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Transit environments for physical activity: Relationship between micro-scale built environment features surrounding light rail stations and ridership in Houston, Texas

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ABSTRACT

Introduction: Health professionals promote transport-related physical activity because travelers often times walk or bike to and from transit stops or stations. Although previous studies have examined the associations between macro-scale built environment features surrounding light rail transit (LRT) stations (e.g., density) and LRT ridership, this study examined the associations between numerous micro-scale features (e.g., street-level noise pollution) and ridership.

Methods: This analysis originated from the Houston Travel-Related Activity in Neighborhoods (TRAIN) Study, a project evaluating how an LRT extension impacted adult physical activity in Houston, Texas. In 2014, researchers used the Analytic Audit Tool to quantify 58 micro-scale built environment features within six categories: Land Use Environment, Transportation Environment, Facilities, Aesthetics, Signage, and Social Environment. Feature data were obtained from 590 street segments within 0.25 miles of 22 LRT stations. For each station, separate composite indices were created per category by averaging the computed feature scores (1–7) within each category, with higher scores signifying more physical activity-promoting features. Station-level LRT ridership data were obtained from monthly ridership reports for the 12 months following station opening. Linear mixed models were constructed to examine the associations of the six built...
environment categories with ridership, adjusting for season, weekday vs. weekend day, and station as a random intercept.

Results: Holding all other variables constant, every one-unit increase in composite index scores for Transportation Environment and Social Environment was associated with an increase in daily ridership by 425 and 488 riders, respectively (p < 0.05). Every one-unit increase in composite index score for Signage was associated with a decrease of 722 riders daily (p < 0.05). The relations of Land Use Environment, Facilities, and Aesthetics with ridership were statistically null (p > 0.05).

Conclusions: Enhancements to the Transportation Environment and Social Environment may slightly increase overall LRT ridership, and consequently, utilitarian physical activity.

1. Introduction

Public transportation is secondary to the automobile as a means of commuting in the United States; however, only an estimated five percent of all work trips are completed by bus, rail, and other publicly financed mass transit services (U.S. Census Bureau, 2019a). Automobile dependence carries health risks. Research finds those who spend greater than 10 h per week riding in a car have an 82% greater risk of dying from cardiovascular disease than those who ride in cars for less than 4 h per week (Warren et al., 2010). Conversely, public transit has been lauded for its public health benefits, along with its recognized energy savings and lower greenhouse gas emissions compared to automobiles (Dirghayani, 2013; Kwan and Hashim, 2016; Shapiro et al., 2016). Public transit correlates with less traffic injuries and air pollution than automobiles (Xia et al., 2015), and with reductions in both depressive symptoms and feelings of loneliness (Reinhard et al. 2018). Furthermore, public transit advances social equity for its relative affordability and by providing mobility to essential services such as jobs, medical care, education, and healthy foods (Litman, 2018; Porter et al., 2015).

Public transit use may also prompt physical activity, a major health benefit since inadequate physical activity is related to the development of 40 chronic diseases (Ruegsegger and Booth, 2018). The first mile/last mile problem—the distance between a commuter’s transit stop and their origin or final destination—is considered an opportunity for active transportation (e.g., walking and cycling) to reach the transit stop or destination (Knell et al., 2018; Lachapelle et al., 2011; Lachapelle and Pinto, 2016; Miller et al., 2015; Saelens et al., 2014). In the United States, more than two-thirds of transit users walk to reach their stop or destination (American Public Transportation Association, 2017). Previous cross-sectional studies have indicated use of public transit is associated with higher levels of moderate- and vigorous-intensity physical activity and less sedentary time (Knell et al., 2018; Brown et al., 2016; Brown et al., 2015; Hong et al., 2016; Saelens et al., 2014). A systematic review found that public transit use was associated with an additional 8–33 min of walking per day (Rissel et al., 2012). In a quasi-experimental study, researchers found individuals increased their physical activity by 10.6 min, on average, on transit-use days versus non-transit-use days (Miller et al., 2015). This additional physical activity is consequential, as 10 min of moderate-intensity physical activity each weekday equates to more than a third of the weekly recommended physical activity levels for adults (Piercy et al., 2018).

To inform physical activity promotion strategies, researchers have utilized ecological models to understand which factors impact population-level physical activity patterns (Sallis et al., 2012). Studies have found positive associations between active transportation and several environmental characteristics including accessibility (e.g., number of destinations); infrastructure for walking, cycling, and public transportation (e.g., presence of benches); and walkability—defined as high levels of street connectivity, land use mix, and residential density (Cerin et al., 2017; Hajna et al., 2015; Karmeniemi et al., 2018; Tewahade et al., 2019). The environment surrounding light rail transit (LRT) stations, in particular, has been linked to physical activity promotion: more pedestrian-friendly amenities (e.g., wider sidewalks); connectivity (e.g., three- and four-way intersections); crossing aids; and development intensity have been found to associate with the usage of street segments near LRT stations (Rodríguez et al., 2009).

To assess the relations between built environment features and both leisure-time physical activity and active transportation, researchers have used foot-based, environmental audit instruments to estimate the environmental characteristics at the street level (Cain et al., 2018; Clifton et al. 2007; Hawkesworth et al., 2018; Hoehner et al., 2005; Pikora et al., 2002; Sallis et al., 2015). Generally, these audit instruments share many of the same categories of built environment features (e.g., Aesthetics) and features within these categories (e.g., level of physical disorder/cleanliness). The similarities among instruments is oftentimes a product of new versions developed from earlier instruments. For instance, the Microscale Audit of Pedestrian Streetscapes (MAPS) tool originated from the Analytic Audit Tool (Vanwolleghem et al., 2016), and has since been adapted to both shorter versions (i.e., MAPS-Abbreviated and MAPS-Mini) intended for specific end users (e.g., practitioners, advocacy, and community members) (Active Living Research, 2020), and universal versions to be used beyond the United States (i.e., MAPS-Global) (Cain et al., 2018). Other audit instruments have been designed for specific study populations such as the Older People’s Environments and CVD Risk (OPEC-R) tool, which was designed for older adults in the United Kingdom (Hawkesworth et al., 2018).

Yet to our knowledge, no studies have utilized estimates derived from environmental audit instruments to understand the associations of environmental characteristics surrounding LRT stations with ridership. Secondly, previous studies have focused on the association between transit ridership and macro-scale built environment features (i.e., connectivity, density, land-use diversity, and walkability) surrounding transit stations and stops (Choi et al., 2012; Guerra and Cervero, 2011; Ryan and Frank, 2009) rather than on micro-scale built environment features (e.g., presence of bike lanes). Lastly, no studies have examined how the many micro-scale built environment features associated with physical activity impact LRT ridership in concert.

Therefore, the purpose of this cross-sectional study was to determine how different built environment categories—each of which...
comprises numerous micro-scale built environment features—surrounding LRT stations associate with LRT ridership. We posit more physical activity-promoting features (i.e., Land Use Environment, Transportation Environment, Facilities, Aesthetics, Signage, and Social Environment) surrounding LRT stations will be associated with higher levels of ridership, and that different categories of features will exhibit different magnitudes of association with LRT ridership. Findings from this assessment may be able to inform city planners, public health professionals, and other decision makers on where to direct efforts for promoting LRT ridership, and consequently, utilitarian physical activity.

2. Materials and methods

2.1. Site selection

This work was based on the Houston Travel-Related Activity in Neighborhoods (TRAIN) Study, a prospective natural experiment conducted by The University of Texas Health Science Center at Houston (UTHealth) School of Public Health and the Texas A&M Transportation Institute. The Houston TRAIN Study assessed the short- and long-term impacts of a newly constructed extension of the METRORail—a 22.7-mile light rail system in Houston, Texas—on adult physical activity (Durand et al., 2016). In 2011, the Federal Transit Administration’s New Starts transit program awarded $900 million to the City of Houston to extend the preexisting 7.5-mile, one-line system to three rail lines. The Red Line—the initial rail line that serviced North Houston—received a 5.3-mile extension northward that opened on December 21, 2013. Both the newly constructed 6.6-mile Purple Line and 3.3-mile Green Line opened on May 23, 2015, providing service to Southeast Houston and the East End of Houston, respectively. Construction issues delayed the opening of the most eastern portion of the Green Line (i.e., Cesar Chavez/67th Street station and Magnolia Park Transit Center station) until January 11, 2017.

2.2. Development of built environment variables

Built environment data for this study originated from the Houston TRAIN Study. Detailed explanations of the methods used to collect and process these micro-scale built environment features have been discussed elsewhere (Oluyomi et al., 2019). From late spring through early summer 2014, project members performed an environmental audit of the area surrounding the newly constructed stations (n = 22) of the LRT extension using the Analytic Audit Tool, a measurement instrument to understand the relationships between street-scale environments and physical activity behavior (Active Living Research, 2019). This tool is a reliable method of measurement that has been successfully implemented to measure perceived and objective characteristics of the environment that are associated with physical activity (Brownson et al., 2004; Hoehner et al., 2005). The Analytic Audit Tool consists of questions (n = 27) and sub-questions (n = 142)—with count, Likert scale, and ordinal response choices—organized into six environmental categories: Land Use Environment, Transportation Environment, Facilities, Aesthetics, Signage, and Social Environment. Examples of features within these categories include land use mix and vacant lots (i.e., Land Use Environment); sidewalks and street lighting (i.e., Transportation Environment); public recreational facilities and playground equipment (i.e., Facilities); garbage, litter, or broken glass in the street or on the sidewalks (i.e., Aesthetics); no trespassing/beware of dog signs (i.e., Signage); and presence of teenagers or adults (i.e., Social Environment).

Selection of audit locations for the Houston TRAIN Study relied on a geographic information systems analysis in ArcGIS 10.1 (Esri, Redlands, CA). The research team created 0.25-mile circular buffers, with each centroid being one of the new LRT stations (n = 22) along the extension of the Red Line and the newly developed Purple and Green Lines. Oluyomi et al. (2019) provide a map illustrating the audited LRT stations and developed buffers of the Houston TRAIN Study. The rationale behind a buffer of 0.25 miles (~400 m) was that this distance roughly equates to a 5-min walk, a realistic distance for an individual to cover when moving to or from an LRT station (Mehaffy et al., 2010). These buffers resulted in the final sample of distinct street segments (n = 590) across US census blocks (n = 892) for the environmental audit. After a two-day training on the Analytic Audit Tool, seven graduate students performed the audit over eight weeks (i.e., May 19th through July 14th, 2014), followed by data entry into an electronic database in Qualtrics (Qualtrics, Provo, UT).

To package 58 micro-scale built environment features measured by the Analytic Audit Tool into six categories (i.e., Land Use Environment, Transportation Environment, Facilities, Aesthetics, Signage, and Social Environment), we adapted a previously developed method that created a single composite index for each environmental category (Oluyomi et al., 2019). Development of composite indices for each LRT station—from each station’s audited street segments—included five steps. First, we transformed micro-scale built environment features from each sub-question into the positive direction so that a higher value signified an expected higher level of physical activity. For instance, the sub-question for “presence of sidewalks” is already in the positive direction with physical activity, while the sub-question for “presence of physical disorder” is in the negative direction. The transformation of “presence of physical disorder” resulted in higher values signifying less physical disorder and an expected higher level of physical activity. Second, we dichotomized feature values into “present” and “absent.” Third, we calculated the percentage of street segments for each feature with the value of “present.” Fourth, we scored the percentage from one to seven (0–10% = 1; 11–30% = 2; 31–45% = 3; 46–55% = 4; 56–70% = 5; 71–90% = 6; 91–100% = 7), leading to a composite index score for each individual micro-scale built environment feature (minimum = 1.0; maximum = 7.0), with higher scores signifying more of that physical activity-promoting feature. Lastly, we averaged the feature scores within each category, resulting in six composite index scores—one for each category of micro-scale built environment features—per LRT station.
2.3. Light rail transit ridership as the study outcome

LRT ridership data for this work originated from Ridership Reports that are publicly available on the METRO website (Metropolitan Transit Authority of Harris County, 2019). Each report includes LRT station-level data on the average daily number of boardings per month, stratified by weekday, Saturday, and Sunday services. We utilized Ridership Reports for the 12 full months following station opening, with our rationale being this time period most closely aligned with the timing of the environmental audit (i.e., May–July 2014). As weekday and weekend ridership were expected to respond differently to environmental features, we computed and identified weekend ridership (i.e., average of Saturday and Sunday ridership) separately from weekday ridership.

2.4. Statistical analyses

To account for the nested structure of the data (i.e., repeated measures of LRT ridership nested within individual LRT stations), we specified a linear mixed model, or multilevel model, with a random intercept at the station level (Singer et al., 2003). An unstructured covariance structure was utilized because of heterogeneous variance among the model variables. To assess the appropriateness of a linear mixed model, the intraclass correlation (ICC) was computed from the unconditional model. The ICC was 77.0%, indicating that more than three-fourths of the variance in ridership is attributable to the LRT station. Linear mixed modeling followed a stepwise approach: 1) unconditional model, 2) model with independent variables of interest, and a 3) model adding potential covariates to the second model. The dependent variable was daily LRT ridership (i.e., number of boardings) per LRT station, averaged individually over each of the preceding 12 months. The independent variables of interest were the composite index scores for each category of micro-scale built environment features per LRT station. The third model included as potential covariates a dichotomous variable for weekend versus weekday and a categorical season variable, along with the LRT station as a random intercept. From this three-model set, the final model was selected based on best fit, as determined by Akaike information criterion and Bayesian information criterion. All statistical analyses were completed in SPSS 24 (IBM, Armonk, NY, USA).

3. Results

Across the 22 LRT stations included in the Houston METRORail extension, daily ridership varied by season and day of week (Fig. 1). Weekdays had generally higher ridership than weekends and summer had the lowest weekday ridership of the four seasons, with a 27.4% higher daily ridership in fall, compared to summer. The average sum of the composite index scores for the six categories of micro-scale built environment features was 18.1 (standard deviation = 1.7) (Table 1), considerably lower than the highest possible sum (42.0). Composite index scores for environmental categories were highest, on average, for Aesthetics (mean = 4.1; standard deviation = 0.6), and lowest for Facilities (mean = 1.2; standard deviation = 0.4). Station-level descriptive statistics can be found in the appendix.

In the final linear mixed model (Model 3), every one-unit increase in composite index scores for Transportation Environment and Social Environment categories of micro-scale built environment features was associated with an increase in ridership by 425 and 488 riders per day, respectively, when holding all other variables constant (p < 0.05) (Table 2). Every one-unit increase in composite index score for Signage was associated with a decrease of 722 riders per day (p < 0.05). No significant associations were found for the Land Use Environment, Facilities, and Aesthetics categories (p > 0.05). The summer season and weekends were negatively associated with

![Fig. 1. Daily light rail transit ridership per season for the 22 Houston METRORail stations in LRT extension, stratified by weekday and weekend (January 2014–December 2017). Error bars indicate standard deviation.](image-url)
### Table 1
Descriptive statistics on micro-scale built environment features surrounding 22 Houston METRORail stations (May–July 2014), ranked in order (high to low) of mean composite index score per environmental category (n = 6) and feature (n = 58).

| Micro-Scale Built Environment Features within Environmental Categories | Composite Index Scores (1.0–7.0)\(^a\) |
|---|---|
| **AESTHETICS**\(^b\) | Mean | Standard Deviation |
| Presence of air pollution, visible or detectable through odors (e.g., diesel fumes, factory emissions) | 4.1 | 0.6 |
| Presence of comfort features (e.g., shade trees, benches, or other types of amenities) | 6.0 | 0.6 |
| Presence of noise pollution (e.g., loud ambient sounds like trains, construction, factories) | 4.8 | 1.7 |
| Presence of attractive features (e.g., architectural design, building variety, open space) | 4.7 | 1.3 |
| **TRANSPORTATION ENVIRONMENT**\(^b\) | 3.8 | 0.5 |
| Presence of street lighting for sidewalks, street shoulders, and/or bike lanes at night | 6.9 | 0.3 |
| Connectivity (i.e., straight with intersections vs. cul-de-sac) | 6.5 | 0.6 |
| Presence of traffic calming devices to reduce volume or speed (e.g., traffic signals, speed bumps) | 6.1 | 0.6 |
| Presence of sidewalks | 5.8 | 1.3 |
| Presence of obstructions (i.e., artificial: cars, construction debris; or natural: trees, bushes, rocks) | 5.7 | 1.0 |
| Alternative transportation modes (i.e., level of availability to pedestrian and bicyclist facilities) | 5.7 | 1.4 |
| **SOCIAL ENVIRONMENT**\(^b\) | 3.2 | 0.5 |
| Presence of stray dogs or animals (i.e., not squirrels or rabbits) | 6.4 | 0.7 |
| Presence of teenagers or adults (i.e., 13–65 years old) | 5.6 | 1.0 |
| Presence of teenagers or adults engaging in active behaviors (e.g., playing a sport, walking, biking) | 4.9 | 1.3 |
| Presence of other services (e.g., beautician, lawyer, accountant) | 1.7 | 0.6 |
| Presence of office building | 1.5 | 0.9 |
| Presence of airport, train bus station, or other transportation facility | 1.4 | 0.6 |
| Presence of fast food restaurant | 1.4 | 0.6 |
| Presence of playground equipment (e.g., swings, slide) | 1.1 | 0.3 |
| Presence of security warning sign | 2.9 | 0.4 |
| Presence of share the road sign  | 6.1 | 0.7 |
| **FACILITIES**\(^b\) | 1.2 | 0.3 |
| Presence of public recreational facilities | 1.3 | 0.5 |
| Presence of public recreational equipment | 1.2 | 0.4 |
| Presence of obstructions (i.e., natural: trees, bushes, rocks) | 3.8 | 0.5 |
| Presence of political message or event | 1.2 | 0.4 |
| Presence of basketball/basketball court | 1.1 | 0.3 |

\(^a\) Composite index scores range from 1.0 to 7.0 with higher scores signifying more of a physical activity-promoting, micro-scale built environment feature surrounding the light rail transit station.
daily ridership per LRT station (p < 0.05).

4. Discussion

4.1. Major findings explained

This study found daily LRT ridership to exhibit 1) a significant positive association with the Transportation and Social Environment categories of micro-scale built environment features surrounding LRT stations; 2) a significant negative association with the Signage category; and 3) an insignificant association with the Land Use Environment, Facilities, Aesthetics categories.

We expected more micro-scale built environment features surrounding LRT stations within the Transportation and Social Environment categories would be associated with higher LRT ridership levels. Features measured in this study within the Transportation Environment—such as presence of sidewalks, presence of bike lanes, and connectivity—closely align with transit ridership and the physical activity domain of active transportation. A study of public transit in three metropolitan regions of Oregon revealed multi-use pedestrian and bicycle paths, bike lanes, and street connectivity associated with increased transit ridership (Dill et al., 2013). Similarly, a study of older adults in Singapore found high street connectivity was associated with higher frequency of walking for transportation purposes (Nyunt et al., 2015).

Regarding the Social Environment, features measured by the Analytic Audit Tool included the presence of teenagers or adults in the street segment, as well as the presence of teenagers or adults engaging in active behaviors. The Social Environment around LRT stations may promote ridership because of the increased likelihood for interacting with others. Research reveals there has been an increase in American public life in recent years, with more travel in groups and by women, and more time spent in the public sphere (Hampton et al., 2015). Social interaction in public spaces can improve individuals’ well-being by providing opportunities for bonding with others and by fostering a sense of community (Cattell et al., 2008). Urban spaces that are vital, or “socially successful,” have been deemed healthier and safer, and may induce a cycle where the attraction of people to a vital place may make that place even more attractive (Jalaladdini and Oktay, 2012). The positive relationship between the Social Environment and LRT ridership in our work mirrors that of another study, which found that place attachment—defined as the “affective, cognitive, and behavioral bonding with places and people associated with a setting”—was associated with both new and preexisting transit riders (Brown et al., 2016).

Our finding that more Signage (e.g., pedestrian or bicyclist friendly traffic signs) was associated with lower LRT ridership may be related to traffic signage being disproportionately located in areas with poor walking and cycling conditions, and these signs may not offer any measurable improvements in pedestrian or cycling safety. In addition, individuals may have negative perceptions of signage. Although the presence of traffic light signals has been shown to be associated with higher odds of utilitarian walking (Odds Ratio = 1.59; 95% Confidence Interval = 1.17 to 2.17) (Doescher et al., 2014), the literature does not sufficiently cover the relationship between traffic signage and physical activity or LRT ridership. Researchers have revealed the messaging on traffic signs has inconsistent levels of comprehension and effects on perceived safety, with “Share the Road” signage not increasing comprehension or perceptions of

| Table 2 | Linear mixed model results. |
|---|---|
| Fixed effects | Final Model |
| Land Use Environment | −72.2 |
| Transportation Environment | 425.4* |
| Facilities | −141.7 |
| Aesthetics | −74.3 |
| Signage | −722.4*** |
| Social Environment | 487.8* |
| Time of week | |
| Weekend | −178.5*** |
| Weekday (referent) | |
| Season | |
| Summer | −43.4* |
| Fall | 35.5* |
| Winter | −14.5 |
| Spring (referent) | |
| Random effects | |
| τ₀₀ (intercept) | 54,779.4*** |
| σ² | 19,112.2*** |

Dependent variable: daily ridership per light rail transit station.
* p < 0.05; ** p < 0.01; *** p < 0.001.
safety (Hess and Peterson, 2015). Traffic signage may decrease LRT ridership because individuals may view signage as distracting, unnecessary, or unhelpful.

Although certain features within the Land Use Environment (e.g., land use mix) have been found to exhibit significant positive associations with active transportation (Nyunt et al., 2015; Saelens and Handy, 2008), these features may have a different relationship with transit ridership. Previous studies have found insignificant associations between land use mix and transit ridership (p > 0.05)—comparable to the results of our work—and mixed associations and levels of significance between transit ridership and single-family residential, multifamily residential, commercial, and parks (Chakraborty and Mishra, 2013; Dill et al., 2013). Furthermore, Dill et al. (2013) found land use characteristics had lower explanatory power in determining transit ridership in large urban areas than small urban areas, which may explain the insignificant association between the Land Use Environment and LRT ridership in Houston, estimated to be the fourth most populous incorporated place in the United States (U.S. Census Bureau, 2019b).

The composite index score for the Facilities category, which included the availability of both public recreational facilities and equipment, may have exhibited an insignificant association with LRT ridership in our study because these features are associated with physical activity, and not ridership. That is, the amount of public recreational facilities and equipment surrounding LRT stations does not directly relate to an individual’s decision to take the train to another destination. Studies have provided evidence for the impact of recreational facilities on both overall physical activity and walking for transportation (Chen et al., 2016; Doescher et al., 2014; Kurka et al., 2015; Saelens and Handy, 2008; Todd et al., 2016), but no studies to our knowledge have evaluated the relationship between recreational facilities and LRT ridership.

The outcome that Aesthetics surrounding LRT stations—such as the presence of attractive features (e.g., architectural design, building variety, vegetation, signage, open space) and presence of physical disorder (e.g., litter, rubbish, graffiti, broken glass, or discarded items)—were not associated with LRT ridership in Houston corroborates previous studies measuring the correlation between aesthetics and physical activity (Bentley et al., 2010; Hawkesworth et al., 2018). However, the influence of aesthetics may depend on the type of physical activity (e.g., active transportation or recreational physical activity) (Saelens and Handy, 2008), and on who is measuring the quality of the environment, a trained researcher or a study participant (Nyunt et al., 2015). The relationship between transit ridership and aesthetics at the stop level is understudied, with a single study showing commuters prefer LRT stations with higher aesthetic quality over traditional stations (Cascetta and Cartenì, 2012).

4.2. Implications of study findings

With approximately 56,000 riders and 23,000 riders, on average, using the METRORail every weekday and weekend day (2014–2018), respectively (Metropolitan Transit Authority of Harris County, 2019), the observed measures of association of the six categories with ridership signify the potential impact of micro-scale built environment features surrounding LRT stations on ridership is relatively modest (Table 2). However, these modest magnitudes of association are significant from a health equity perspective. Individuals who are low-income, Black, and/or Latinx are more likely to take public transportation—a potential source of physical activity—on a daily or weekly basis compared to other populations (Pew Research Center, 2016). These same individuals are also less likely to reach recommended levels of physical activity than other populations (U.S. Office of Disease Prevention and Health Promotion, 2020).

Results of this study provide city planners, public health professionals, and other decision makers with evidence for which categories of features to invest resources. Specifically, results of linear mixed modeling suggest investment surrounding LRT stations should be focused on micro-scale built environment features within the Transportation and Social Environment categories, rather than on features within the Signage, Land Use Environment, Facilities, Aesthetics categories. However, enhancements to the Social Environment around LRT stations may prove challenging during a pandemic, such as coronavirus disease 2019 (COVID-19), when individuals are maintaining physical or social distance to reduce the spread of the disease (U.S. Centers for Disease Control and Prevention, 2020).

In the face of limited resources, evidence-based improvements to transit environments may encourage individuals to use LRT systems and shift their travel mode from passenger vehicles to public transit. This potential mode shift has been estimated to moderate traffic congestion, increase utilitarian physical activity, and reduce greenhouse gas emissions (Aftabuzzaman et al., 2010; Rabl and De Nazelle, 2012; Rojas-Rueda et al., 2012). This study brings attention to the need for future research exploring the separate effects of individual micro-scale built environment features surrounding stations on ridership, as well as potential interactions among features and between features and other characteristics (e.g., local policies).

4.3. Study limitations and future work

The cross-sectional study design allows for correlative, not causal, relationships to be determined between micro-scale built environment features and daily LRT ridership. A second study limitation is data were not collected at the same time, with environmental audit data collected from May through July 2014, and ridership data collected from January 2014 through December 2017. This temporal mismatch of data may have resulted in assessment of environmental conditions that varied from the actual conditions during the selected ridership period. Another concern is research staff did not audit all street segments within the 0.25-mile buffer for each LRT station, due to budget and time restraints of the Houston TRAIN Study. Study staff deemed the 35.7% coverage of street segments for each LRT station to be generally acceptable (Oluyomi et al., 2019), with full coverage of street segments within the 0.25-mile buffer being impractical. An additional concern was one auditor conducted the environmental audit per street segment, which may introduce measurement errors. The potential for errors from this lack of inter-rater reliability may have been moderated by
In this study, we hypothesized that categories of micro-scale built environment features that promote walking and cycling were associated with average daily LRT ridership, but features within these categories may be insignificant to those individuals who choose other modes, such as motor vehicles, to reach their stop or destination. In the United States, 11% of transit users drive to their transit stop, and 4% drive to their destination after disembarking public transit (American Public Transportation Association, 2017). Researchers have found that individuals with access to private vehicles had increased probability of driving and parking when connecting to light rail, and crime at LRT stations was associated with females being more likely to be picked up and dropped off at stations (Kim et al., 2007). However, a systematic review and meta-analysis found no evidence of an association between personal safety from crime and active transportation (Cerin et al., 2017). To better understand the choice of travel mode to and from LRT stations, future work can measure the availability of public parking at LRT stations, estimate the mode choice through surveys or observations at LRT stations, and update the audit instrument to include items about personal safety from crime such as those found in the Pedestrian Environmental Data Scan (PEDES) instrument (Clifton et al., 2007).

Regarding measurement of micro-scale built environment features, in particular those features within the Social Environment and Aesthetics categories, this study was limited by “point in time” observational data collection for the Analytic Audit Tool. The number of individuals visible on street segments and the amount of noise pollution, for example, may vary by time of day. When predicting the association between daily LRT ridership and categories of micro-scale built environment features, we chose to equally weight all of the micro-scale built environment features, rather than assigning weights that reflect the magnitude of association on LRT ridership. Within the Land Use Environment category, for instance, the presence of office buildings and automobile repair shops were weighted the same, even though these land uses may have different levels of association with LRT ridership. The rationale for equal weighting of features was based on the literature not yet providing sufficient evidence of the magnitude of association for the many features in the study. Future research can focus on assigning weights to these features.

Lastly, we lacked access to sociodemographic data of LRT riders, which prevented us from investigating equity issues around whether categories of micro-scale built environment features exhibited different associations, based on the sex, age, race, ethnicity, and income level of transit riders. Future work can explore these associations, along with the association of categories of micro-scale built environment features on physical activity patterns.

5. Conclusions

This study is the first extensive assessment of the association between micro-scale built environment features surrounding LRT stations and daily LRT ridership at the stop level. The use of the validated Analytic Audit Tool to measure built environment features of the street segments surrounding stations allows for improved spatial resolution in capturing the experience of individuals over previously employed strategies that measured macro-scale built environment features and walkability indices. The packaging of 58 built environment features into six distinct categories provides a higher-level understanding of how dimensions of the environment relate to public transportation use. This study can serve as a basis for assessment of the effect magnitude of micro-scale built environment features on transit ridership, and of the influence of built environment features on different population groups. Study results can assist practitioners with making informed investment decisions for promoting use of light rail systems, in particular the financing of improvements to transportation infrastructure and the social environment surrounding LRT stations. As Americans struggle to gain automobile independence and reach healthy levels of physical activity, the need to incentivize active travel modes, such as light rail, cannot be understated.

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CRediT authorship contribution statement

Kevin Lanza: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization. Abiodun Oluymomi: Conceptualization, Methodology, Validation, Data curation, Writing - review & editing, Project administration. Casey Durand: Conceptualization, Methodology, Writing - review & editing, Project administration. Kelley Pettee Gabriel: Writing - review & editing, Project administration. Gregory Knell: Writing - review & editing, Project administration. Deanna M. Hoelscher: Writing - review & editing, Supervision, Project administration. Nalini Ranjit: Methodology, Writing - review & editing. Deborah Salvo: Writing - review & editing, Project administration. Timothy J. Walker: Writing - review & editing, Project administration. Harold W. Kohl: Writing - review & editing, Supervision, Project administration, Funding acquisition.
Appendix. Station-level descriptive statistics on light rail transit ridership (January 2014–December 2017) and the environment surrounding 22 Houston METRORail stations (May–July 2014)

| Light Rail Line (Service Area) | Light Rail Transit Station Name | Daily Weekday Ridership (#) | Daily Weekend Ridership (#) | Audited Street Segments (#) | Composite Index Scores for Categories of Micro-Scale Built Environment Features (1.0–7.0) | References |
|--------------------------------|--------------------------------|-----------------------------|-----------------------------|----------------------------|--------------------------------------------------------------------------------|------------|
| Red (North)                    | Burnett Station                | 1048.9 (82.2)               | 142.9 (32.3)                | 27                         | 2.8 3.4 1.0 4.1 2.9 3.4                                                      |            |
|                                | Cavalcade                      | 344.8 (28.3)                | 230.5 (24.4)                | 36                         | 2.9 3.3 1.0 4.0 2.7 2.4                                                      |            |
|                                | Fulton/North Central           | 704.3 (120.5)               | 446.3 (56.0)                | 26                         | 3.2 3.7 1.0 4.1 2.6 3.4                                                      |            |
|                                | Lindale Park                   | 127.9 (12.4)                | 79.8 (12.0)                 | 34                         | 2.8 3.2 1.0 5.1 2.7 2.7                                                      |            |
|                                | Melbourne/North Lindale        | 319.9 (54.0)                | 215.7 (52.3)                | 26                         | 3.0 3.4 1.3 4.3 3.0 3.3                                                      |            |
|                                | Moody Park                     | 295.1 (142.5)               | 191.6 (29.1)                | 33                         | 2.8 3.2 2.0 4.1 2.7 3.3                                                      |            |
|                                | Northline Transit Center/Houston Community College | 1318.4 (227.4) | 961.3 (91.8) | 28 | 2.9 3.6 1.7 3.9 2.6 3.6 | |    |
| Purple (Southeast)             | Quilman/Near Northside         | 716.3 (109.2)               | 508.8 (61.3)                | 32                         | 2.8 4.2 1.0 3.9 3.0 3.0                                                      |            |
|                                | Elgin/Third Ward               | 286.9 (58.5)                | 230.2 (35.9)                | 22                         | 2.6 3.4 1.0 3.6 3.0 3.0                                                      |            |
| 3.1                            | Leeland/Third Ward             | 132.9 (14.1)                | 103.4 (14.3)                | 14                         | 2.9 4.0 1.0 3.9 2.7 2.6                                                      |            |
|                                | MacGregor Park/ Martin Luther King, Jr. | 227.4 (57.9) | 150.7 (21.0) | 25 | 3.2 4.0 2.0 5.1 2.9 3.6 | |    |
|                                | Palm Center Transit Center     | 510.8 (131.9)               | 391.2 (173.0)               | 35                         | 2.8 3.5 1.0 4.5 2.6 3.3                                                      |            |
|                                | University of Houston Oaks     | 303.6 (117.0)               | 151.6 (60.7)                | 20                         | 2.9 3.8 1.7 5.0 3.0 3.0                                                      |            |
| Green (East End)               | Altic/Howard Hughes           | 429.8 (74.3)                | 327.8 (81.7)                | 22                         | 2.7 3.8 1.0 4.1 2.6 2.4                                                      |            |
|                                | Coffee Plant/Second Ward       | 170.5 (35.3)                | 132.3 (29.5)                | 31                         | 2.6 3.6 1.0 3.8 2.9 2.7                                                      |            |
|                                | Lockwood/Eastwood             | 437.3 (177.1)               | 261.9 (84.9)                | 25                         | 2.7 3.6 1.0 3.9 2.6 3.1                                                      |            |
|                                | Cesar Chavez/67th Street       | 240.1 (19.2)                | 190.8 (16.7)                | 25                         | 3.0 3.5 1.0 3.3 2.9 3.1                                                      |            |
|                                | Magnolia Park Transit Center   | 855.4 (61.5)                | 572.3 (39.6)                | 11                         | 3.0 4.4 1.0 3.5 3.4 3.7                                                      |            |
| Purple/Green                   | East Downtown/Stadium Convention Center | 690.6 (90.9) | 639.2 (76.7) | 29 | 2.4 4.3 1.0 3.3 3.0 2.9 | |    |
|                                | Convention District            | 300.3 (76.6)                | 344.4 (128.2)               | 29                         | 2.8 4.5 1.0 3.6 3.4 3.3                                                      |            |
|                                | Theater District              | 608.2 (128.8)               | 328.9 (34.6)                | 29                         | 3.3 4.8 1.7 5.4 4.1 4.7                                                      |            |
| Red/Purple/Green              | Central Station               | 1510.4 (312.7)              | 1052.4 (167.3)              | 31                         | 3.4 4.5 1.0 4.6 2.9 3.6                                                      |            |

Composite index scores for an environmental category are the average of composite index scores for micro-scale built environment features within that category. Scores range from 1.0 to 7.0 with higher scores signifying more physical activity-promoting, micro-scale built environment features surrounding light rail transit stations.

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