively). Areas of the univariate map that proved a strong association with crime magnitude were designated as crime generators. Applying this triangulation process on the six univariate maps (land use, street network, bus stop buffer, park and park buffer, highway buffer, and LED street lights) showed that when a single variable coincide with the crime analysis, not clear evidence of association between both was detected. Only when commercial and/or mixed-use areas were examined, a partial association between commercial/mixed-use area and moderate crime hotspots was evident mostly in southeast and northwest portions of Gardendale. Additionally, LED wattage concentration had an inverse-association with moderate to severe DPV crime hotspots. Primary areas where high and moderate crimes from 2012 to 2016 were identified encompass:

- Northwest and east portions of Gardendale
- South portion of Five Points

Gardendale and Five Points neighborhoods are located north of the intersection of I-10 and I-410. Areas within the two neighborhoods where multiple variables overlapped resulted in severe to moderate crime hotspots. These hotspots are associated with the interstate I-10 buffer, non-grid street network, park and bus stops buffers, and mixed-use area. However, in the two neighborhoods, there is no evidence of the association of these hotspots with LED wattage. In Five Points, LED higher wattage concentration was associated with moderate to low crimes, however, in this part of the neighbourhood (Five Points), there were other variables exist including interstate buffer, bus stops buffers, and non-grid. In the south portion of Gardendale, LED wattage concentration was associated with high to moderate crime hotspots, however, in this area there was also mixed-use and bus stops buffers.

It is worth mentioning that even though the utility company has retrofitted the light sources across the study area from High Pressure Sodium Vapor to LED during 2013, changes in crime severity were not detected in 2014, rather in 2016 with one persistently high crime area located in the northwest portion of Gardendale. This portion of the neighborhood encompassed a concentration of commercial and mixed-use areas, park buffer, bus stops buffers, yet, it is a grid street network with lower wattage LED sources. From this analysis, it is clear that a significant association of environmental design variables and DPV crime is detected when multiple variables overlap, and thus act as crime generators.

CONCLUSION

The study provides evidence that when multiple environmental design variables exist in an area, they validate the crime generators theory of Katyal, N. K. (2002) and Hirschfield, A. (2008), and thus act to incite drug, property, and violent crimes. LED street lights, particularly with higher wattage showed less association with severe to high crimes across the study timeline. Only in southeast portion of Gardendale neighbourhood, LED street lights were associated with the magnitude of crime that continued to decrease (from high in 2014 and 2015 to moderate in 2016). When combined, the following variables showed significant associations with high to moderate crime incidents: commercial and mixed-land use, open spaces around parks and bus stops, non-grid street network, highway buffers, and sparse LED street lights. A further analysis is needed through allocated a different weight for each variable to identify variables with higher association with crime.

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Street Lighting and Public Safety: New Nighttime Lighting Documentation Method

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ABSTRACT: While the rapid transition of street lighting technologies is occurring across the country for its promising benefits of high energy efficiency, higher intensity, long lamp life, and low maintenance, there is a lack of understanding on the impacts from street lighting's physical characteristics on public safety. Nighttime lighting and its impact on the incidence of crime and roadway accidents has been investigated since the 1960s in the United States and the United Kingdom. However, prior research has not presented any scientific evidence such as quantified lighting characteristic data and its impacts on public safety because they relied on subjective survey inputs or over-simplified quantification of nighttime lighting conditions. To overcome the limitation of previous studies, extensive documentation of street lighting characteristics was conducted in downtown San Antonio, Texas, which adopts both conventional and new street lighting technologies. Two different sets of light level data were collected on roadways in order to measure the amount of light falling on the ground and on drivers' eyes inside a car. Correlated color temperature and a color rendering index of nighttime lighting were recorded. The collected lighting data was mapped in a Geographic Information Systems database in order to spatially analyze lighting characteristics. The paper first highlights the potential issues with lighting analysis in previous studies. Next, the proposed research methodology to address these issues for both data collection and spatial analyses is explained. Finally, the preliminary documentation and analysis of street lighting characteristics are presented.

KEYWORDS: street lighting, public safety, nighttime environment, LED, High Pressure Sodium

INTRODUCTION

Currently, 10% of existing street lighting in the United States has been converted to Light Emitting Diode (LED) lighting technology with promising benefits for energy efficiency, higher intensity, long lamp life, and low maintenance (Kraus, 2016). While the rapid transition of street lighting technologies from conventional high pressure sodium (HPS) or metal halide (MH) to LED occurs across the country, there is lack of understanding on the impacts from street lighting's physical characteristics on public safety and security. Nighttime lighting and its impact on the incidence of crime and roadway accidents has been investigated since the 1960s in the United States and the United Kingdom. Previous research claims that brighter nighttime lighting environments do not simply guarantee positive impacts on public safety at night. On the contrary, excessive and uncontrolled street lighting can even cause negative impacts to communities. Discomfort or disability glare from unshielded or poorly designed street lighting can reduce human eye visibility at night that eventually decreases levels of safety and creates roadway hazards (Gibbons and Edwards, 2007; Lin et. al., 2014; Tyukhova, 2015). In 2016, the American Medical Association (AMA) Council on Science and Public Health concluded that pervasive use of nighttime lighting creates potentially harmful effects related to discomfort and disability glare and addressed the urgent need for more extensive research on lighting's impact on human health and safety, particularly in the rapid transitions and installations of new lighting technology (Kraus, 2016).

After reviewing a number of previous research studies on the topic, two potential issues were identified. First, the studies misinterpreted increased light levels or increased number of street lighting as improved nighttime lighting conditions. This oversimplified interpretation of improved nighttime lighting conditions caused other important lighting characteristics to be overlooked. Improvement of the nighttime lighting environment should be determined by a level of nighttime visibility and visual comfort instead of the number of streetlight poles. Secondly, subjective survey inputs from community residents were relied on without collecting and analyzing quantifiable lighting characteristics such as illuminance, luminance, uniformity, color temperature, and the color rendering index. For instance, a Chicago Alley Lighting Project study considered how many new lighting fixtures were added to an experimental area compared to a controlled area. No fixture location, illuminance levels, uniformity, color temperature, and beam optic data were documented or analyzed (Morrow and Hutton, 2000). Also, the AMA report was generated by literature reviews and lab tests without collecting or measuring physical characteristics of street lighting such as light spectrum, amount of light, duration of exposure, spatial distribution, and timing (Rea and Figueiro, 2016). These examples clearly show that more in-depth analysis on physical characteristics of lighting is required to truly understand street lighting's role on public safety.

Across the United States, there is on-going efforts to improve nighttime lighting environments and energy efficiency. Recently developed communities already have advanced lighting systems such as LED lighting technology to provide a higher energy efficiency and longer life while conventional lighting technologies, such as HPS or normal MH, are common in existing communities. However, existing communities have been rapidly replacing conventional lighting to new lighting technology. It is imperative to fully understand the impacts and consequences from this lighting transition. To overcome the limitation of previous studies, extensive documentation of street lighting characteristics was conducted in downtown San Antonio, Texas, which adopts both conventional and new street lighting technologies. Two different sets of light level data were collected on roadways in order to measure the amount of light falling on the ground and on a drivers' eyes inside a car. Correlated color temperature and a color rendering index of nighttime lighting were recorded. The collected lighting data was mapped in a Geographic Information Systems database in order to spatially analyze lighting characteristics.

The City of San Antonio has a city-wide street lighting redevelopment plan which will eventually introduce new LED lighting technology throughout the entire city. This redevelopment project provides an opportunity to use San Antonio as a case study. While the redevelopment plan is being implemented, the City of San Antonio has also created a working group to evaluate and develop a new dark sky policy in San Antonio. Dark sky is a worldwide effort to minimize the negative influence of street and architectural lighting on nighttime environments. The policy has been incorporated into the building codes and standards of major cities. It is crucial to measure the current status of nighttime lighting conditions in San Antonio and to evaluate the need for new guidelines to limit the amount of man-made light pollution into the nighttime sky. The findings from the study will also help validate and improve existing lighting guidelines of roadways, sidewalks, and public spaces.

EXISTING STREETLIGHT GUIDELINES

Currently, street lighting design and installations are determined by the pre-determined horizontal illuminance levels and uniformity ratios on roadways and sidewalks, which were developed by the Illuminating Engineering Society of North America (IESNA) and approved by the American National Standards Institute (ANSI). ANSI/IESNA RP-8-00 Roadway Lighting Guidance recommends to provide a range of 3.0 to 17.0 lux of average maintained horizontal illuminance level on local, collector, and major roadways (Table 1). It also recommends the roadways to maintain 3:1, 4:1, or 6:1 uniformity ratio between average and minimum illuminance levels depending on roadway types. This recommendation varies depending on the roadway type, pedestrian conflict potential, and road pavement classifications (Table 1).

Table 1: American National Standard Practice for Roadway Lighting ANSI/IESNA RP-8-00

<i>Road</i>	<i>Pedestrian conflict area</i>	<i>Average maintained illuminance</i>			<i>Illuminance uniformity ratio</i> E_{avg}/E_{min}
		<i>R1</i>	<i>R2/R3</i>	<i>R4</i>	
<i>Major</i>	High	12.0 lux	17.0 lux	15.0 lux	3:1
	Medium	9.0 lux	13.0 lux	11.0 lux	
	Low	6.0 lux	9.0 lux	8.0 lux	
<i>Collector</i>	High	8.0 lux	12.0 lux	10.0 lux	4:1
	Medium	6.0 lux	9.0 lux	8.0 lux	
	Low	4.0 lux	6.0 lux	5.0 lux	
<i>Local</i>	High	6.0 lux	9.0 lux	8.0 lux	6:1
	Medium	5.0 lux	7.0 lux	6.0 lux	
	Low	3.0 lux	4.0 lux	4.0 lux	

Besides ANSI/IESNA RP-8-00 Roadway Lighting Guidance, American Association of State Highway and Transportation Officials (AASHTO) Roadway Lighting Design Guide is referenced when streetlights are designed and installed on roadways. It shows similar recommendations as ANSI/IESNA guidelines but there are slight differences in required illuminance levels and uniformity ratios. Based on the roadway classifications, including secondary arterial, collectors, and local roads, AASHTO recommends average maintained horizontal illuminance levels ranging from 3.0 lux to 14.0 lux (Table 2). Also, a 4:1 or 6:1 uniformity ratio between average and minimum illuminance levels is recommended.

Table 2: AASHTO Roadway Lighting Design Guide

Roadway classification	General land use	Average maintained illuminance			Minimum illuminance	Illuminance uniformity ratio avg./min.(max)
		R1	R2/R3	R4		
Minor Arterials	Commercial	9.0 lux	14.0 lux	10.0 lux	As uniformity ratio allows	4:1
	Intermediate	8.0 lux	10.0 lux	9.0 lux		
	Residential	5.0 lux	7.0 lux	7.0 lux		
Collectors	Commercial	8.0 lux	11.0 lux	9.0 lux	As uniformity ratio allows	4:1
	Intermediate	6.0 lux	8.0 lux	8.0 lux		
	Residential	4.0 lux	6.0 lux	5.0 lux		
Local	Commercial	6.0 lux	8.0 lux	8.0 lux	As uniformity ratio allows	6:1
	Intermediate	5.0 lux	7.0 lux	6.0 lux		
	Residential	3.0 lux	4.0 lux	4.0 lux		

These existing guidelines are effective to determine the efficiency and evenness of street lighting design and installations. However, the guidelines do not consider the human biological response such as the level of visibility, potential discomfort or disability glare, light color perception, etc. In other words, public safety of nighttime environments cannot be guaranteed or ensured by simply meeting the guidelines. Other critical factors such as light color temperature, the color rendering index, and vertical illuminance levels on people's face should be considered to increase and enhance safety at night.

METHODOLOGY

The objective of this project is to determine if a correlation between quantifiable street lighting characteristics and public safety exists. In order to achieve this objective, extensive documentation of street lighting characteristics is presented in this paper to understand the existing street lighting characteristics in downtown San Antonio neighborhoods (Figure 1). Neighborhoods in downtown San Antonio were selected based on the types and locations of existing street lighting. Surrounded by major express ways, the selected neighborhoods include various zoning districts such as downtown, commercial, industrial, infill development, and residential districts. Based on existing street lighting data provided by CPS Energy, the project has a mixture of conventional and new lighting technologies and various lighting characteristics. The existing nighttime lighting environments in the selected area are documented and evaluated in a GIS.

Based on the roadway classification of the City of San Antonio, the project scope includes the roadways classified as major (or arterials), collectors, and local roads. Santa Rosa Avenue, South Alamo Street, and Cesar Chavez Boulevard are examples of major roadways (arterials). The remaining roadways in the project scope are either collector or local roadways. Express ways are not included within the project boundary.

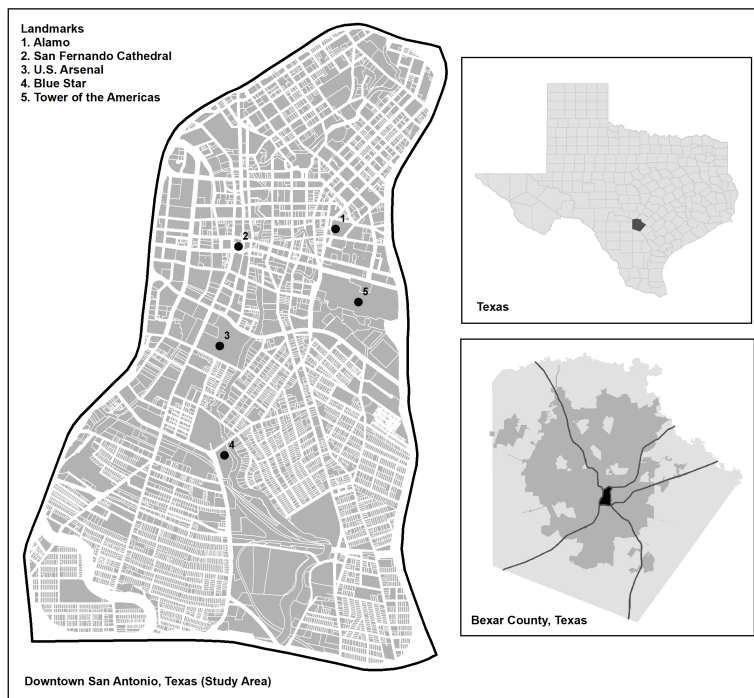


Figure 1: Selected project scope in downtown San Antonio

The following lighting documentation methodologies were utilized. Two different sets of light level data were collected on the roadways: horizontal illuminance levels at the ground level and vertical illuminance levels at the human eye height. These two illuminance data sets measure the amount of light falling on the ground and on the eyes of a driver inside a car. Correlated color temperature and a color rendering index of nighttime lighting is recorded at different locations within the project scope. The collected data was entered into the GIS database in order to analyze spatially the lighting characteristics which will be used in a future study to examine the relation to the incident rates and locations of both crime and roadway accidents.

For illuminance level measurements, one Li-Cor photometric sensor was mounted on a car to measure horizontal illuminance levels arriving on the roadway at 1 second intervals. Another Li-Cor photometric sensor was mounted inside a car simultaneously to measure vertical illuminance levels arriving at a driver's eye position. Both photometric sensors were connected to a Li-Cor LI-1500 data logger with a Global Positioning System (GPS) tracking function for data storage. Illuminance level measurements were made in multiple site visits during the nighttime. Driving routes were carefully planned by using Google Drive in order to avoid measuring the same roads multiple times and also to ensure driving directions and road closures in advance. The entire project scope was divided into seven different sections and a total of seven site measurements were made between November 1st, 2017 and December 14th, 2017. Each field measurement began after sunset (after 8:00PM) and took at least three hours to cover every single roads and alleyways in each section of the project scope.

Correlated color temperature and a color rendering index were measured by using Sekonic Spectromaster C-700. Different from the photometric sensors and datalogger utilized for illuminance measurements, the spectrometer is a hand-held device without data logging capability and GPS tracking function. Measurement locations were determined based on the streetlight types so that typical light color temperature and CRI values from each type of the streetlights can be recorded. Multiple measurements were made for each type of HPS, LED, MH, and Sodium Vapor streetlights. The ranges of measured color temperature and CRI values were then organized for analysis.

RESULTS AND ANALYSIS

Streetlight data obtained from CPS Energy was analyzed in order to understand the types of streetlight luminaires and their performance specifications. As of November 17th, 2017, a total of 119,714 streetlights exist in the City of San Antonio. Within the selected project scope of downtown San Antonio, a total of 3,061 streetlights have been installed. Table 3 shows the quantity and percent share of each installed streetlight lamp type including HPS, LED, MH, and Sodium Vapor. HPS streetlight is still a dominant type in the project scope. Currently, 32% of the total streetlights include various LED sources. The number of LEDs is expected to increase in the coming years due to the city-wide street lighting redevelopment plan.

Table 3: Streetlight lamp types in downtown San Antonio (CPS Energy 2017)

<i>Lamp Type</i>	<i>Count</i>	<i>Percent</i>
<i>High Pressure Sodium</i>	1,666	54.43%
<i>LED</i>	981	32.05%
<i>Metal Halide</i>	381	12.45%
<i>Sodium Vapor</i>	25	0.82%
<i>Missing Data</i>	8	0.26%

Different lamp wattages ranging from 100 Watts to 1,000 Watts are being used in the existing streetlights. HPS streetlight lamps are in 100W, 150W, 175W, 250W, 400W, and 1000W. MH streetlights are in 100W, 175W, 250W, and 400W. 40W, 96W, and 160W. LEDs were installed to replace the conventional HPS and MH streetlights. In prior studies, it was believed that a higher lamp wattage would improve nighttime lighting environments as it helps to make streets brighter. While lamp wattage determines lumen outputs from streetlights, it cannot be the only factor to determine whether nighttime lighting conditions are improved or not. Other lighting characteristics such as beam optic, color temperature, and CRI should also be considered to determine improved visual acuity and visual comfort at night.

Streetlight pole heights vary depending on the roadway types. Streetlights are mounted at 9.7 meters (32 ft) above ground at major and collector roadways while they are at 7.9 meters (26 ft) from the ground level on local roadways. Major roadways have 400W, collectors have 250W, and local roadways have 100W streetlights. The streetlight lamp specifications were also obtained from CPS Energy. HPS and LED streetlight specifications are described in Table 4. MH and Sodium Vapor streetlight specifications were not available. Both HPS and LED streetlights are very efficient and generate around 100 lumens per watt. However, it is important to understand that initial lumens of HPS streetlights are lamp lumens, which are different from fixture lumens of LED streetlights. As light generated from HPS lamps passes through system enclosures, the

amount of light decreases. It makes fixture lumens of HPS streetlights lower than fixture lumens of LED streetlights. HPS lamp color temperatures vary depending on manufacturers but it is known that HPS lamps typically produce very low (warm) light color temperatures around 2,500K and 2,700K with low color rendering index values. LED streetlights in the project scope have 4,100K correlated color temperature. Based on the specification comparisons, it is possible to conclude that LED streetlights are more energy efficient than HPS streetlights and also provide higher (cooler) color temperature and higher CRI values which help improve visual acuity in nighttime environments.

Table 4: Streetlight specifications of HPS and LED pole luminaires (CPS Energy 2017)

<i>Lamp Type</i>	<i>Watt</i>	<i>Lumens</i>	<i>Correlated color temperature</i>
<i>High Pressure Sodium</i>	100	9,500 (lamp)	N/A
	150	16,000 (lamp)	
	250	25,000 (lamp)	
	400	47,000 (lamp)	
<i>LED</i>	40	3,600 (fixture)	4,100K
	96	7,500 (fixture)	4,100K
	160	14,619 (fixture)	4,100K

Figure 2 shows streetlight types and locations within the project boundary. Red dots represent HPS streetlight locations and blue dots represent LED streetlights. Yellow dots are MH streetlights and purple dots are Sodium Vapor. All four types of streetlights are mixed in the downtown district (top half of the map). HPS and LED streetlights are randomly mixed in residential, commercial, and industrial districts (bottom half of the map). It is obvious that the downtown district has very dense streetlight installations on roadways compared to residential, commercial, and industrial districts. Based on the density of streetlight locations, it is possible to assume that there is a higher chance for over-illumination in the downtown district compared to the rest of areas. However, it is difficult to quantify actual illuminance levels or visual discomfort chances solely based on the map in Figure 2. In order to avoid overly simplified definitions of lighting conditions and to fully understand existing nighttime environment, accurate lighting data was measured on different roadways.

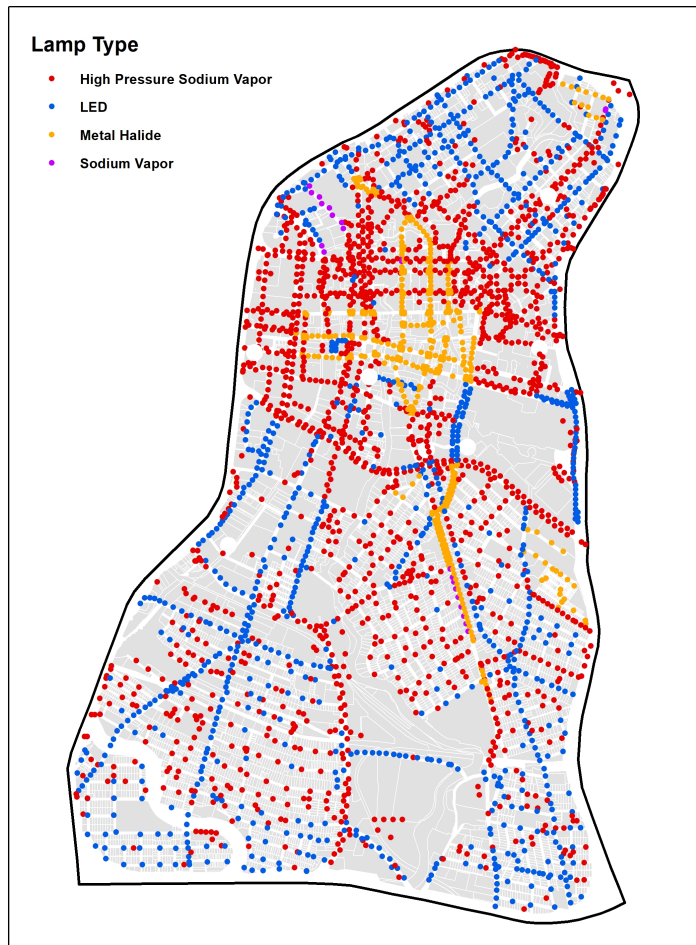


Figure 2: San Antonio Streetlight locations and types in the selected project scope

Collected illuminance data on roadways and driver's eyes were organized and the data were incorporated into ArcGIS software for analysis. Table 5 shows descriptive statistics of the collected illuminance data from the field measurements. Illuminance levels on roadways are not uniform as the range of illuminance levels on roadways is from 0.00 lux to 293.78 lux. Mean illuminance level on roadways is 13.43 lux, which is slightly brighter than what is required for local and collector roadways, but it is still an acceptable range for major roadways. Further statistical analysis is required to understand existing light levels in different land uses such as downtown, commercial, industrial, and residential districts. Different from the horizontal illuminance levels on roadways, collected vertical illuminance levels on driver's eyes show much lower light levels and less drastic contrast between minimum and maximum values. The mean vertical illuminance value of 2.35 lux shows that light level inside a car is much darker than what is available on roadways. The minimum value is still 0.00 lux while vertical illuminance level is up to 73.03 lux when incoming car headlight directly shines light towards driver's eyes. It is possible to assume that drastic changes of vertical illuminance levels on driver's eyes would negatively impact driver's night-time visibility and visual comfort while driving.

Table 5: Statistics of the collected illuminance levels within the entire project boundary

<i>Value</i>	<i>On roadways</i>	<i>On driver's eyes</i>
<i>Mean illuminance</i>	13.43 lux	2.35 lux
<i>Median illuminance</i>	6.43 lux	1.56 lux
<i>Min. illuminance</i>	0.00 lux	0.00 lux
<i>Max. illuminance</i>	293.78 lux	73.03 lux

The existing streetlight guidelines were referenced to check whether or not existing light levels in the project scope are sufficient and balanced. ANSI/IESNA RP-8-00 Roadway Lighting Guidance recommends local roadways to have a range of 4.0 to 9.0 lux of horizontal illuminance level on roadway, 6.0 to 12.0 lux for collectors, and 7.0 lux to 17.0 lux for major roadways. Based on these recommended illuminance levels and required uniformity ratios between average and minimum illuminance levels, it was possible to determine illuminance ranges for insufficient, acceptable (moderate), and excessive lighting conditions on various roadways. Based on the uniformity ratio 6 to 1, we can determine that illuminance levels below 0.66 lux is not sufficient for all roadway types. An illuminance range between 0.66 lux and 3.99 lux is lower than what is required but it is still acceptable for local and collector roadways. An illuminance range from 4.00 lux to 8.99 lux is appropriate for local and collector roadways. Also, it is an acceptable illuminance range for major roadways. An illuminance range between 9.00 lux and 17.00 lux is appropriate for major roadways but it is considered to be higher than what is required for local roadways. Illuminance levels above 17.00 lux may still be acceptable but it is unnecessary to provide this level of illumination for all three types of roadways.

Figure 3 illustrates existing illuminance levels on roadways. Different illuminance levels on roadways were color coded by the calculated illuminance ranges from the existing streetlight guidelines: 0.00-0.66 lux in blue (very low illuminance), 0.67-3.99 lux in green (low illuminance), 4.00-8.99 lux in yellow (moderate illuminance-local), 9.00-17.00 lux in orange (high illuminance-major), and above 17.00 lux in red (very high illuminance). As expected, a clear distinction between the downtown district and the rest of the neighborhoods can be made based on the nighttime lighting condition in Figure 3. The downtown district (the area inside the dashed white line) has much brighter nighttime lighting conditions than the rest of the areas in the project scope. Most of the roadways in the downtown district are either green, yellow, orange, or red in color, which represents acceptable or excessive lighting conditions. The roadways in either residential, commercial, or industrial districts have, in general, insufficient illuminance levels. Local roadways in residential and industrial districts are mostly in blue color, which shows that illuminance levels do not meet the required minimum light levels. Higher light levels are observed in intersections and also along the major and collector roadways. Further investigation is required to understand uniformity issues of different types of roadways and how this impacts public safety.



Figure 3: Collected street light level data mapped in ArcGIS

Besides the illuminance levels, correlated color temperature levels were collected from different locations of the project scope. Multiple measurements were made to record correlated color temperature ranges of each streetlight lamp type such as HPS, LED, MH, or Sodium Vapor. Locations of the measurements were determined based on the streetlight map. As expected, light color temperatures on roadways with HPS and Sodium Vapor streetlights are much lower than the ones with LED or MH (Table 6). Roadways with HPS and Sodium Vapor streetlights provide very warm (orange) light color that ranges from 1,800K to 2,600K. On the contrary, LED and MH streetlights provide cold (blue) light color that ranges from 3,900K to 9,300K. It is quite surprising that roadways with MH streetlights have light color temperatures up to 9,300K, which is an extremely cold light color. Color rendering index ranges are also shown in Table 6. LED streetlight shows the highest CRI values in a range of 74 to 78. MH streetlight also provides similar but a slightly lower color rendering index. HPS and SV streetlights show very low CRI values. As CRI values represent how different object and surface colors can be seen by our eyes, it determines human visibility at night. Human visibility is one of the most important factors that affect public safety. Therefore, the importance of good CRI light on roadways does not need to be highlighted again. The existing HPS and Sodium Vapor streetlights should be replaced by streetlights with a higher CRI value.

Table 6: Collected light color temperature and color rendering index (CRI)

<i>Value</i>	<i>Color temperature</i>	<i>Color rendering index</i>
<i>High Pressure Sodium</i>	1,963K-2,594K	14.9-41.9
<i>LED</i>	3,899K-4,370K	74.1-77.9
<i>Metal Halide</i>	4,190K-9,303K	62.6-76.9
<i>Sodium Vapor</i>	1,807K	-3.0

CONCLUSION

With the help of advanced lighting measurement technologies and a Geographic Information Systems (GIS) database, this study overcame the limitations of the previous studies by creating a database to analyze quantifiable data of nighttime lighting conditions. The new lighting data collection methodology allows for very detailed and accurate horizontal and vertical illuminance level measurements from all roadways within the

project scope. The collected illuminance levels on roadways show that local roadways in residential and industrial districts do not have sufficient light levels to maintain visual acuity at night. On the contrary, the central downtown district currently has sufficient light levels on roadways but many of the roadways are overly illuminated by streetlights. Correlated color temperature and the color rendering index data helps to accurately describe the quality of existing nighttime lighting in downtown San Antonio. As stated earlier, this paper addresses the documentation of nighttime lighting environments. The next step is to investigate the collected roadway light levels in relation to crime data and roadway accident data. This investigation will help clarify the role of streetlight characteristics on public safety.

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