Operationalizing Land Use Diversity at Varying Geographic Scales and Its Connection to Mode Choice

Evidence from Portland, Oregon

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Although substantial consideration has been given to analyzing the relationship between land use diversity and travel behavior, the selection of the most suitable geographic scale for operationalizing these measures has received considerably less attention in the research. General consensus favors an examination of the complex relationship between travel behavior and such built environment measures explained at a finer spatial scale. The reasons for supporting a more disaggregate neighborhood scale include statistical advantages, such as a minimization of the modifiable areal unit problem, and more applied intentions, such as a preference for site-specific design measures seen as responsive to urban policy. Complementing this decision about how best to define the geographic extent of the built environment is the determination of which built environment measures are significantly related to travel mode choice. Of these measures, an increased diversity of land uses has often been linked with an individual's heightened likelihood for using transit, bicycling, and walking. This research advances the knowledge of which land use diversity measures best predict mode choice and explores the proper geographic scale for operationalizing these indicators. Seven diversity indexes represented at four geographic scales encompassing the origins and destinations of discretionary trips in the Portland, Oregon, metropolitan region were examined with a series of multinomial logit models. This study, which introduced several indexes previously unrecognized in transportation research, suggests common diversity measures, and the most disaggregate spatial scale may not always best represent the link between land use diversity and nonautomotive travel.

A central refrain supporting an increase in nonautomotive travel mode choice is that the built environment may be manipulated by decision makers as a policy lever for generating travel outcomes in line with planning goals (*1*). Although research supporting the transportation–land use link is salient in mode choice literature, many studies lack the quality in a built environment measure to effectively operationalize land use diversity. The ability to properly describe land use diversity at the neighborhood scale has long been sought by land use planners who favor a heterogeneous built environment representation and who believe a greater mix of land uses promotes nonmotorized travel (*2*). Synergy results when complementary land uses are in close proximity; reduced distances between trip origins and destinations enables substitution of nonmotorized modes for motorized modes (*3*).

Inseparable from land use diversity measures explaining travel mode choice is the geographic scale chosen to operationalize the extent of mixing. Despite the idea that scale is pervasive in studies of time and space (*4*), few studies exploring the influence of land use diversity on travel behavior have examined the result of varying geographic scales (*5*). This literature gap is unexpected, given the acceptance within transportation–land use research that land use diversity and other local accessibility pattern characterizations depend on the neighborhood boundary definition (*6*). An improved understanding of nonmotorized travel likely has been hampered by this inability to provide refined reflections of land use diversity, which are often constrained in their development by availability or crudeness of appropriate built environment data sources (*7*). This consideration of geographic scale coupled with more disaggregate land use representations will improve the understanding of how increased mixing of land use relates to travel behavior (*8*).

To explore the impact of measuring land use diversity at varying geographic scales on mode choice, this research (*a*) tests whether an increased diversity of land uses affects nonautomotive travel differently than alternative modes, (*b*) examines measures that best capture the relationship between diversity and mode choice at both the household and the activity location, and (*c*) provides insight into what scales may best operationalize land use diversity.

The next section reviews the literature on the link between nonautomotive travel mode choice and land use diversity, offers a catalog of diversity measures related to spatial pattern, and synthesizes operationalization issues about geographic scale. A description of the methodological approach, which includes an overview of these diversity indexes and the specification of a multinomial logit model base model, follows the background section. Model estimation results and a discussion of prospective directions for future research conclude the paper.

BACKGROUND

In their updated review of the transportation–land use literature, Ewing and Cervero stated that the potential for influencing travel demand by altering the built environment was the most researched topic in urban planning (*9*). When discretizing built environment measures based on the expanding taxonomy originally proposed

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by Cervero and Kockelman (*10*), other researchers illustrated that measures of diversity matter more than density (*9, 11*). Furthermore, research has recognized that an increase in land use diversity has a stronger influence on nonmotorized mode choice than other travel options for discretionary (*12*) as well as mandatory (*13*) trip purposes.

Frank et al. (*14*) and Buehler (*15*) found an increase in land use diversity to be related to an increase in the likelihood an individual will undertake a home- or work-based trip by walking, bicycling, or transit; the reverse trend held for automotive travel. Forsyth et al. (*16*) and Rajamani et al. (*17*) confirmed these findings and noted that land use diversity was a significant factor in the decision to walk. Similarly, Heinen et al. (*18*) and Nielsen et al. (*19*) found that an increase in utilitarian bicycling was significantly influenced by an increase in land use diversity. Pinjari et al. noted that a heightened degree of land use diversity contributed to increased transit use (*20*); however, Rajamani et al. found no significant association between land use diversity and the propensity to select transit as a discretionary travel mode (*17*). Although the latter result is a reasonable finding, the decision to represent the neighborhood unit as a census block group highlights a suggestion by Hong et al. that land use policies function at different geographic scales and, accordingly, these relationships may be appropriately described only by certain spatial extents (*21*). Related to this assumption is the literature centered on the modifiable areal unit problem and the potential for this phenomenon to produce inconsistent findings in observations of the link between travel and the built environment at varying spatial aggregations (*22, 23*).

This complication of scale selection has rested on judgments of how to operationalize land use diversity, which has varied in scale representation and categorization in the literature as an accessibility, intensity, or pattern measure (*24*). Measures of land use patterns found in transportation studies often borrow from environmental research that explains biodiversity patterns in ecological systems. Peet provided a convenient taxonomy for classifying various diversity measures into a set of categories (*25*). The first category refers to the richness of a given species within an identified area and may be transferred to research on the built environment as the number of parcels or establishments of a unique land use type within a neighborhood. In their characterization of land use diversity, van Eck and Koomen applied the richness measure of dominance, which has the drawback of accounting for only one land use type (*26*).

A second class of pattern measures considers this richness in different land uses while accounting for the contribution of each land use toward balance within a defined geographic boundary. The Shannon (*27*) and Simpson (*28*) indexes are two such evenness measures commonly applied in ecological and transportation–land use research. An initial application of the Shannon index, referred to as an entropy index, was introduced by Frank and Pivo as a representation of evenness in the building size of seven land use types within a U.S. census tract (*29*). Kockelman similarly examined land use at this aggregate scale but varied the number of distinct land uses depending on whether the travel was discretionary or mandatory (*30*). Duncan et al. also employed the entropy-based index using administrative geographies but with corrections in geographic scale to account for variations in area (*8*). The Simpson index, also referred to as the Herfindahl index in economics, has been widely adopted as a pattern measure of evenness in land use research. Clifton et al. calculated the balance of residential and nonresidential land uses within one-quarter-mile areal buffers of a crash site to investigate the association between diversity and pedestrian–vehicle crashes (*31*); Voorhees et al. operationalized Simpson's index at a one-half-mile network buffer to examine the connection between neighborhood design and nonmotorized travel (*32*). Aside from these two common indexes, Bhat and Gossen presented a measure to capture the evenness among three land uses within traffic analysis zones to study the influence of land use diversity on discretionary travel (*12*).

Also within this latter class of nonparametric measures are several promising biological diversity measures (*33*), which to the authors' knowledge have yet to be applied to transportation research. These nonparametric diversity measures are independent of the richness component and may represent balance as a simple index accounting for one of the above measures and the range of calculated values for that particular measure (*25*) or as an arrangement of the Shannon index and the Simpson index known as Hill's ratio (*34*). More recently, the Smith–Wilson evenness index (*35*) has received attention in ecological research as the most satisfactory evenness measure (*33*). The following section provides the formulation of the Smith–Wilson evenness index and six other pattern measures to be operationalized at four geographic scales.

METHOD

Data Sources

Person-level travel data provided by the 2010 Oregon household activity survey were used to examine the relationship between land use diversity and mode choice for the Portland, Oregon, metropolitan region. In total, 4,183 home-based social and recreational trips with destinations in Multnomah, Clackamas, and Washington Counties were analyzed. In addition to providing travel-related attributes, the survey identified sociodemographic characteristics of the decision maker. Supplemental data describing the built environment surrounding the individual's residence and activity destination were provided by the 2010 U.S. census and Portland Metro's 2010 Regional Land Information System (RLIS). The parcel-level RLIS data were aggregated into three land use typologies and explored with seven diversity indexes. These land use categories and diversity indexes were measured at both the origin and the destination of the observed home-based trip and operationalized at four geographic scales.

Land Use Categories

The RLIS data set classified each land parcel within the tricounty region by one of eight land use types: agricultural, commercial, forest, industrial, multifamily residential, public, rural, and single-family residential. Those land uses without classification or that were vacant were removed so as not to introduce bias toward underdeveloped neighborhoods or areas with abundant transportation infrastructure. These land uses were then aggregated into three typologies combining land uses with similar roles:

- Four land use categories:
  – Type 1. Agricultural, multifamily residential, and single-family residential land uses;
  – Type 2. Commercial and industrial land uses;
  – Type 3. Forest and rural land uses; and
  – Type 4. Public land uses;
- Three land use categories:
  – Type 1. Agricultural, multifamily residential, and single-family residential land uses;
  – Type 2. Commercial and industrial land uses; and
  – Type 3. Forest, public, and rural land uses; and

- Two land use categories:
  – Type 1. Agricultural, multifamily residential, and single-family residential land uses and
  – Type 2. Commercial, forest, industrial, public, and rural land uses.

Land Use Diversity Measures

Seven diversity measures were calculated after similar land use types were aggregated into three typologies. The first land use diversity measure was the land use mix diversity measure proposed by Bhat and Gossen (*12*). Equation 1 is the formulation of this index (E_{Bhat}), where T_i reflects the total acres of land use type i in a given neighborhood and T_N represents the total acreage for all land uses in a category (N). The land use mix diversity measure, like all the subsequent measures, ranged in value from zero to one, where a zero value reflected the dominance of a single land use type and a value of one represented an equal balance among all land uses in the typology.

$$E_{\text{Bhat}} = 1 - \left[\frac{\sum_{i=1}^{N} \left| \left(\frac{T_i}{T_N} \right) - \left(\frac{1}{N} \right) \right|}{\frac{(2N-2)}{N}} \right] \tag{1}$$

Equation 2 represents a formulation of the Shannon evenness measure (E_{Shannon}) widely applied under the entropy-based index pseudonym. In this distinction, the Shannon index was divided by the natural log of the total number of land use types (*27*). The denominator normalizes the entropy measure, enabling the same zero-to-one range as the prior diversity index (*30*). The variable p_i represents the proportion of developed land for the ith land use type in the geographic scale.

$$E_{\text{Shannon}} = \frac{-\sum_{i=1}^{N} p_i (\ln p_i)}{\ln N} \tag{2}$$

The third land use diversity measure is a form of the Simpson index (*28*) referred to as Simpson's measure of evenness (*35*). This adaptation is denoted in Equation 3:

$$E_{\text{Simpson}} = \frac{\frac{1}{\sum_{i=1}^{N} p_i^2}}{N} \tag{3}$$

In addition to these three diversity measures commonly found in transportation–land use research, four pattern indexes described in the biological diversity literature are introduced here for finding the best measure for capturing the relationship between land use diversity and mode choice. One such measure, Heip's index of evenness (*36*), is formulated in Equation 4. In this equation, the numerator is defined by the constant e raised to Shannon's index without normalization and subtracted by one:

$$E_{\text{Heip}} = \frac{e^{-\sum_{i=1}^{N} p_i (\ln p_i)} - 1}{N - 1} \tag{4}$$

Hill's ratio represents a second biological diversity measure adopted in this exploration into the land use diversity and mode choice connection (*34*). Similar to the first three diversity indexes, there are variations to Hill's ratio, which in total are referred to as Hill numbers and embody the conversion of raw indexes into true diversity measures (*37*). In Equation 5, Hill's ratio has the inverse of Simpson's index representing the numerator and e raised to the Shannon's index as the denominator:

$$E_{\text{Hill}} = \frac{\frac{1}{\sum_{i=1}^{N} p_i^2}}{e^{-\sum_{i=1}^{N} p_i (\ln p_i)}} \tag{5}$$

A potential shortcoming of Hill's ratio is the difficulty in interpretation of values closer to zero. In previous indexes, a value at the lower bound simply refers to the existence of one aggregated land use within the selected geographic unit; however, a lower Hill's ratio may also reflect the dominance being spread across the more common land use types within the geographic scale.

A transformation of McIntosh's measure of diversity (*38*) from a richness measure of dominance to an evenness measure, as proposed by Pielou (*39*), represents the sixth land use diversity index. Equation 6 details the formulation of this measure:

$$E_{\text{McIntosh}} = \frac{T_N - \sqrt{\sum_{i=1}^{N} T_i^2}}{T_N - \left(\frac{T_N}{\sqrt{N}} \right)} \tag{6}$$

The final land use diversity measure, the Smith–Wilson evenness index (*35*), represents the newest biological diversity measure in this spectrum. In evaluating the performance of an assortment of evenness measures, including most of those described above, Smith and Wilson found their own index as the only diversity measure to sufficiently address all the essential requirements and desirable criteria for a comprehensive evenness measure (*35*). Equation 7 provides a formulation for this index:

$$E_{\text{Smith+Wilson}} = 1 - \frac{2}{\pi} \left[\tan^{-1} \left(\sum_{i=1}^{N} \frac{\left(\ln T_i - \sum_{j=1}^{N} \frac{\ln T_j}{N} \right)^2}{N} \right) \right] \tag{7}$$

Geographic Scales

In this exploration of the influence of land use diversity on travel mode choice, each diversity measure was operationalized at two fixed neighborhood representations according to census geographies and two sliding scale neighborhood representations based on network buffers (*40*). U.S. census tracts and block groups exemplified the fixed neighborhoods; the two sliding representations conveyed the abstract neighborhood concept as 1- and 2-mi buffers extending along the adjacent street network of the trip maker's household or activity location. Area of the fixed neighborhood representations across the tricounty region averaged 5,461 acres per census tract and 1,862 acres per block group. The average area for the sliding scale neighborhoods around the trip origins was 3,352 acres for the 2-mi network buffer and 815 acres for the 1-mi network buffer; the average area for the sliding scale neighborhoods around the trip destinations were larger with the 2-mi network buffers averaging 3,699 acres in area and the 1-mi network buffers averaging 941 acres. Table 1 describes the median and mean as well as the standard error calculated at the origin of each home-based trip for each land use diversity measure and neighborhood representation for the three land use categories. Similarly, Table 2 offers descriptive statistics for the cross tabulation of diversity and geographic unit measured at the discretionary trip's destination.

Base Model Specification and Estimation

The seven land use diversity measures, operationalized at four geographic scales, were individually and iteratively added to the base multinomial logit (MNL) model comprising attributes of the decision maker, housing structure, and trip context. Borrowing from classic discrete choice modeling literature (*41*), the functional form noted in Equation 8 was used to model the probability of a resident of the Portland metropolitan region choosing one of five travel modes in his or her choice set:

$$P_n(i) = \frac{e^{V_{in}}}{\sum_{j \in C_n} e^{V_{jn}}} \quad (8)$$

where

$P_n(i)$ = probability of individual n choosing the ith alternative within his or her feasible choice set,
C_n = modal choice set available to individual n,
V_{in} = utility of individual n traveling by mode i, and
V_{jn} = utility function for individual n traveling by mode j.

TABLE 1 Descriptive Statistics of Land Use Diversity Measures Operationalized at Origin

Land Use Diversity Measure, by Geographic Unit	Four Land Use Categories			Three Land Use Categories			Two Land Use Categories		
	Median	Mean	SD	Median	Mean	SD	Median	Mean	SD
U.S. Census Tract									
Bhat	0.31	0.30	0.14	0.35	0.37	0.19	0.63	0.67	0.18
Heip	0.31	0.31	0.14	0.45	0.45	0.21	0.70	0.69	0.24
Hill	0.87	0.87	0.05	0.87	0.87	0.05	0.91	0.92	0.04
McIntosh	0.42	0.43	0.19	0.49	0.50	0.22	0.66	0.65	0.26
Shannon	0.47	0.46	0.16	0.59	0.57	0.20	0.77	0.74	0.22
Simpson	0.40	0.42	0.11	0.53	0.56	0.14	0.77	0.79	0.14
Smith and Wilson	0.13	0.14	0.07	0.33	0.37	0.23	0.18	0.18	0.05
U.S. Census Block Group									
Bhat	0.26	0.25	0.15	0.29	0.31	0.20	0.58	0.61	0.19
Heip	0.24	0.25	0.15	0.35	0.36	0.22	0.62	0.59	0.30
Hill	0.89	0.89	0.05	0.89	0.90	0.05	0.91	0.92	0.04
McIntosh	0.35	0.35	0.21	0.41	0.42	0.25	0.57	0.56	0.31
Shannon	0.39	0.38	0.19	0.49	0.47	0.24	0.70	0.64	0.29
Simpson	0.37	0.39	0.11	0.49	0.52	0.14	0.72	0.74	0.16
Smith and Wilson	0.17	0.18	0.08	0.22	0.30	0.21	0.23	0.24	0.10
2-mi Network Buffer									
Bhat	0.36	0.35	0.10	0.42	0.42	0.14	0.70	0.71	0.13
Heip	0.36	0.37	0.11	0.53	0.54	0.16	0.80	0.78	0.16
Hill	0.84	0.85	0.05	0.84	0.86	0.04	0.92	0.93	0.04
McIntosh	0.49	0.49	0.14	0.58	0.57	0.16	0.77	0.75	0.18
Shannon	0.53	0.53	0.11	0.66	0.66	0.14	0.85	0.83	0.13
Simpson	0.44	0.45	0.08	0.58	0.59	0.11	0.83	0.83	0.11
Smith and Wilson	0.08	0.14	0.12	0.45	0.48	0.19	0.11	0.11	0.02
1-mi Network Buffer									
Bhat	0.30	0.30	0.12	0.34	0.36	0.16	0.63	0.66	0.15
Heip	0.30	0.31	0.13	0.44	0.45	0.18	0.71	0.69	0.22
Hill	0.84	0.85	0.05	0.85	0.86	0.05	0.91	0.92	0.04
McIntosh	0.41	0.42	0.17	0.48	0.49	0.20	0.66	0.65	0.24
Shannon	0.46	0.46	0.15	0.58	0.57	0.18	0.77	0.74	0.20
Simpson	0.39	0.41	0.09	0.53	0.55	0.12	0.77	0.78	0.13
Smith and Wilson	0.12	0.14	0.07	0.36	0.39	0.21	0.16	0.17	0.03

NOTE: SD = standard deviation.

TABLE 2 Descriptive Statistics of Land Use Diversity Measures Operationalized at Destination

Land Use Diversity Measure, by Geographic Unit	Four Land Use Categories			Three Land Use Categories			Two Land Use Categories		
	Median	Mean	SD	Median	Mean	SD	Median	Mean	SD
U.S. Census Tract									
Bhat	0.33	0.33	0.13	0.42	0.41	0.18	0.67	0.69	0.18
Heip	0.33	0.34	0.14	0.49	0.50	0.20	0.76	0.73	0.23
Hill	0.87	0.87	0.06	0.87	0.88	0.05	0.92	0.93	0.04
McIntosh	0.48	0.47	0.18	0.57	0.55	0.21	0.72	0.69	0.25
Shannon	0.50	0.49	0.15	0.62	0.61	0.18	0.81	0.78	0.21
Simpson	0.44	0.44	0.10	0.58	0.59	0.14	0.80	0.81	0.14
Smith and Wilson	0.13	0.15	0.08	0.36	0.41	0.23	0.18	0.19	0.06
U.S. Census Block Group									
Bhat	0.33	0.31	0.15	0.40	0.39	0.20	0.66	0.67	0.18
Heip	0.31	0.31	0.15	0.46	0.46	0.23	0.75	0.69	0.27
Hill	0.89	0.89	0.05	0.89	0.90	0.05	0.92	0.93	0.04
McIntosh	0.47	0.44	0.20	0.55	0.52	0.24	0.71	0.65	0.29
Shannon	0.47	0.45	0.18	0.59	0.57	0.22	0.80	0.73	0.25
Simpson	0.42	0.43	0.11	0.57	0.57	0.15	0.79	0.79	0.15
Smith and Wilson	0.18	0.20	0.10	0.27	0.38	0.24	0.26	0.27	0.11
2-mi Network Buffer									
Bhat	0.39	0.39	0.10	0.48	0.48	0.14	0.76	0.76	0.13
Heip	0.40	0.41	0.12	0.59	0.59	0.16	0.87	0.83	0.16
Hill	0.86	0.86	0.05	0.87	0.87	0.05	0.95	0.95	0.04
McIntosh	0.54	0.54	0.14	0.64	0.63	0.16	0.84	0.81	0.17
Shannon	0.57	0.57	0.11	0.71	0.70	0.14	0.90	0.87	0.14
Simpson	0.47	0.48	0.09	0.63	0.64	0.12	0.88	0.87	0.10
Smith and Wilson	0.08	0.14	0.12	0.51	0.52	0.20	0.11	0.11	0.01
1-mi Network Buffer									
Bhat	0.36	0.36	0.12	0.47	0.45	0.17	0.73	0.72	0.15
Heip	0.36	0.37	0.13	0.54	0.55	0.19	0.83	0.78	0.20
Hill	0.86	0.87	0.05	0.87	0.88	0.05	0.94	0.94	0.04
McIntosh	0.52	0.50	0.17	0.62	0.59	0.20	0.80	0.75	0.22
Shannon	0.53	0.53	0.14	0.67	0.66	0.17	0.87	0.82	0.18
Simpson	0.46	0.46	0.10	0.61	0.61	0.13	0.86	0.84	0.13
Smith and Wilson	0.12	0.13	0.08	0.42	0.46	0.23	0.16	0.17	0.02

The feasible choice set of travel modes available to an individual was determined with the following logic. For single-occupant vehicles, the individual had to possess a driver's license and have access to a household vehicle; however, high-occupancy-vehicle selection was not restricted to either of these constraints because it may be may assumed that the individual could be picked up by someone residing outside of his or her home. The third travel alternative, transit, encompassed the modes of bus, light rail, and streetcar. For an individual to have the transit option within the feasible choice set, the nearest bus stop or rail station had to be located within 0.5 mi and 1 mi of his or her residence, respectively. The travel mode option for bicycle was available if the individual's household possessed at least one bicycle and the destination of the individual's trip could be reached within 2 h, assuming an average speed of 10 mph. Similarly, the alternative nonmotorized option for walking was determined to be within one's feasible choice set if the destination could be reached within 2 h, assuming an average walk speed of 3 mph. The alternative-specific travel time attribute, which was measured in minutes, was collected with 2010 midday travel skims provided by Portland Metro.

In addition to travel time, several sociodemographic characteristics as well as attributes reflecting the individual's housing structure and surrounding built environment were specified in the base MNL model. The decision-maker attributes, which were added through a stepwise model building strategy, included a binary explanatory variable denoting whether the trip maker possessed a college education, another binary variable signifying whether the individual was a male, the continuous variable reflecting the traveler's age, another continuous variable representing the personal income of the traveler in $10,000 intervals, a binary variable detailing whether the trip maker resided in a single-family detached housing unit, and a variable representing the net residential density of the census block group in which the traveler resides, measured in persons per square mile. The last explanatory variable was statistically controlled for in the base model to ensure any potential benefit provided by land use diversity exceeded the neighborhood effect of

TABLE 3 Base MNL Model Estimation Results

	Travel Mode Alternative[a]											
	High-Occupancy Vehicle			Public Transit			Bicycle			Walk		
Explanatory Variable	Coeff.	SE	Sig.	Coeff.	SE	Sig.	Coeff.	SE	Sig.	Coeff.	SE	Sig.
Constant	.41	0.21	*	–1.79	0.35	****	–2.25	0.41	****	1.40	0.29	****
Travel time	–.00	0.00	NS	–.00	0.00	NS	–.05	0.01	****	–.10	0.01	****
Sociodemographics												
College education[b]	–.19	0.11	*	.01	0.25	NS	1.22	0.31	****	.34	0.18	*
Gender (male)[b]	–.06	0.08	NS	.12	0.19	NS	.66	0.20	****	.06	0.13	NS
Age (10 years)	–.01	0.00	****	.00	0.01	NS	–.02	0.01	****	–.01	0.00	****
Income ($10,000)	–.13	0.02	****	–.10	0.05	**	–.19	0.06	****	–.01	0.03	NS
Single-family unit[b]	.46	0.12	****	–1.57	0.20	****	–.13	0.25	NS	–.42	0.16	***
Built environment												
Persons per mi^2	–.00	0.00	NS	.00	0.00	**	.00	0.00	****	.00	0.00	****

NOTE: Coeff. = coefficient; SE = standard error; sig. = significance; NS = not significant. Observations = 4,183; log likelihood: zero coeff. = –5,022.01; beta coeff. = –3,601.59; McFadden's R^2: unadjusted = .2828; adjusted = .2812.
[a]Base = single-occupancy vehicle.
[b]Binary explanatory variable.
*$p < .1$; **$p < .05$; ***$p < .01$; ****$p < .001$.

population density on mode choice. Base model estimation results are provided in Table 3.

The base model results for the association between explanatory variables and nonmotorized mode decisions are intuitive and echo the observed links commonly denoted in the literature. On average, an individual was more likely to bike for home-based discretionary travel than drive alone when he or she had a college education or resided in a neighborhood with a greater density. An individual was also more likely to drive alone than bike or walk when the individual was older, was wealthier, or lived in a single-family house. Male survey participants were more likely to bike than drive alone compared with their female counterparts; gender was not statistically significant when other modal choices were considered against the base case. Finally, individuals were more likely to ride transit than drive alone if they resided in a multifamily structure, earned a lower income, or resided in a neighborhood characterized by a higher population density.

RESULTS

Building on the base model, a succession of models was estimated to explore whether land use diversity had a significant relationship with mode choice when measured at either the origin or the destination and, if so, which pairing of land use type classification and geographic scale best operationalized each diversity measure. Each land use diversity measure, operationalized at the four geographical units, was individually added to the base model, and a likelihood ratio test was conducted to conclude whether the addition of a diversity measure significantly improved the model's log likelihood. These diversity measures were examined across the three land use typologies and at both the origin and the destination of the trip. This strategy led to estimation of 168 mode choice models, which are synthesized in the following subsections.

Land Use Diversity Operationalized at Origin

When the original eight land use types were aggregated into four categories, the operationalization of the Smith–Wilson evenness index at the 2-mi network buffer provided the greatest improvement in log likelihood; however, the negative direction of the relationship for transit and the two nonmotorized modes in comparison with the base alternative of drive alone was counterintuitive. The inclusion of one of the other six land use diversity measures operationalized at any spatial scale provided no statistically significant improvement to the base MNL model estimation. An assessment of land use diversity measured at the trip origin that adopted the three-class typology provided even less conclusive results. Within the three-category typology, the Smith–Wilson evenness index, which embodied the only significant diversity index for the four-land-use classification scheme, provided no significant improvement to the base model when measured at any of the four geographic scales. No combination of index and scale produced a diversity measure that significantly improved the base model. Of all land use diversity indexes measured at the trip origin, the operationalization of the Smith–Wilson evenness index at the census tract with a binary residential and nonresidential land use type categorization provided the greatest improvement in log likelihood. A heightened balance between residential and nonresidential land uses, as dictated by the Smith–Wilson index, at this most aggregate geographic representation of the neighborhood concept significantly increased the probability of an individual either bicycling, walking, or riding transit from his or her residence, compared with the base decision to drive alone.

Land Use Diversity Operationalized at Destination

As a complement to the previous analysis, Table 4 provides an overview of the seven diversity measures and the geographic scale that best captures the potential connection between mode choice and land use balance found at the trip destination. Unlike the analysis into these connections when measured at the origin, each index measured at the trip destination had at least one geographic scale representation whose addition to the base model significantly improved the model's performance. For the four-land-use typology, the operationalization of Hill's ratio at the 2-mi network buffer represented the measure that produced the best MNL model performance. Moreover, the estimation of land use evenness with Hill's ratio produced the only model

TABLE 4 MNL Estimation Results of Land Use Diversity Measures Operationalized at Destination

Land Use Diversity Measure	Geographic Unit	Travel Mode Alternative[a] HOV Direction of Relationship	HOV Sig.	Public Transit Direction of Relationship	Public Transit Sig.	Bicycle Direction of Relationship	Bicycle Sig.	Walk Direction of Relationship	Walk Sig.	Model Performance Log Likelihood
Four Land Use Categories										
Bhat	2 mi	+	**	+	***	+	NS	–	NS	–3,594.04
Heip	2 mi	+	**	+	****	+	NS	–	NS	–3,592.25
Hill	2 mi	+	**	+	****	+	****	+	*	–3,571.59
McIntosh	2 mi	+	**	+	****	+	**	–	NS	–3,586.89
Shannon	2 mi	+	**	+	****	+	NS	–	NS	–3,592.69
Simpson	2 mi	+	**	+	****	+	**	–	NS	–3,585.97
Smith and Wilson	2 mi	–	NS	–	****	–	**	–	****	–3,579.97
Three Land Use Categories										
Bhat	2 mi	+	**	+	****	+	**	–	NS	–3,587.51
Heip	2 mi	+	**	+	****	+	NS	–	NS	–3,590.13
Hill	2 mi	+	*	+	****	+	****	+	NS	–3,578.25
McIntosh	2 mi	+	**	+	****	+	**	–	NS	–3,586.55
Shannon	2 mi	+	**	+	****	+	NS	–	NS	–3,591.00
Simpson	2 mi	+	**	+	****	+	**	–	NS	–3,585.42
Smith and Wilson	2 mi	+	NS	+	**	–	NS	–	NS	–3,596.87
Two Land Use Categories										
Bhat	2 mi	+	**	+	****	+	***	–	NS	–3,585.99
Heip	2 mi	+	**	+	****	+	*	–	NS	–3,591.52
Hill	2 mi	+	***	+	****	+	***	+	NS	–3,582.40
McIntosh	2 mi	+	**	+	****	+	**	–	NS	–3,590.46
Shannon	2 mi	+	**	+	***	+	NS	–	NS	–3,593.49
Simpson	2 mi	+	***	+	****	+	**	–	NS	–3,588.04
Smith and Wilson	Tract	–	NS	+	****	+	****	+	****	–3,569.63

NOTE: + = positive direction of relationship; – = negative direction of relationship; HOV = high-occupancy vehicle.
[a]Base = single-occupancy vehicle.
*$p < .1$; **$p < .05$; ***$p < .01$; ****$p < .001$.

in which the association between land use diversity and the decision to walk was both statistically significant and intuitive in direction of the relationship. As with the four-class analysis of land use diversity at the origin, the inclusion of the Smith–Wilson index of evenness offered a significant improvement in log likelihood; however, the direction of the relationship for the nonmotorized modes compared with the drive-alone alternative was unanticipated. Of the three land use indexes commonly found in the travel behavior literature, only Simpson's index found a significant connection between evenness among the four land use types and the likelihood for a person to choose either nonmotorized mode over the drive alone option.

Akin to these findings, the operationalization of Hill's ratio at the 2-mi network buffer to quantity diversity also provided the greatest improvement to the base model when the three-class typology was used. For use of a two-class dichotomy for land use type, the operationalization of the Smith–Wilson evenness index at the census tract offered the greatest enhancement to the base MNL model estimation. The representation of land use diversity with this combination of index, geographic scale, and land use classification scheme led to the greatest log likelihood measure for any of the models estimating diversity at the household origin or activity location. An increase in the Smith–Wilson index measured at the activity destination's census tract resulted in an increased likelihood of an individual selecting either nonmotorized mode or public transit to conduct his or her home-based trip. This exemplification of land use diversity was the only index that revealed a significant, positive relationship between an increase in the evenness of residential and nonresidential land uses at the activity location and the choice to walk rather than drive alone for discretionary travel.

Correlation of Land Use Diversity Measures

Because no single index best characterized the link between mode choice and land use diversity at the origin or destination, a reasonable extension was to examine the correlation between indexes. Table 5 provides a summary of the Spearman rank correlation coefficients between the land use diversity measure producing the best-fitting model for each categorization and the other six measures operationalized at the same scale. As expected, correlations existed between measures; however, no moderate or strong correlation was found between the use of the Smith–Wilson evenness index at the tract as a measure of activity location diversity and any other index. Furthermore, for all combinations of diversity index, geographic

TABLE 5 Correlations of Land Use Diversity Measures with Best Fitted MNL Model at Destination

Land Use Diversity Measure	Four Land Use Types 2-mi Network Buffer Hill		Three Land Use Types 2-mi Network Buffer Hill		Two Land Use Types U.S. Census Tract Smith and Wilson	
	Coeff.	Sig.	Coeff.	Sig.	Coeff.	Sig.
Bhat	.50	****	.81	****	.06	****
Heip	.43	****	.61	****	.06	****
Hill	1.00	****	1.00	****	.06	****
McIntosh	.67	****	.77	****	.06	****
Shannon	.43	****	.61	****	−.03	****
Simpson	.67	****	.77	****	.06	****
Smith and Wilson	−.29	****	.15	****	1.00	****

NOTE: *$p < .1$; **$p < .05$; ***$p < .01$; ****$p < .001$.

scale, and land use categorization, the measurement of the Smith–Wilson evenness index or Hill's ratio at the destination represented the preferred land use diversity measure. In the three instances, no strong correlation existed between these two newly presented measures of land use diversity to transportation research.

DISCUSSION OF RESULTS

This study provided an exploration into the effect on mode choice of measuring land use diversity at various geographic scales. Debates about the extent of this connection will continue, but this study produced several informative outcomes about the selection of diversity index, spatial scale at which to operationalize the index, and significance of examining this association at either the trip origin or the trip destination. Additional themes for future consideration in efforts to extend this research beyond the tricounty Portland metropolitan region were underscored.

Although no single index best explained the association between land use diversity and mode choice, two measures uncommon to transportation-land use research improved model performance more than traditionally used diversity indexes. In trials exploring diversity at the destination with either the three- or the four-land-use categorization schemes, the operationalization of Hill's ratio at a 2-mi network buffer outperformed those MNL models defining diversity by the Shannon, Simpson, or Bhat indexes at comparable geographic scales. In each instance, models incorporating land use diversity measured by Hill's ratio not only produced a greater log likelihood value than those MNL models defining diversity by a more common measure but also offered intuitive directions in the relationship between walking and land use diversity compared with the decision to drive alone. In aggregation of land use types as either residential or nonresidential, the operationalization of the Smith–Wilson index at the census tract produced the greatest improvement to the base MNL model when measured at either the trip origin or the trip destination. This finding is of interest because this binary representation of land use type is a widely adopted classification scheme that has its theoretical underpinnings in more regional measures such as jobs–housing balance. The ability to best capture the relationship of land use diversity and nonmotorized mode choice at an aggregate geographic scale also has practical implications concerning gained efficiencies for data-intensive forecasting models used to predict mode share.

The operationalization of land use diversity at a 2-mi network buffer surrounding the activity destination outperformed all other geographies in all but one instance, a result that supports adoption of the sliding scale neighborhood representation for operationalizing land use diversity in this context. The overall trend toward operationalizing land use diversity with a larger average geographic extent was unforeseen and counterintuitive to the notion that a more disaggregate geography is the most appropriate scale for reflecting the association between land use diversity and nonautomotive mode choice for discretionary travel. The exception to this trend was the use of the Smith–Wilson index, which significantly improved model performance when calculated at the most aggregate fixed-scale neighborhood representation. Although this finding contrasts the use of traditional land use diversity indexes such as the entropy index, an examination of more disaggregate scales (e.g., census block, half-mile network buffer) and different regional contexts must be made before any preference toward one land use diversity index over another can be concluded.

Future research must explore the common perception that a perfect balance in land use types is an ideal condition for measuring the influence of land use diversity on travel behavior. Although this study functioned under that assumption, results from the three- and four-land-use category typologies highlighted the potential theoretical inaccuracy of previous studies to presume that land use evenness within a neighborhood is related to heightened nonautomotive travel. Accordingly, greater attention should be given by researchers to understanding the proper balance of land use types for a specific typology. Additional insight is also needed regarding the choice of land use types to analyze when exploring the link between diversity and the mode choice for a certain trip purpose. For an examination of home-based discretionary travel at a neighborhood scale, such as this study, an evenness of land use types may be more important to nonmotorized mode choice than automotive travel; however, a perfect balance may be less imperative for work-related trip purposes because an individual is less likely to be concerned about alternative work destinations when commuting to his or her workplace. Improved recognition of these discussion points that builds on this exploration into the operationalization of land use diversity will help researchers to better understand its link to mode choice.

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