Density, Diversity, and Design: Three Measures of the Built Environment and the Spatial Patterns of Crime in Street Segments

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Abstract

Purpose: The current study simultaneously examines the effects of three different characteristics of the built environment based on the theoretical conceptualizations of density, diversity, and design (3D).

Methods: By using data of 211,155 street segments in the Southern California metropolitan region across 130 cities, we estimated a set of negative binomial regression models including the 3D measures of the built environment, while accounting for the effects of social structural characteristics of place. Furthermore, the current study examines the potential moderating effects of each 3D feature on crime.

Results: We found that higher levels of business density are consistently associated with higher levels of crime. The diversity measure is associated with moderately higher levels of crime, whereas the design measure consistently exhibited a negative relationship with crime. Furthermore, we found that the diversity and design measures moderated the business density relationship with crime.

Conclusion: The results of the current study suggest that it is necessary to examine the different types of physical environment simultaneously to understand the effects of physical environment and the spatial patterns of crime.

Keywords: Crime, Place, Physical Environment, 3Ds

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Introduction

Routine activity and criminal opportunities theories suggest that a physical environment that engenders more foot traffic increases the risk of crime at place. Specifically, crime pattern theory looks at how physical settings (or the activity backcloth) of areas can produce different criminal opportunities in place (Brantingham and Brantingham 1984; Brantingham and Brantingham 1995). The Brantinghams viewed certain places as *crime generators* because they tend to draw a large amount of foot traffic coming into the area including potential offenders and targets. Other businesses can be seen as *crime attractors* as they have well-known reputations for criminal activities. Indeed, studies have empirically found that business facilities such as bars, liquor stores, or restaurants have crime-enhancing effects (Bernasco and Block 2011; Bernasco, Ruiter, and Block 2016; Block and Block 1995). Other studies have looked at how various land uses are associated with crime at place (Stucky and Ottensmann 2009; Boessen and Hipp 2015; Kurtz, Koons, and Taylor 1998; Wo 2019). These studies measured the proportions of different land uses in a location, and concluded that non-residential land uses are generally associated with higher risk of crime at place.

On the other hand, there is an alternative expectation for the association between the physical environment, foot traffic, and crime at place. The “New Urbanism” literature suggests that busier areas with more foot traffic are at lower risk of crime due to enhanced levels of natural surveillance. Specifically, regulars on the street including local residents, business owners, employees, and visitors can develop a web of social interactions, which encourages them to form an effective system of social control – e*yes on the street* (Jacobs 1961; Talen 1999, 2002). Some of these studies have particularly focused on mixed land use – heterogeneity among several land uses in one location—and argued that mixed land use exhibits crime-reducing effects given that areas with more heterogeneous physical settings garner lively and diverse activities, which potentially draws more foot traffic, and thus higher capability of guardianship from the presence of more eyes on the street (Wo 2019; Browning et al. 2010).

Although studies have looked at various physical environmental features and how they matter for understanding the spatial patterns of crime, prior research tends to focus exclusively on just one, or a few, dimensions of the physical environment. For instance, some studies have exclusively examined the effects of the presence/density of different types of business facilities or land uses in place (Wilcox et al. 2004; Bernasco and Block 2011; Steenbeek et al. 2011; Kim and Hipp 2021; Stucky and Ottensmann 2009), while others have focused solely on other concepts of physical environment such as land use mix (Wo 2019; Zahnow 2018; Wo 2019) or street network connectivity (Kim and Hipp 2019; Summers and Johnson 2017; Frith, Johnson, and Fry 2017; Davies and Johnson 2015; Beavon, Brantingham, and Brantingham 1994). The result is a less comprehensive theoretical and empirical explanation for the effects of different types of physical environmental dimensions on crime at place. In the current study, we attempt to fill this gap by simultaneously examining the effects of different dimensions of the built environment based on the theoretical conceptualizations of *density*, *diversity*, and *design*—the 3D features of the built environment of Cervero and Kockelman (1997)—while accounting for the effects of social structural characteristics of place. An important contribution is that we empirically examine how such physical environmental dimensions can work together to produce different spatial patterns of crime by testing the moderating effects among them. In the subsequent sections, we explain our theoretical motivations for the 3Ds of the built environment and the spatial patterns of crime. Then, we describe our data and the methods employed in the current study, including specific analytic strategies, followed by our findings and their implications.

Density, Diversity, Design: 3Ds of Built Physical Environment

A body of studies has theorized and empirically revealed that the urban built physical environment can largely shape routine activities, travel patterns, and thus the amount of foot traffic into an area (Cervero and Kockelman 1997; Montgomery 1998; Jacobs 1961). Cervero and Kockelman (1997) introduced the 3Ds (density, diversity, and design) to conceptualize the built environment and argued that the 3D features are important factors for the routine activities and travel patterns in urban settings. Specifically, *density* refers to the level of vitality in place (Montgomery 1998). According to Montgomery (1998), vitality conceptualizes the extent to which a place feels lively with various activities. Busier areas with various types of business activities draw voluminous foot traffic coming in-and-out of the area so that the place feels more alive. Vitality can be measured by the number (or proportion) of business facilities (or employees) or the composition of land uses in place. Hereafter we refer to density interchangeably as *business activity*.

Closely related to density, *diversity* is another important dimension of the built environment. Diversity refers to the degree to which different types of activities occur in a place. Jane Jacobs (1961) recognized the importance of land use compositions or business facilities because they are primary factors that can determine the number and type of people visiting the area, and thus vitality at a location. However, it is equally important for vitality that primary land use types should be placed within proximity of one another. Therefore, a built environment that can promote diverse activities is a necessary condition to have more vitality in place. This is because areas with more mixed land use or mixed types of businesses will draw more people visiting the area given the ability to obtain a variety of goods and services in one single location without further travel to other activity nodes. The idea of *temporal heterogeneity* is particularly important for diversity. That is, Jacobs (1961) posited that different types of amenities will draw different groups of people at different times of day. The consequence is that the street will be less likely to have “dead times” in which there are few people on the street and therefore be more vulnerable to crime due to the relative lack of guardians. Thus, density and diversity can enhance pedestrian movement rather than vehicular movement as they increase the proximity between origins and destinations of activity nodes. We refer to diversity interchangeably as *land use mix* hereafter.

Finally, street *design* is the third theoretical dimension to consider for understanding the built environment. Previous ecological studies have paid relatively less attention to the street, yet it is one of the most important physical features in urban settings (Kim and Hipp 2019; Jacobs 1993; Jacobs 1961; Taylor 1997). Streets are places where various social, economic, and cultural activities occur. Streets can promote social interactions by providing opportunities for social contacts. Moreover, another primary function of a street is that it shapes travel patterns of people moving from one location to another. Therefore, as Jacobs (1961) stated “streets and their sidewalks, the main public places of a city, are its most vital organs. If a city’s streets look interesting, the city looks interesting; if they look dull, the city looks dull" (p.39). Street design is the physical layouts of individual streets and their faces (Frank, Engelke, and Schmid 2003). Although street design includes various elements, one important feature is the street network configuration (road layout), or more specifically, how well an area is connected with others via the street network. This is because they can directly affect the level of connectivity of a given area with other areas via the street network; this can determine the amount and type of foot traffic. We hereafter refer to design interchangeably as *street connectivity*.

The 3Ds and Crime at Place

A body of studies focuses on the spatial distribution of crime within cities. Much of this literature builds on the theoretical insights of criminal opportunities – the confluence of potential offenders and targets along with the absence of capable guardians at a given time and place (Cohen and Felson 1979; Brantingham and Brantingham 1993; Felson and Boba 2010). This theoretical perspective implies that busier places with more foot traffic are at higher risk of crime, which has been studied extensively (Bernasco and Block 2011; Brantingham and Brantingham 1993; Brantingham and Brantingham 1995). However, another body of research suggests an alternative hypothesis: that this increased foot traffic can reduce crime and disorder through enhanced natural surveillance and informal social control from eyes on the street (Jacobs 1961; Browning et al. 2010; Carr 1992; Oldenburg 1999; Williams and Hipp 2019). We propose here that an important feature of the 3D's is that they may be able to alter the mix of targets, offenders, and guardians at a location, rather than simply increasing the number of people. In this section, we discuss these competing theoretical perspectives and pose hypotheses to test, accordingly.

Density and crime

Considering the impact of density—based on the number of business activities—there is arguably a strong reason to expect this to have a positive relationship with crime. Based on the framework of criminal opportunities, areas with more density will have greater foot traffic, which will bring together more offenders and potential targets. The result would be greater risk of crime in these areas. Whereas this greater foot traffic will also bring more potential guardians, research consistently finds that the effect of these potential guardians is more likely to be overwhelmed in locations with many businesses. Thus, prior studies have typically found that busier areas with more businesses, or non-residential activities, are generally at higher risk of crime (Bernasco and Block 2011; Stucky and Ottensmann 2009; Brantingham and Brantingham 1995; Kinney et al. 2008; Boessen and Hipp 2015; Kubrin and Hipp 2014).

Indeed, crime pattern theory posits that certain types of business facilities (i.e., malls, shopping centers, etc.) can work as *crime generators* because of the large amount of foot traffic they draw into the area including potential offenders and targets. Therefore, areas with more business facilities tend to have more criminal opportunities – the probability of the convergence of potential offenders and targets at the same time and place. Other types of businesses (i.e., alcohol outlets, check-cashing stores, marijuana dispensaries, etc.) are *crime attractors* with known criminal reputations. These facilities do not necessarily bring large number of people visiting the area, yet their function makes them well suited for motivated offenders to find attractive and weakly guarded victims or targets (Bernasco and Block 2011). Thus, we hypothesize that our measure of density will be associated with more crime:

H1. The presence of more density will be related to more crime.

Diversity and crime

Regarding mixed land uses (diversity), there is more uncertainty about its potential impact on crime. On the one hand, these mixed land uses will bring more population into the area, which potentially brings about more criminal opportunities in the place. It is also possible that the mixing of residential and non-residential land uses may impede the formation of informal social control by reducing territoriality – the level of separation between the private and public space. This would result in weakened social control effectiveness and guardianship in place (Taylor et al. 1995; Newman 1972; Kurtz, Koons, and Taylor 1998). This mixed land use may increase the ambiguity of who belongs in the area, and thus as Wo (2019) stated, in areas with mixed land uses, “even if residents demonstrate a willingness to intervene under conditions of challenge, the overriding sense of anonymity that results may impair residents’ ability to detect suspicious, crime-related activity” (p. 171). Indeed, Taylor et al. (1995) found that blocks with more mixed land uses have more physical deterioration. Likewise, Kurtz, Koons, and Taylor (1998) also found that mixed land use can weaken resident-based control in blocks.

A counter-viewpoint is that although land use mix attracts people to the environment, it may change the timing of when people come to the area, which may minimize crime opportunities. That is, an effective mix of land use settings in a location can promote activities in an area, and bring people in at different times of the day. Jane Jacobs (1961), in particular, noted that areas with more diverse built environmental settings tend to be more alive consistently throughout the day with visitors and regulars. Busier areas can facilitate casual interactions among people on the street. Such diverse settings also encourage the public social interaction between residents, business owners, employees, and visitors through which they form a web of public respect and trust (Jacobs 1961), and enhanced levels of natural surveillance from eyes on the streets. The argument of Jacobs for eyes on the streets and guardianship is similar to theorizing of informal social control and collective efficacy (Sampson and Graif 2009; Sampson, Raudenbush, and Earls 1997). These countervailing predictions yield two competing hypotheses:

H2a. The presence of more land use mix will bring more offenders and targets to the street segment, and result in more crime.

H2b. The presence of more land use mix will bring more active guardians to a location more consistently throughout the day, and result in less crime.

Design and crime

The third important feature is design, and street connectivity is an important physical environmental feature to consider for understanding criminal opportunities and guardianship in place. There are also competing perspectives regarding how street connectivity will impact crime. On the one hand, the Brantinghams (1993) argued that pathways through the street network are crucial elements for understanding the spatial patterns of crime because they can largely shape travel patterns and routine activities of people including potential offenders, targets, and guardians. Better connected areas through the physical configurations of the street network are easier to access and likely familiar for potential offenders. Additionally, in terms of guardianship, better connected areas along the street network tend to have more foot traffic including non-regulars coming from outside who can undermine the effectiveness of natural surveillance due to reduced territoriality. Some previous studies have indeed found that better connected areas via the street network have more crime, presumably because the increased pedestrian or vehicular traffic includes both potential offenders and targets (Ackerman and Rossmo 2015; Johnson and Bowers 2010 ; Bevis and Nutter 1977; White 1990; Beavon, Brantingham, and Brantingham 1994; Frith, Johnson, and Fry 2017; Kim and Hipp 2019). Nonetheless, it is important to highlight that these studies typically do not simultaneously take into account density or diversity, so it is not clear that such increased crime can actually be attributed to street connectivity.

A contrary perspective is that the physical layout of the street network can be a crucial feature given that it can determine movement patterns in an area. One possibility is that the street network can increase the number of pedestrians in an area, which might then increase the number of passive guardians nearby. That is, the presence of many pedestrians can reduce crime simply because an offender may view them as potential witnesses to a crime, and therefore act as guardians. For instance, Frith, Johnson, and Fry (2017) found that *local* pedestrian traffic was associated with a decrease in burglary risk. Therefore, it is possible that greater street connectivity, holding constant the level of business density, might bring more potential guardians to a street segment and therefore reduce crime.

Birks and Davies (2017) explained these two competing hypotheses as the “encounter” vs. “enclosure ” principles. In the encounter hypothesis, busier places with more passers-by will have lower risk of crime due to the enhanced guardianship capabilities from more eyes on the street. In contrast, the enclosure hypothesis suggests that increased foot traffic results in more criminal opportunities as there will be higher chance of spatial and temporal convergence of potential offenders and targets that outweigh any guardianship effect; thus more “enclosed” places will be at lower risk of crime. Birks and Davies (2017) employed an agent-based simulation to examine these alternative processes. Their results provided support for both hypotheses, and highlighted that the relationship between street network permeability and crime may be nonlinear. Indeed, Kim and Hipp (2019) found a curvilinear relationship between the connectivity of an area (betweenness centrality) and crime at place. Specifically, they found that although crime initially increases as the level of street connectivity increases, the pattern peaks and begins falling at very high levels of street connectivity. We therefore hypothesize that:

H3a. The presence of more street connectivity (design) will result in more crime.

H3b. The presence of more street connectivity (design) will result in less crime.

H3c. Street connectivity (design) will result in an inverted-U relationship with crime.

Working Together? Potential Interaction Effects between 3Ds on Crime at Place

Up to this point, we have discussed the theoretical framework of each 3D feature of the physical environment and its association with crime at place, and emphasized the importance of measuring each of these dimensions while accounting for the other two dimensions. We next extend this idea theoretically and consider how the 3Ds might collectively work together for the structure of criminal opportunities and guardianship capability. That is, how do 3D features interact with each other to produce different spatial patterns of crime? For example, whereas existing studies often focus on business density alone in assessing its relationship with crime, it may be that the impact of business density on crime is moderated by the land use mix of an environment, or by the street connectivity of an environment. It is plausible that combinations of the 3Ds can induce more foot traffic and social activities in a place, consistent with the ideas of Jane Jacobs.

Previous ecological studies tend to focus on one or a few types of built environment features at a time, and they tend to pay relatively less attention to possible moderating effects among different built environment features. For example, studies on land use, businesses, and crime at place tend to focus solely on the density aspect of the built environment (Bernasco and Block 2011; Bernasco, Ruiter, and Block 2016; Boessen and Hipp 2015, 2018; Stucky and Ottensmann 2009; Taylor et al. 1995; Wo 2019). Likewise studies on mixed land use (Wo 2019; Browning et al. 2010) or street network configurations (Johnson and Bowers 2010 ; Frith, Johnson, and Fry 2017; Kim and Hipp 2019) typically consider only the diversity or design parts of the 3Ds. Although these studies have advantages of specificity, they typically fail to simultaneously take into account multiple characteristics of the built environment to capture a more comprehensive picture of crime at place. Therefore, the current study examines the associations between each 3D feature and crime while controlling for each other as well as their potential moderating effects on crime.

H4a. The hypothesized crime-enhancing (or crime-reducing) effect of 3Ds will be reinforced if there are also higher levels of another type of 3D– a positive interaction effect.

H4b. The hypothesized crime-enhancing (or crime-reducing) effect of 3D will be dampened if there are also higher levels of another type of 3D– a negative interaction effect.

Data and Methods

Our unit of analysis is the street segment – both sides of a street between two intersections. We employed the street segment as a micro geographic unit of analysis because previous studies argued that physical environments can influence the routine activities and thus the spatial patterns of crime only insofar as the residents can perceive these environments with their senses, or so-called "naked eyes" (Sherman, Gartin, and Buerger 1989) and these environments are arguably small scale (Oberwittler and Wikstrom 2009). Our study area is the Southern California metropolitan region which is the urbanized area in the Counties of Los Angeles, Orange, San Diego, Riverside, San Bernardino, and Ventura defined by the Census. Among all street segments in the region, we included 211,155 segments in the models with crime data.

Dependent Variables

The five dependent variables of the present study are the counts of aggravated assault, robbery, burglary, motor vehicle theft and larceny. We utilized crime data from the Southern California Crime Study (SCCS). The SCCS researchers collected incident level crime data from local police departments in the region with geographic information of each incident (i.e., street address). Crime incidents in each city were separately geocoded to corresponding latitude and longitude points using ArcGIS 10.2 and subsequently aggregated to the closest street segment based on the geographic proximity. In the current study, we computed the average of each of five crime types across 2009, 2010, and 2011 as the dependent variables. The average geocoding hit rate was 97.2% across the cities, with the lowest value at 91.4%. Incidents at intersections are legitimate crime incidents in our data and we therefore included them by proportionately assigning them to the contiguous street segments (Kim 2018; Hipp and Kim 2017). Therefore, if a crime incident occurred on a typical intersection where two roads cross, each of the four segments is given 0.25 of a crime incident.

Independent Variables

Our main independent variables are the 3D measures (density, diversity, and design) of the built environment. We operationalized *density* as the number of consumer facing business employees divided by the length of street segment. We used the number of business employees instead of the number of business establishments based on an assumption that busier businesses will have more customers visiting the area (more foot traffic), and therefore have more employees to serve them. The consumer facing business types include *Retail* (Apparel, General Merchandise, Home Products, Personal Products, and Specialty), *Restaurants* (Full-Service and Limited-Service), *Food/Drug Stores* (Convenience Stores, Drug Stores, Groceries, and Specialty Food), and *Services* (Auto Services, Child Care Services, Gas Stations, Laundry, Hair Care Services, Other Personal Services, and Repair Services).[1] These business types were identified to be consumer-facing in previous studies (Kane, Hipp, and Kim 2017; Porter 2000; Delgado, Porter, and Stern 2014). They tend to draw customers to the business locations resulting in frequent face-to-face interactions among business owners, employees, and customers.[2] We obtained information on the number of business employees from the Reference USA data in 2010. The data include a wide array of information for each business at the establishment level in the study area including the types of business by 6-digit North

[1] Here is the list of 6-digit NAICS codes associated with the business types included in the consumer facing business measure: *Retail* (448110, 448120, 448130, 448140, 448150, 448190, 448210, 452111, 452112, 452910, 452990, 453310, 453210, 443141, 442110, 442210, 442291, 442299, 444210, 444220, 444130, 444110, 444120, 444190, 453991, 446120, 446199, 453910, 453998, 451211, 451212, 443142, 451140, 451110, 451120, 446130, 453220, 453110, 448310, 448320, 451130); *Restaurants* (6-digit NAICS code 722511, 722514, 722515, 722513); *Food/Drug Stores* (445120, 446110, 445110, 311811, 445210, 445220, 445230, 445291, 445292, 445299, 446191); *Services* (532111, 441310, 441320, 811111, 811112, 811113, 811118, 811121, 811122, 488410, 811191, 811192, 811198, 624410, 447110, 447190, 812320, 812310, 611511, 812111, 812112, 812113, 532220, 532299, 541940, 812191, 812199, 812910, 812990, 541921, 812921, 812922, 561622, 811212).

[2] We estimated a set of supplemental models with the measure of the number of total business employees. The results are not substantially different from the models with the measure of the number of consumer facing business employees reported in Tables 2-4.

American Industry Classification System (NAICS) code, the number of employees, street address, annual sales volume, etc. We geocoded addresses of business facilities using ArcGIS 10.2 and then aggregated to the street segments based on their geographic proximity to get information on the total number of business employees in street segments.

Next, we operationally defined *diversity* as land use mix in the area. We used Southern California Association of Governments (SCAG) Land Use Parcel data in 2008. We computed the proportions of 5 types of land parcels (residential, retail, office, industrial, and others) that are on both sides of the street segment. Then, we computed the Herfindahl index to measure the level of heterogeneity of land use in street segments, according to the proportions of five land use categories (residential, retail, office, industrial, and others), which takes the following form:

$$H = 1 - \sum_{j=1}^{J} L_j^2$$

where L refers to the proportion of the land use of type j out of *J* groups.

Finally, we employed a betweenness centrality measure to operationalize the *design* part of the physical environment. Betweenness captures the potential through movement in-and-out of the area along the street network. That is, it measures how frequently a certain street segment is likely used via the street network for travels from origins to destinations within a given search radius: ¼ mile for the current study (Kim and Hipp 2019, 2019). To compute betweenness, we first constructed a street network dataset using the 2010 Environmental Systems Research Institute (ESRI) Street Map. Then, we used the centroids of street segments on the street network as nodes for origins and destinations using the Urban Network Analysis (UNA) toolbox for ArcGIS 10.2. Street segments near the boundary of the study area would systematically have lower values of betweenness if the street network is cut off at the edge. To avoid this, the street network within 5-miles of the study area boundaries were included when computing the betweenness measure. Betweenness of a given segment *i* takes following form (Kim and Hipp 2019; Frith, Johnson, and Fry 2017):

$$Betweenness_i^r = \sum_{j \in N-\{i\}: d[i,j] \leq r} \frac{n_{jk}[i]}{n_{jk}} \quad (1)$$

where $Betweenness_i^r$ is the betweenness of segment *i* within search radius *r* (1/4 mile), n_{jk} is for the total number of shortest routes between segment *j* and *k*, while $n_{jk}[i]$ represents the number of shortest routes from segment *j* to *k* that pass through segment *i*. We were interested in capturing local pedestrian activity. Given that previous empirical evidence suggests that the average American tends to walk ¼ mile distance rather than drive (Atash 1994; Yang and Diez-Roux 2012), we used a ¼ mile radius to capture the local foot traffic by regulars (residents or people with routine activities in the area).

To capture social environmental features of the area, we included several measures of structural characteristics from the U.S. Census. Given that street segments are arguably too small to capture the potential ecological impacts of these measures that attempt to capture informal social control, we constructed these measures with an exponential decay, given evidence from a simulation study that this can capture the spatial movement of potential offenders (Hipp 2020). This decay weights nearer segments more heavily than ones further away. This entails constructing each Census measure in blocks, and then we weight each block within ½ mile by the exponential decay from the focal block (with β =-.5).[3] This strategy also helps account for spatial dependence (Anselin et al. 2000; Cohen and Tita 1999). Specifically, we constructed and included a concentrated disadvantage index – a factor score of four measures: (1) percent at or below 125% of the poverty level; (2) percent single-parent households; (3) average household income; and (4) percent with at least a bachelor's degree. The last two measures had reversed loadings. For measures available at the larger geographic units of block groups (poverty, household income, education) we used the synthetic estimation for ecological inference approach in which the imputation model is built at the block group level and then the data are imputed at the block level (Boessen and Hipp 2015).

For racial/ethnic heterogeneity, we computed and included a Herfindahl index based on five racial/ethnic groups (white, African American, Latino, Asian, and other races). We included the percent homeowners to capture residential stability. We account for the effects from racial composition by including the percent African American and the percent Latino/Hispanic in street segments. We also included the percent occupied units to measure vacancies, and population density to capture general population in the area. We account for the prime offending ages by including a measure of the percent aged between 15 and 29.

Analytic Strategy

We estimated a series of models to test the effects of the 3D measures on the spatial patterns of crime while controlling for the effects of structural characteristics of street segments. Our dependent variables are counts of crime incidents, which are not normally

[3] This β exponent of .5 indicates that a segment about 2/3 a mile away is weighted 75% as much as the focal segment, one 1.4 miles away is weighted ½ as much as the focal segment itself, and one 3 miles away is weighted 22% as much. Thus, β captures the shape of the decay.

distributed. Accordingly, we employed a negative binomial regression approach to account for the count nature of the data, and to effectively deal with over-dispersion (Osgood 2000), with city-fixed effects. Additionally, we included the length of the street segment as the exposure variable, which effectively makes the outcomes interpretable as crime density. The general form of these models is:

$$E(y) = exp(\alpha + B_1\boldsymbol{D} + B_2\boldsymbol{S} + B_3\boldsymbol{C}) \tag{2}$$

where y is crime counts, $\boldsymbol{D}$ is a matrix of the 3D measures (density, diversity, and design), $\boldsymbol{S}$ is a matrix of the structural characteristics, $\boldsymbol{C}$ has the city-fixed effects, and α is an intercept. As stated above, we theorized moderating effects between the 3D measures. To examine whether density, diversity, and design work together, we estimated a set of models including the 3D measures and interaction terms (density-diversity, density-design, and diversity-design), respectively. We also tested for nonlinearity of the 3D measures by creating polynomial versions of the measures and including them in the models following the results of Birks and Davies (2017). Table 1 presents the summary statistics for the dependent and independent variables used in the analyses.

<<< Table 1 about here >>>

Results

Figures 1-3 are maps of the study area with street segments colored according to the levels of the 3D measures. We used a quantile classification method to have each class contain an equal number of features. Red streets have higher levels of density, diversity, or design whereas blue streets indicate lower levels. As shown in Figures 1-3, there exists some variation in terms of the 3Ds of the built environment. Specifically, we observe that street segments near the Los Angeles Downtown area have higher levels of business density (Figure 1) and areas near the city centers of Los Angeles and Long Beach have higher land use mix, whereas areas further away from the centers of these cities tend to have lower land use mix. We also see that larger streets in the study area tend to have higher betweenness (Figure 3), which supports intuition that larger streets would have more potential usage based on the street network.

<<< Figures 1-3 about here >>>

To assess the spatial co-location of the 3D measures, we viewed the correlations between the business density, land use mix, and betweenness measures. We observed that there is a low level of co-location of the 3D measures. For example, the correlation value between the density and diversity measures is .14 while those of density-design and diversity-design are actually slightly negative (at -.07 and -.13, respectively). This suggests that these three 3D measures are each capturing distinct theoretical constructs.

Next, we turn to our findings from the estimated models (Table 2). We see that the 3D measures have relatively strong relationships with the spatial patterns of violent and property crimes, although they differ. First, consistent with Hypothesis 1, we found that density is positively associated with violent and property crime at place. For instance, a one standard deviation increase in business density results in 22 and 48 percent more aggravated assaults (exp (.148 × SD) – 1) and robberies (.283 × SD) – 1), respectively. The positive impact of density on property crimes also occurs, as a one standard deviation increase in business density is associated with 23, 20, and 33 percent more burglaries, motor vehicle thefts, and larcenies, respectively. On the other hand, our land use mix (diversity) measure shows weaker positive relationships with various types of crime. For example, a one standard deviation increase in land use mix is associated with 12 percent more aggravated assaults, 30 percent more robberies, and 8 percent more larcenies. These crimes are more consistent with Hypothesis 2a, but contrary to Hypothesis 2b. However, there is very little relationship between land use mix and burglaries and motor vehicle thefts.

<<< Table 2 about here >>>

The pattern for the betweenness (design) measure is quite different from the other two 3D measures, as it has a negative relationship with the property crimes. For example, consistent with Hypothesis 3b, a one standard deviation increase in betweenness of a street segment is associated with 5 to 8 percent fewer property crimes. Likewise, higher betweenness is also associated with moderately fewer aggravated assaults. The one exception is that higher betweenness enhances robberies, as a one standard deviation increase in betweenness is associated with 16 percent more robberies.

<<< Tables 3 and 4 about here >>>

Given that simulation work by Birks and Davies (2017) suggested that there may be a nonlinear relationship between betweenness and crime, and empirical work has similarly found this effect (Kim and Hipp 2020), we tested this in ancillary models. When included quadratics for the logged betweenness measure, there were no pronounced nonlinear effects (any statistically significant results were extremely modest when plotting them). However, note that the log transformation itself introduces a nonlinearity, and when plotting this logged function we see that there is actually a slowing positive relationship with robbery and a slowing negative relationship with the other crime types. Furthermore, we tested possible non-linear relationships for the other two 3D measures in a similar manner: although we did not find any pronounced nonlinear effects for the quadratic terms, note again that the logged business density measure is in fact capturing a slowing positive relationship.

Our next research question is whether the associations between the built environment and crime are moderated by each 3D measure. That is, we tested interaction effects between density-diversity, density-design, and diversity-design to test whether moderating effects exist between each 3D concept of the built environment. We report the interaction coefficients in Tables 3 and 4. In Figures 4-7, we plotted the predicted crime rates for these interactions, and we report the ones that were substantively meaningful.[4] Specifically, we visually displayed the effect of each 3D at varying levels of another 3D measure (Low = -1 SD and High = +1 SD).

First, in the interaction models between density and diversity, there was a substantively pronounced interaction for burglaries. As seen in the plot in Figure 4, in areas with higher business density, the level of land use mix has minimal impact on the number of burglaries. Instead, land use mix has the strongest impact on burglaries in areas with low business density Thus, the lowest burglary risk occurs on a street segment with low business density combined with high levels of land use mix. For example, for two street segments with low business density, the one with high land use mix has about 3% fewer burglaries than does one with average land use mix. This interaction variable also was positive for the other two property crimes, but just weaker.

<<< Figures 4-7 about here >>>

The pattern of results for the density-design interaction is different, as the impact of design is strongest on street segments with *high* density. Thus, this negative interaction was

[4] All interaction plots are available upon request

observed for all five crime types. As shown in Figure 5, at low levels of business density, the amount of betweenness on the street makes little difference for motor vehicle thefts. Instead, it is on street segments with high business density that betweenness matters, and in this case, it shows a strong protective effect. In other words, the crime-enhancing effect of density is even more pronounced in areas with lower betweenness, which suggests that areas with high business density and low betweenness are at higher risk of motor vehicle theft (and a similar pattern was found for larcenies, although we do not show it here). For example, for two street segments with high business density the one with low betweenness has about 3% more motor vehicle thefts than the one with average betweenness. So it appears there is a protective effect for motor vehicle theft in a high business density environment when the street is potentially used for more street traffic, consistent with Jacobs' eyes on the street hypothesis. This foot traffic may be particularly important for keeping an eye on parked autos.

The diversity-design interactions exhibited two different patterns for aggravated assaults and motor vehicle thefts (and were nonsignificant for the other three crime types). As presented in Figure 6, there is a crime-enhancing effect of land use mix on aggravated assaults; nonetheless, the impact of betweenness is strongest on segments with *low* land use mix. Thus, in segments with high land use mix, betweenness has very little impact. Instead, betweenness has its strongest impact for aggravated assault on segments with low land use mix. As a consequence it is areas with low levels of land use mix but high levels of betweenness that have the lowest risk of aggravated assaults. Thus, for two segments with low land use mix, the one with low betweenness has about 4% more aggravated assaults than does one with average betweenness. However, the moderating effect differs for motor vehicle thefts, as betweenness has its strongest impact in street segments with *high* land use mix (Figure 7). In sum, the interaction findings suggest that the different features of the built environment can work together to produce spatial patterns of crime.

Finally, we briefly discuss the control measures included in the models. More population surrounding street segments results in higher risk of violent and property crime. Concentrated disadvantage has a consistent positive relationship with crime, particularly violent crime. More racial/ethnic heterogeneity in the surrounding area is associated with higher risk of property crime. Areas with a greater concentration of black residents or vacant units generally have more crime, whereas the presence of more homeowners in the surrounding area is associated with less crime.

Discussion

This study incorporated insights of the theoretical framework of the 3D features of the built environment—density, diversity, and design—and assessed how they are related to crime at place. We also empirically tested possible interaction effects between these 3D features, and found evidence of moderating effects. Although previous studies have revealed that these built environment features can have important implications for understanding the risk of crime at place, studies tend to focus exclusively on one feature at a time. Therefore, a primary contribution of the current study is to attempt to capture a more comprehensive picture of the associations between various types of physical settings and crime at place. We next highlight some key findings based on this perspective of the 3D's.

First, business density based on the total number of business employees exhibited positive associations with all types of crime, which is consistent with hypothesis H1 as well as previous studies on businesses and crime at place. Our density measure is a proxy for the presence of business facilities, the size of the facilities, and the magnitude of foot traffic visiting the area based on the assumption that larger business facilities tend to have more employees, and thus more customers visiting the location. Therefore, one possible explanation for such a result is that the businesses may function as criminogenic facilities such as crime generators so that they increase the probability of the convergence of potential offenders and targets at the same time and place (Brantingham and Brantingham 1995; Brantingham and Brantingham 1993; Brantingham and Brantingham 1984). This implies that the increase in the number of targets and offenders outweighs any effect of the increase in guardians. And there was no evidence of a diminishing effect at the highest levels of business density in the models testing for nonlinearity.

Our land use mix (diversity) measure exhibited a weaker positive association with several crime types, and no relationship with others. We had posited competing hypotheses of whether this diversity would have a positive relationship with crime (hypothesis H2a), or a negative one (hypothesis H2b), as some prior studies have found (Wo 2019; Browning et al. 2010). According to Jacobs (1961), primary land uses can have effective social control effects when they are mixed together so that the area can have more diversity in social activities. In this view, diverse areas engender more pedestrian local foot traffic rather than vehicular through movement, which potentially increase the level of natural surveillance from eyes on the street. However, we also noted that it is possible that mixed land use areas can bring about more anonymity if more strangers are present in the area. In our sample, the evidence was more consistent with this latter hypothesis. One way to reconcile these two hypotheses: a) perhaps both the density and diversity measures create more criminal opportunities by bringing together potential offenders and targets at a given time and place (Brantingham and Brantingham 1995; Brantingham and Brantingham 1993; Bernasco and Block 2011); but b) the diversity measure *also* captures guardianship capability (Jacobs 1961). The mix of these two processes would explain why the positive coefficients for the diversity measure were much smaller, or almost zero for some crimes, compared to the density measure. If this is the case, then there would indeed be something about the mix of different land uses that possibly brings about heightened provision of guardianship.

On the other hand, our betweenness measure (design) consistently exhibited a negative relationship with most types of crime, consistent with hypothesis H3b. This is evidence that there is something unique about the street network configuration for understanding the spatial patterns of crime net of the effects from business activities and land use mix. Whereas some prior research has found a negative relationship for betweenness as we did (Frith, Johnson, and Fry 2017), other prior research detected a curvilinear relationship in which the negative relationship was only present at the highest levels of betweenness (Kim and Hipp 2019). Our negative relationship occurred while accounting for the other two dimensions of the built environment, highlighting the importance of considering them all simultaneously. Furthermore, it is quite interesting that although theoretical propositions and empirical measurements of the 3D features are primarily about the amount of foot traffic, they have dissimilar effects on the level of crime at place. This implies that they have different implications for the presence of guardians at locations. The key question is when will the presence of more guardians outweigh the effect of more targets and offenders, and it appeared that our measure of design best captured this scenario.

Our findings for the interaction effects between the 3D features underlined this importance of simultaneously accounting for these three measures. Whereas high business density was associated with higher levels of crime, this effect was moderated by the presence of higher betweenness. The implication is that there are important contexts that can somewhat ameliorate the otherwise crime-inducing effect of business density. The fact that the positive relationship between business density and crime was lessened in a context of high betweenness is consistent with hypothesis H4b and the new urbanist argument of an effective control benefit from eyes on the street. That is, although business activities still enhance the level of crime at place, such effects might be dampened if a sufficient level of potential foot traffic via the street network exists. In contrast, diversity appeared most related to reduced crime in environments with *low* business density. It appears that whatever benefits land use mix might have for reducing crime are undone if there is a high level of potential foot traffic in the area. Although the design and diversity measures were generally associated with reduced crime, and the density measure was associated with increased crime, the interaction effects among them were more complicated. Whereas high betweenness was consistently associated with less crime, this effect was accentuated for motor vehicle thefts in high land use mix locations, but accentuated for aggravated assaults in *low* land use mix locations. So if diversity of land use operates to increase guardianship, it appears to operate differently for an acquisitive crime such as motor vehicle theft compared to a pure violent crime such as aggravated assault. This highlights the need for further research to explore how a mixed land use area impacts the environment and potential guardianship. Nonetheless, the results of the moderating effects confirmed the importance of examining different features of the built environment simultaneously.

We acknowledge some limitations to the current study. Although our approach to measuring the 3D features was theoretically driven, there is still room for methodological refinements. First, for the density measurement, although we utilized the total number of consumer-facing employees, looking at more specific types of businesses may describe a more detailed picture of business activities in place. We hope that future research utilizes more fine-grained business types to better capture the density feature of the physical environment. Regarding diversity, a general challenge for measuring land use mix is deciding which types of land use to include in such a measure. We used broader categories here, believing they capture broad variability in the environment. But some may argue for more fine grained distinctions in the categories: i.e., splitting residential by single family units and apartments, or splitting commercial by different types of retail. Such considerations require further theoretical consideration. In terms of design, more detailed information on street layouts is necessary. Such information includes, but is not limited to, the presence/absence of off-street parking, on-street front or side parking, on-site drive-throughs, sidewalk width, pedestrian lights, etc. as these features matter for pedestrian travel patterns and the amount of foot traffic (Cervero and Kockelman 1997; Ewing and Cervero 2010; Ewing et al. 2015; Boarnet et al. 2011).

Also, the betweenness measure can be refined by considering other physical elements of the street network that have direct or indirect relevance to traveling patterns such as speed limit, elevations, traffic situation, etc. Although studies have employed a betweenness centrality measure, including the current study, they have not incorporated such street network characteristics that might provide a more nuanced measure when operationalizing the potential flow of passers-by. Future research may want to utilize such street network information when creating the betweenness measures. Another limitation is that the current study could not directly examine the specific mechanisms via the structures of criminal opportunities and guardianship capability derived from the built environment. Future research should attempt to examine the roles of the built environment by including more direct measures of mechanisms.

Another limitation is that the current study is cross-sectionally designed. A potential challenge for a cross-sectional study is the risk of temporal endogeneity that crime at a previous time point can affect the 3D features of the area. Indeed, previous studies have shown that business activities are influenced by crime in the area (Greenbaum and Tita 2004; Hipp et al. 2019). Therefore, future research may want to employ a longitudinal research design to capture the association between changes in the 3Ds of place and changes in the spatial patterns of crime. Finally, the study area of the Southern California region has unique features, and although we believe that the findings will remain similar in other contexts, future research will want to assess whether this is indeed the case.

In conclusion, we found that the 3D physical environmental features can affect the risk of crime on street segments, and confirmed the moderating effects between the 3D measures and crime at place. The results of the current study suggest that it is necessary to examine these different physical environment features simultaneously to understand the relationship between the built environment and spatial patterns of crime. Whereas higher levels of business density are associated with higher levels of crime, our design measure consistently exhibited a negative relationship with crime, and the diversity measure exhibited a smaller positive relationship than did the density measure. Furthermore, we found that the diversity and design measures moderated the business density relationship with crime, highlighting the importance of simultaneously accounting for various characteristics of the physical environment when exploring the spatial patterns of crime.

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Tables and Figures

Tables

Table 1. Summary Statistics

	Mean	S.D.	Min	Max
Crime				
Agg. Assault	0.10	0.40	0	50.67
Robbery	0.07	0.31	0	22.67
Burglary	0.19	0.59	0	61.00
M.V. theft	0.15	0.49	0	57.33
Larceny	0.32	1.58	0	185.33
3D Measures				
Business density - Density (Logged)	-6.42	1.37	-7	4.23
Land use mix - Diversity	0.34	0.31	0	1
Betweenness - Design (Logged)	1.17	3.61	-5	8.11
Structural Characteristics				
Concentrated disadvantage	-0.28	0.87	-4	3.06
Racial/ethnic heterogeneity	0.49	0.15	0	0.77
Percent home owners	61.25	23.00	0	100
Percent Black	6.29	11.18	0	100
Percent Latino	40.50	27.84	0	100
Percent occupied units	94.84	3.00	0	100
Percent age 15-29	21.67	5.99	0	100
Land Use				
Proportion of industrial land use	0.03	0.11	0	1
Proportion of office land use	0.03	0.10	0	1
Proportion of residential land use	0.73	0.29	0	1
Proportion of retail land use	0.05	0.13	0	1

S.D. = Standard Deviation

Table 2. Negative Binomial Models of 3D Measures and Various Types of Crime

	Agg. Assault		Robbery		Burglary		M.V. theft		Larceny	
3D Measures										
Business density - logged (Density)	0.148	**	0.283	**	0.149	**	0.133	**	0.206	**
	39.619		72.801		52.317		42.985		89.709	
Land use mix (Diversity)	0.372	**	0.845	**	-0.034	†	0.058	**	0.254	**
	14.435		26.228		-1.821		2.754		15.805	
Betweenness - logged (Design)	-0.007	**	0.042	**	-0.022	**	-0.013	**	-0.018	**
	-3.473		15.472		-14.880		-8.062		-13.493	
Structural Characteristics (1/2-mile Exponential decay)										
Population (logged)	0.628	**	0.823	**	0.369	**	0.366	**	0.309	**
	29.126		33.407		27.943		24.584		28.577	
Concentrated disadvantage	0.508	**	0.433	**	0.184	**	0.192	**	0.142	**
	13.789		10.895		9.145		7.659		8.184	
Racial/ethnic heterogeneity	0.053		-0.128		0.209	**	0.209	**	0.282	**
	0.655		-1.497		4.248		3.672		6.418	
Percent home owners	-0.003	**	-0.001		-0.001	**	-0.008	**	-0.010	**
	-3.775		-1.332		-2.636		-14.441		-23.387	
Percent Black	0.021	**	0.021	**	0.009	**	0.008	**	-0.001	
	23.894		21.913		16.917		11.918		-1.521	
Percent Latino	0.011	**	0.005	**	-0.002	**	0.009	**	-0.005	**
	10.534		4.456		-3.611		12.432		-10.602	
Percent occupied units	-0.044	**	-0.033	**	-0.020	**	-0.018	**	-0.022	**
	-14.176		-8.698		-9.689		-6.771		-11.560	
Percent aged 15-29	-0.005	*	0.003		0.003	**	0.005	**	0.000	
	-2.537		1.566		3.363		3.935		0.116	
Intercept	-8.260	**	-11.136	**	-6.256	**	-8.889	**	-4.953	**
	-24.754		-26.617		-30.926		-32.277		-27.032	
N	211,155		211,155		211,155		211,155		211,155	

*** p < .01(two-tail test), * p < .05 (two-tail test), † p < .05 (one-tail test)*

T-values below coefficient estimates.

City fixed effects are included but not reported in the tables

Table 3. Interaction Models for Violent Crime

	Agg. Assault						Robbery					
	Density x Diversity		Density x Design		Diversity x Design		Density x Diversity		Density x Design		Diversity x Design	
Business density (Density)	0.146	**	0.149	**	0.147	**	0.308	**	0.286	**	0.283	**
	32.048		39.848		39.579		65.922		73.229		72.796	
Land use mix (Diversity)	0.368	**	0.369	**	0.382	**	0.971	**	0.850	**	0.845	**
	13.881		14.346		14.673		27.667		26.385		26.230	
Betweenness (Design)	-0.007	**	-0.011	**	-0.009	**	0.042	**	0.058	**	0.043	**
	-3.484		-4.654		-4.019		15.636		17.050		14.063	
Interaction terms	0.009		0.004	**	0.016	*	-0.126	**	-0.009	**	-0.006	
	0.613		3.664		2.562		-8.828		-8.318		-0.649	
Intercept	-9.081	**	-9.189	**	-9.054	**	-12.683	**	-12.936	**	-12.630	**
	-27.275		-27.450		-27.173		-30.535		-31.035		-30.223	
N	211,155		211,155		211,155		211,155		211,155		211,155	

*** p < .01(two-tail test), * p < .05 (two-tail test), † p < .05 (one-tail test)*

T-values below coefficient estimates.

City fixed effects and other controls for structural characteristics were included but not reported in the tables

Table 4. Interaction Models for Property Crime

	Burglary			M.V. theft		
	Density x Diversity	Density x Design	Diversity x Design	Density x Diversity	Density x Design	Diversity x Design
Business density (Density)	0.136 **	0.141 **	0.150 **	0.129 **	0.125 **	0.133 **
	38.795	47.168	52.307	34.603	39.203	43.018
Land use mix (Diversity)	-0.058 **	-0.027	-0.037 †	0.050 *	0.066 **	0.047 *
	-3.001	-1.425	-1.872	2.313	3.099	2.203
Betweenness (Design)	-0.022 **	-0.017 **	-0.022 **	-0.014 **	-0.005 **	-0.013 **
	-14.997	-10.586	-14.747	-8.095	-2.811	-7.462
Interaction terms	0.075 **	-0.008 **	-0.002	0.021 †	-0.010 **	-0.014 **
	7.045	-11.195	-0.441	1.777	-12.575	-2.682
Intercept	-7.228 **	-7.301 **	-6.299 **	-9.722 **	-9.791 **	-8.921 **
	-35.867	-36.196	-31.224	-35.382	-35.738	-32.459
N	211155	211155	211155	211155	211155	211155

*** p < .01(two-tail test), * p < .05 (two-tail test), † p < .05 (one-tail test)*

T-values below coefficient estimates.

City fixed effects and other controls for structural characteristics were included but not reported in the tables

Figures

Figure 1. Density (Business Density) in the Study Area

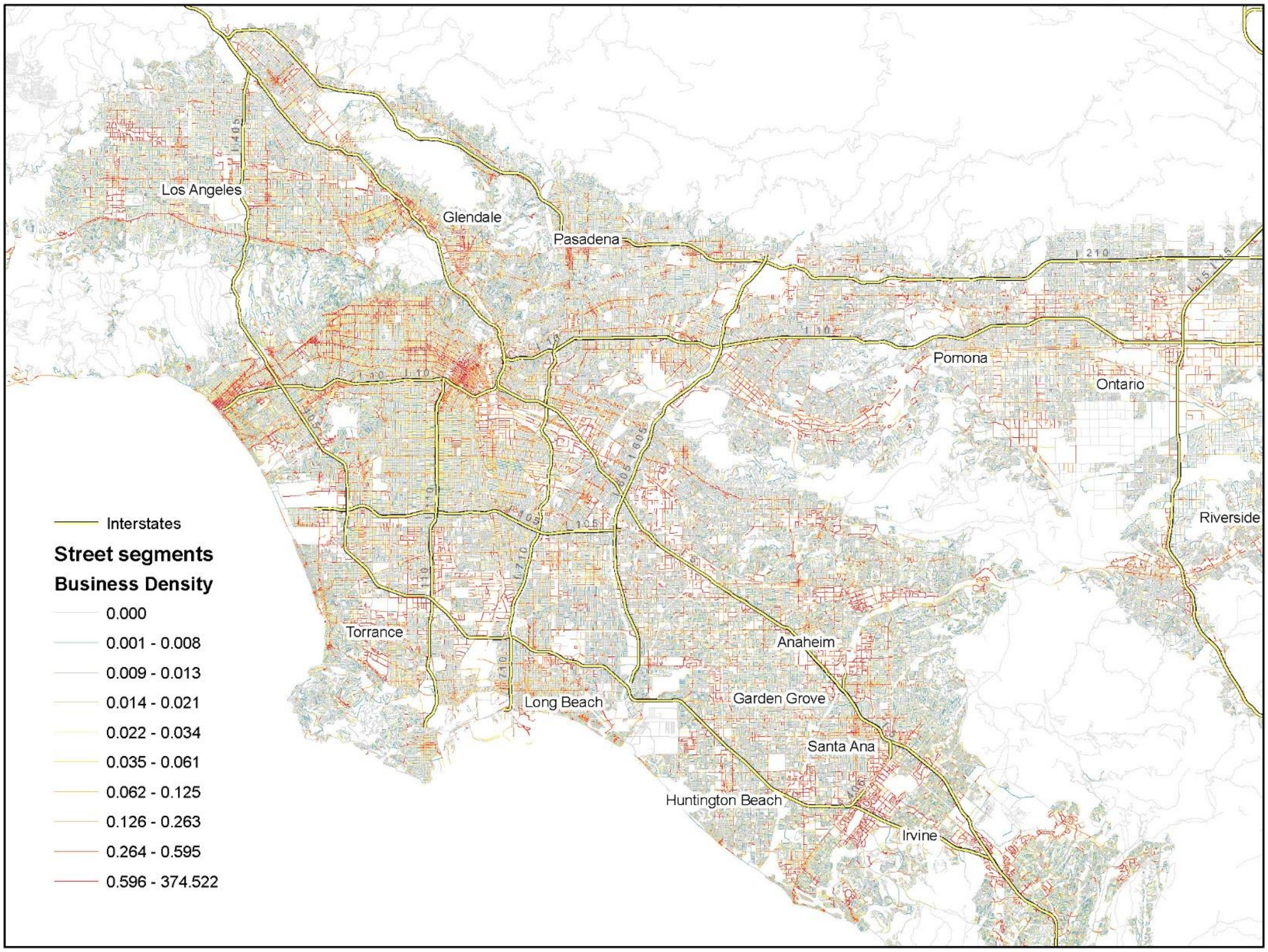

Figure 2. Diversity (Land Use Mix) in the Study Area

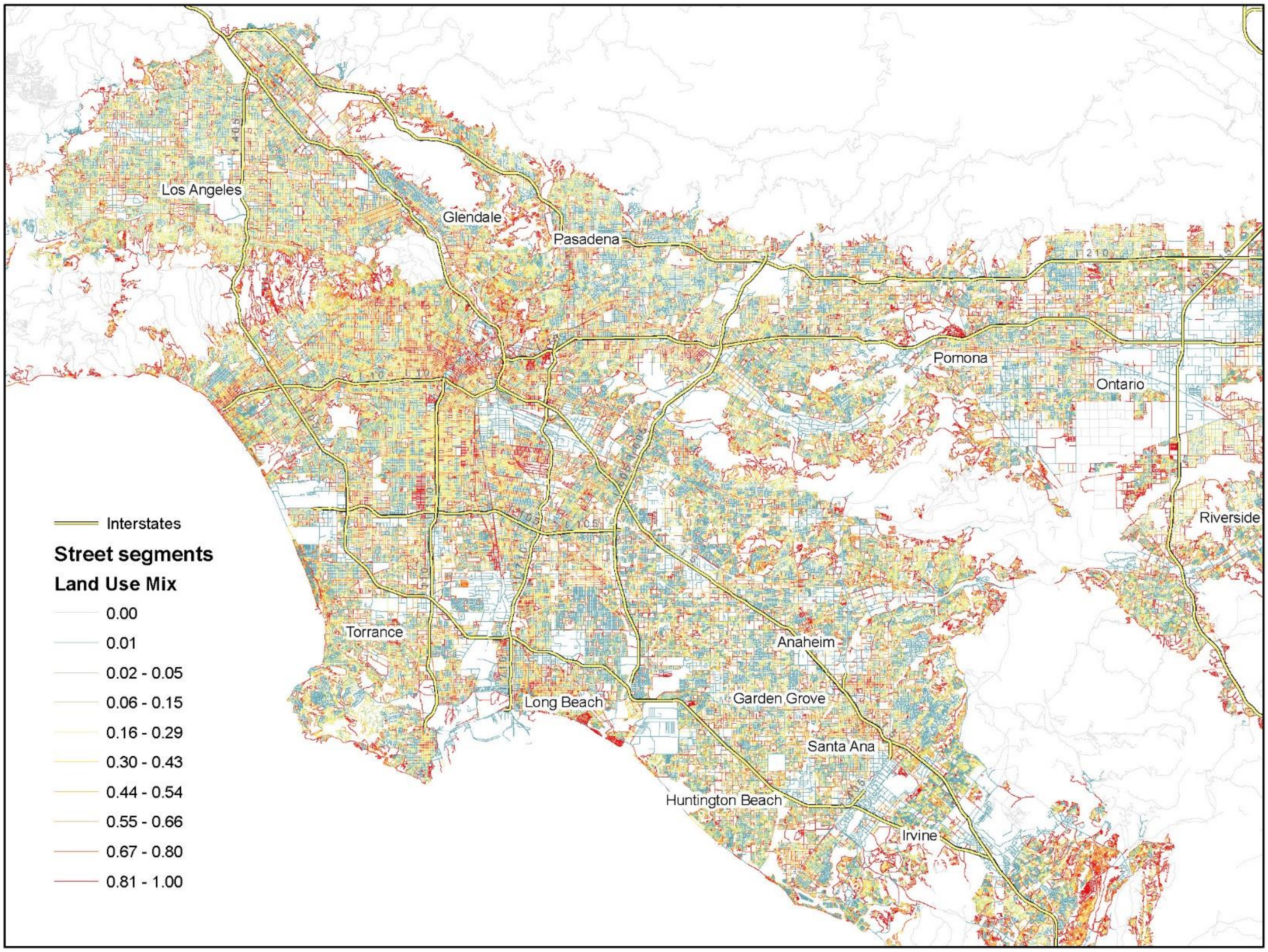

Figure 3. Design – Street Connectivity (Betweenness) in the Study Area

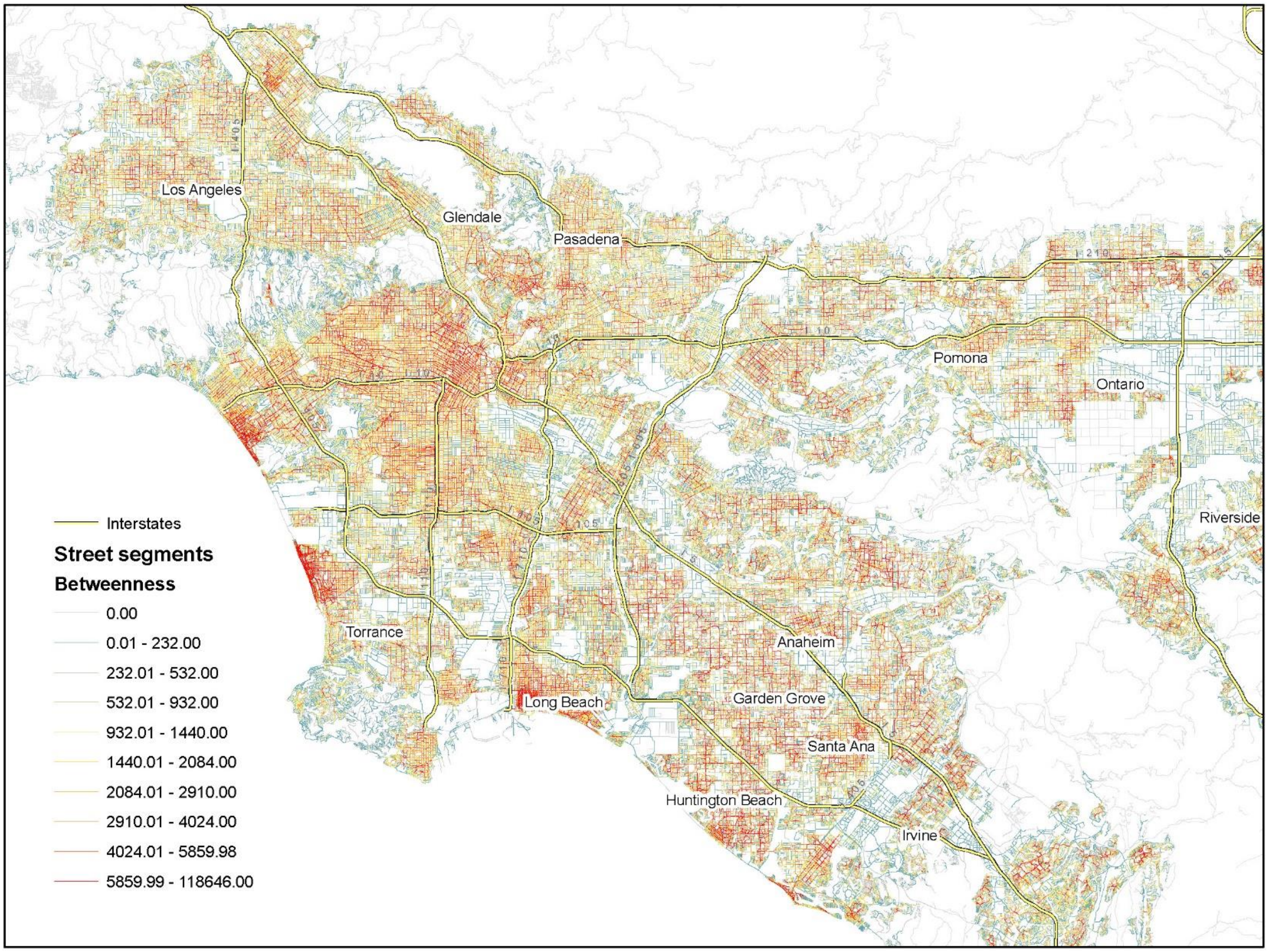

Figure 4. Interaction: Density and Diversity (Burglary)

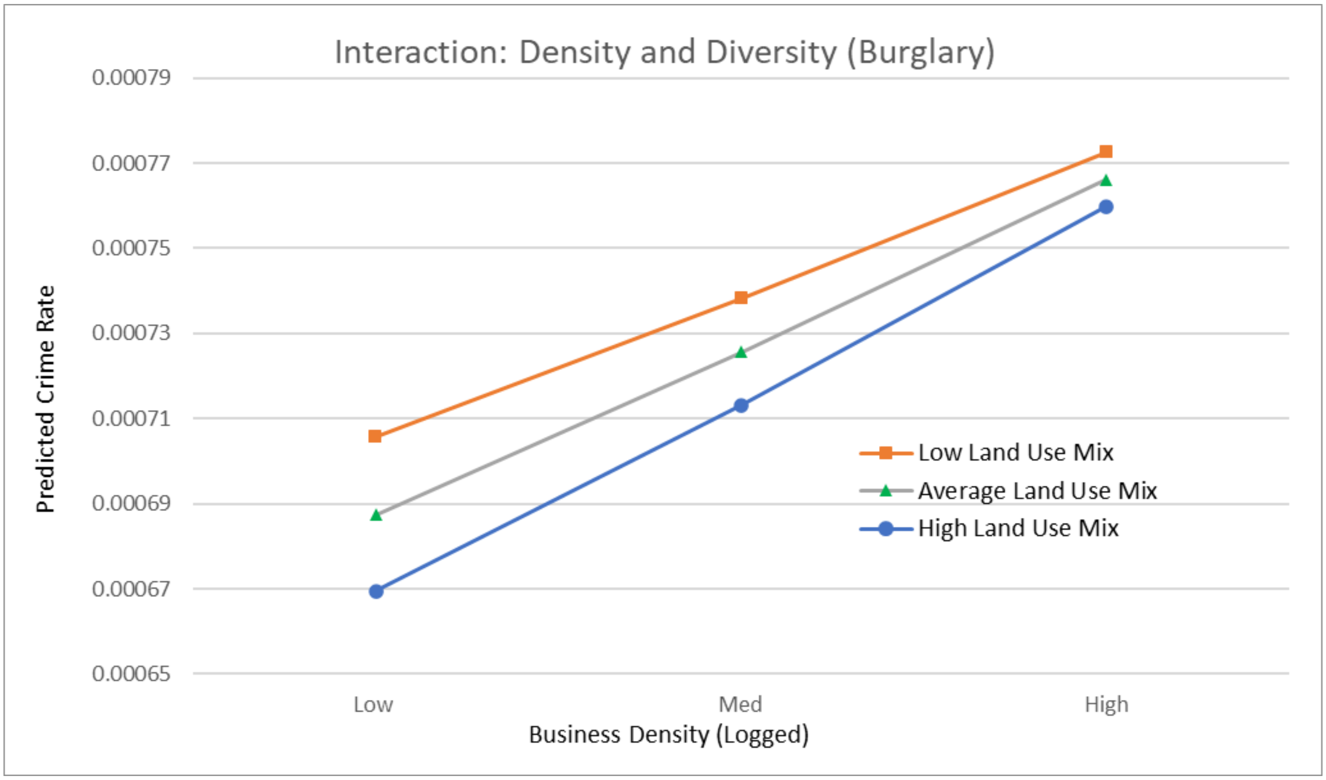

Figure 5. Interaction: Density and Design (Motor Vehicle Theft)

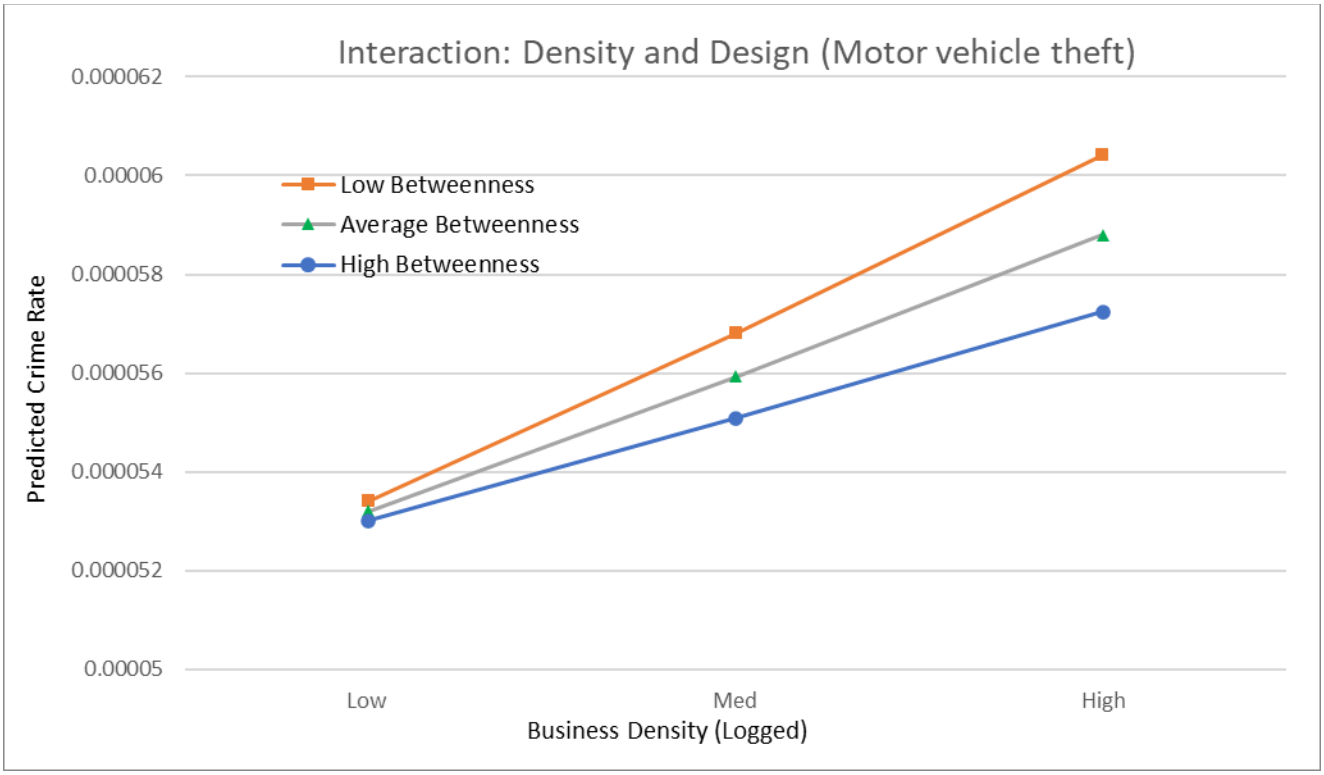

Figure 6. Interaction: Diversity and Design (Aggravated Assault)

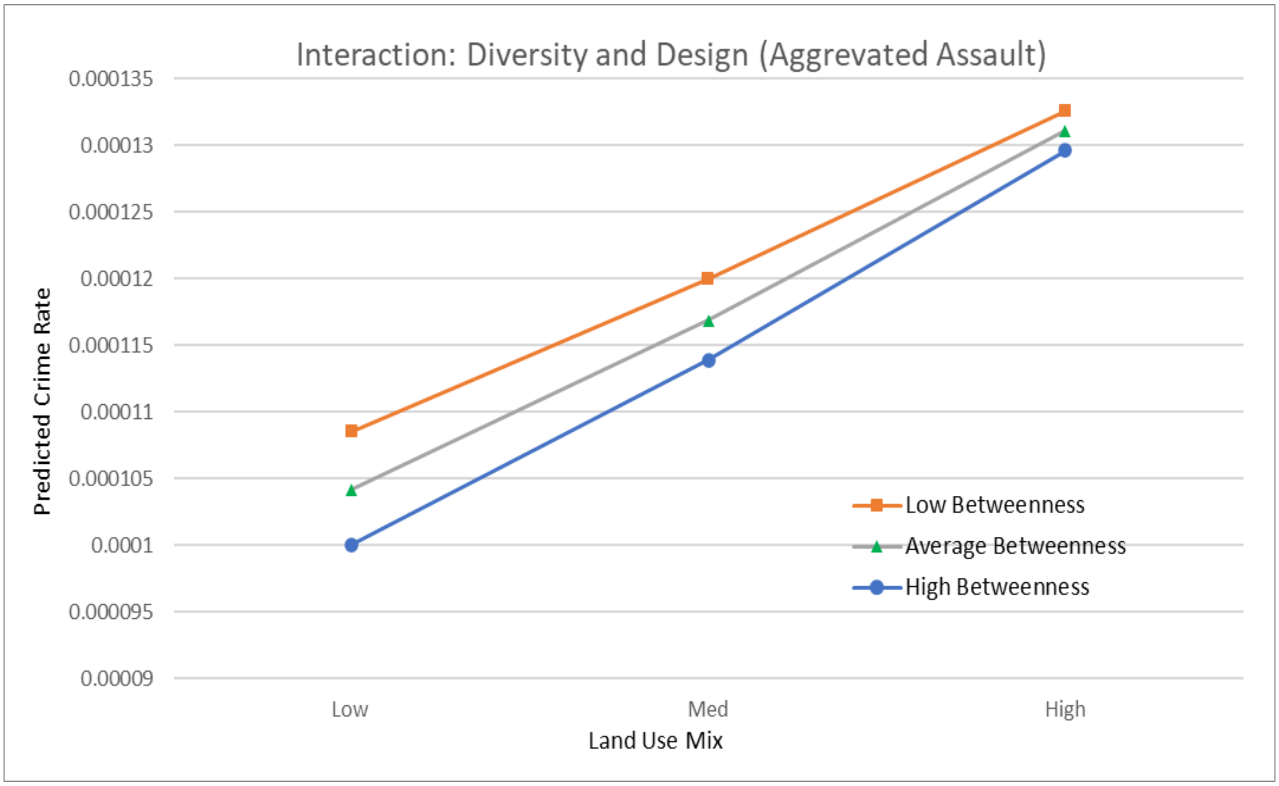

Figure 7. Interaction: Diversity and Design (Motor vehicle theft)