‘Listening’ to urban form characteristics in transit-oriented developments (TODs)

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Revised version received 18 May 2021

Abstract. *Understanding the relationship between urban form and sound is important for managing the adverse implications of noise. This study explores the nexus between urban form characteristics – namely buildings, plots, and streets – and sound, within the Dallas-Fort Worth Metroplex. It focuses on transit-oriented developments (TODs), which are emerging urban forms adjacent to transit stations. Previous studies have examined various aspects of TODs, including the neighbourhood design and transportation services, but have not investigated the impact of urban form on sound within TODs. This paper probes that concept and provides recommendations for urban design practice related to sound and urban form characteristics.*

Keywords: urban form, sound, noise, transit-oriented developments (TODs), Dallas-Fort Worth Metroplex

The characteristics of urban forms have been investigated across numerous fields because of their potential to address quality of life concerns globally. Playing a vital role in urban environments, urban morphology seeks to understand spatial aspects, including connections, components, and interactions within cities. In terms of interactions, the characteristics of building density and pattern, street layout and land use have been widely studied using various methods (Xie *et al.*, 2006). However, increased vehicle miles traveled and more dispersed urban settlements have made it even more imperative for urban designers to promote walkable environments and public transportation. A nexus between urban morphology and transportation systems has emerged both theoretically and practically.

https://doi.org/10.51347/UM25.0011
Urban Morphology (2021) 25(2), 151–72 ISSN 1027–4278

Concepts addressing this connection include new urbanism (Scheer, 2008) and transit-oriented development (TOD), a compact and walkable urban form with a concentration of well-connected neighbourhoods surrounding multi-modal transit stops (Bertolini *et al*., 2012; Stojanovski, 2019). While many studies have examined TODs in various aspects, the concept primarily incorporates complex built-environment configurations including train stations, their surrounding connections, and elevation changes of streets as well as competing land uses for ideal TOD settlements. These circumstances present challenges of accessibility and connectivity for developing optimal urban forms. These factors also hinder achieving the core TOD attributes such as neighbourhood facilities and densities, as the elevation of train stations and freeways adjacent to train stations may impede the robustness of TODs. Such complications of limited place and transportation-related aspects lead to concerns about air and noise pollution. The implication of noise is an under-explored concept within urban morphology. Considering the broad scope of the topic, this paper revisits the fundamentals of urban form elements applied to the sound environment while considering urban design implications. It examines the essential characteristics of urban morphology in relation to sound aspects in the context of TOD urban forms.

The development of urban morphology has been examined alongside the study of land use (Relph, 1987), culture (Conzen, 1996), urban design (Moudon, 1986), and neighbourhood (Scheer and Scheer, 1998; Patricios, 2002). Given the extensive scholarly discussion regarding definitions of urban morphology and urban form and their interdisciplinary complexity, along with the scales of application ranging from the building level to the regional scale, there is no broad consensus for any one definition. Even though the terms 'urban morphology' and 'urban form' are sometimes (and inappropriately) interchangeably used, demarcation of urban form has essentially become a separate field, particularly in recent decades in the U.S. (Muller, 1995; Warner and Whittemore, 2013).

The literature proposes key characteristics such as buildings, façades and streets as various components of understanding urban forms; however, this proposition does not lead to a conceptual recognition of the full morphological content, and far less to any systematic investigation of morphology as a spatial configuration of the buildings, plots and streets. Such characteristics are almost forgotten elements in the U.S. for urban design practice, as small-scale urban design approaches – including new urbanist developments and TODs – concentrate on high-resolution architecture and profitable developments (Scheer, 2008). To draw attention from the urban morphology aspect, this research investigates the building, plot and street layout within TODs as they include spatially delineated urban form characteristics.

TODs aim to bring residents closer to transit facilities and improve quality of life by reducing personal vehicle use, increasing mass transit ridership and promoting a sense of community. Reducing private vehicle use decreases transportation costs for societies, lowers vehicle emissions and enhances local amenities, in addition to promoting walking and cycling. Further, the mixed-use and compact urban form aspects of TODs have additional cultural, recreational and health-related benefits relating to public spaces such as plazas, parks, gardens and playgrounds for diverse age groups (Curtis *et al*., 2009). While TODs offer these benefits of multi-modal transportation and neighbourhood amenities, sound remains one of the most under-explored features of TODs and urban morphology. To the authors' best knowledge, there is no study that has explored the association between urban morphology, TODs and sounds. To fill this gap in the literature, this research explores the urban form features of TODs and their relationships to sound.

The research questions to be explored here are whether the characteristics of urban morphology – buildings, plots, and streets – affect and/or create patterns for sounds and how this research could improve urban design practice through the examination of sound from urban morphological aspects. Through answering these questions, the study seeks to address gaps in the urban morphology literature and develops a methodology for identifying sound in selected TODs.

Previous studies

Reviewing urban morphology

American urban patterns generally originated from a ‘soft’ European architectural style, attempting to enhance the developments of technological and social transformations concurrently through the approach of American circumstances (Pierson, 1970). According to Conzen (1978), the concept of urban morphology emerged after the 1930s to demonstrate a functional spatial structure, as the urban form discussion had been limited to societal and economic perspectives before that time. Moreover, the Chicago School pioneered by Ernest Burgess and Homer Hoyt contributes to teaching and research in urban morphology, particularly in the U.S., although such approaches receive criticism for the lack of concentration on physical aspects (Larkham and Conzen, 2014).

Considering the physical settlement of American neighbourhoods, as Conzen (2001) highlighted, Moudon’s building-scale study was a fundamental analysis of traditional American form (Moudon, 1982). Moudon (1986) examined residential building types in a neighbourhood in San Francisco by applying building typologies relating to local architectural history, finding significant variations between the spatial structure of residences built in the 1920s and those built in the 1960s. In another study, Ryan (2006) examined morphological transformations in Detroit between 1951 and 2000. Six housing redevelopments from the 1990s were compared with former developments on the same sites in 1951. The later developments were significantly different in design, having abandoned several pedestrian access ways and public spaces. Schmiedeler’s assessment of town forms in Minnesota and Iowa (2007) discussed spatial meanings for Midwestern urbanization, finding that railroads held the potential to shape urban form. However, these studies are based upon empirical approaches and there are also conceptual attributes, rather than based on a region-specific context, as was Marshall and Calıskan’s (2011) urban morphology-based approach in terms of explanatory and diagnostic aspects. Marshall and Calıskan adopted several methods for identifying elements, types, and patterns of urban form that apply as design units for further design interventions.

While several studies have contributed to the context of urban morphology in the U.S., scholars emphasized how small-scale architectural decisions inaugurated urban design approaches based on land use (Scheer, 2008), such as new urbanism and transit-oriented development. A further examination of characteristics relevant to TODs is warranted.

Characteristics of TODs

TODs are not a new phenomenon in the United States; however, they have experienced major advances in recent decades as transit services continue to grow not only in facilitating mobility but also in promoting better communities and in utilizing enhanced technology (Curtis *et al*., 2009). TOD projects utilize urban planning and design strategies, including multi-modal transportation, mixed-use activities and public space hierarchies. Although several researchers have explored the relationship between urban design and TODs, their projected implications fall short regarding sound and urban morphology outcomes (Calthorpe, 1993; Ewing and Bartholomew, 2013; Jacobson and Forsyth, 2008).

Advocates of TOD, however, emphasize that TODs have positive effects through design-related aspects and the promotion of active living, although equity and inclusivity issues, air quality and sound remain problematic. TODs aim to create functional and healthy places for people in conjunction with transportation facilities, which requires changes to urban forms including increased average density. Thus factors such as air quality and sound also affect the quality of life in TODs (Kimball *et al*., 2013). Sound can become particularly problematic when it is generated by transit services, and this can adversely affect residents.

TODs, urban morphology and urban design

Despite the challenge of having ample literature on urban morphology and TODs, few studies have investigated case-specific features of TODs in the urban morphology context. The node-place model is perhaps the foremost urban morphological description of TODs in the literature (Bertolini, 1999). Based on this framework, the node refers to the transit station, while the place represents the surrounding area. The model simply provides an urban morphological interpretation for the dynamics of TODs from two aspects: enhanced transport facilities and increased heterogeneity and densification of land use. This transformation between transportation and land use also results in further urban morphological changes. Therefore, TODs include a twofold urban morphological connotation – they are both transport facilities and places for individuals to live, work, socialise, recreate and shop (Bertolini, 1999; Li *et al*., 2019). The node-place model includes five categories. The first is the dependence category, in which transportation facilities as well as land use are underdeveloped even though they may both have the potential for growth. Another category is stress, where transport and land use are both overdeveloped and there is strong competition for locations. The balanced category is the most desired for a TOD as transportation facilities and land use are coordinated and integrated appropriately, resulting in benefits for both. The remaining two categories are unbalanced node and unbalanced place. While transportation facilities overwhelm land use developments in an unbalanced node, land-use developments dominate transportation facilities in the unbalanced place.

Several studies have proposed various index and typology-related measurements based on Bertolini's model (Atkinson-Palombo and Kuby, 2011; Kamruzzaman *et al*., 2014; Lyu *et al*., 2016). The literature explores the node-place model in terms of transportation and urban planning in numerous regions (Vale, 2015; Wegener, 2004) but has not examined the urban morphological interrelations between transportation, land use and sound.

As Kong and Pojani (2017) highlighted, TODs seek to harmonize transit facilities, compact urban form, dense population, and public spaces. In a recent study, Stojanovski conducted a series of observations and analyses of TODs in nine selected locations in Sweden, finding that commercialization of the TOD occurred up to 100 m away from transit stops (Stojanovski, 2019). While he highlighted the overall final form of TODs, the process of this emergence might be more important to examine. Loukaitou-Sideris *et al*. (2013) investigated 14 elevated and freeway-median light rail stations in Los Angeles from an urban design implementation aspect; they called for a better investigation of two-dimensional plans amongst transportation facilities in terms of urban design.

Extending TOD attributes through sound

While numerous studies discuss urban morphology features (Lyu *et al*., 2016; Wegener, 2004), this research develops a node-place sound model of TOD urban form characteristics. This study, therefore, extends the study of TODs through incorporating the 'sound' dimension. Sound propagation in urban built environments is significantly influenced by urban characteristics. King *et al*. (2013) compared residential areas with mixed-use areas, showing that residential areas had lower sound levels. Similarly, Baloye and Palamuleni (2015) investigated four main land-use categories – residential, commercial, transportation, and educational – in Nigeria. Their findings supported the argument that residential and educational facilities have the quietest land uses. Yildirim *et al.* (2020) investigated the building-related attributes as well as neighbourhood factors on sound levels, demonstrating that the buildings within

TODs are subject to experiencing a noisy environment as well as overall TOD environments (Yildirim and Arefi, 2021a). Yildirim and Arefi (2021b) also examined new urbanist developments and they, too, are exposed to higher sound levels.

On the other hand, TODs may also create high noise levels due to conflicts between transportation, land use, and built environment, especially in a context lacking good urban design. Various morphological parameters, including buildings, roads, and green areas have been examined in terms of how these features characterize sounds in urban forms (Margaritis and Kang, 2017; Wang and Kang, 2011). Noland *et al*. (2014), from a negative externality aspect, calculated the costs associated with noise in Jersey City based on a scenario case, in which the total daily TOD benefits were approximately $20,000 to the city and the diseconomy for noise was $14. Furthermore, decreased vehicle numbers correlate with lower sound levels. Investigating traffic noise from different types of vehicles in urban communities in San Francisco, Seto *et al*. (2007) showed that enhancing walking, biking, car sharing, public transit and home-office working contribute to reduced urban noise and improve quality of life. However, these studies have primarily been limited to specific contexts of sound levels, which may not represent all types of urban form features. In another study, Renne (2009) explored the opinions of TOD residents on sound as an urban design indicator. More than 40 per cent of participants considered TODs to be noisy locations, while 38 per cent believed that they were quiet, representing a fairly even distribution of opinions about sound in TODs.

Adding elements of an urban form framework to the study of the TOD concept opens up a wealth of prospective comparative data, analyses and methodologies, with the potential to generate a deeper understanding of present and future developments. However, given that the literature is primarily focused on streets, building density and façade-related performance sound assessments, very little attention has been given to a systematic understanding of buildings, plots and streets and their cumulative impacts on sound. Therefore, it is necessary to provide a comprehensive study methodology on the relationships between urban morphology elements and sound.

Study method

The study was conducted in the Dallas-Fort Worth region, owing to the rapid growth of the region in terms of population and development. After unifying to rebrand Dallas and Fort Worth as a larger area, the region has experienced rapid urbanization and transformation of its urban form (Hanlon *et al*., 2010). The metroplex typifies the growth and prosperity of the U.S. Sunbelt since the 1970s. Gathering information from cities (Dallas, Richardson, and Plano), TOD design companies, Dallas Area Rapid Transit (DART), and TOD-related technical reports (NCTCOG), five TODs within the Dallas-Fort Worth metroplex were selected for the study: Cedars, Downtown Plano, Galatyn Park, Mockingbird and Park Lane (Figure 1).

Data collection and sampling

To extend Bertolini's (1999) node-place model to the context of sound, the study applied two main procedures to the selected TODs: examining the degree of transportation and land use integration in order to characterize each TOD in terms of sound, and further investigating urban form characteristics analytically and spatially. The literature suggests that the radius of a TOD from its station ranges from a half-mile to one and a half miles (Atkinson-Palombo and Kuby, 2011; Guerra *et al*., 2012). This study used the suggested TOD area of a half-mile radius to obtain more detailed sound samples. Data on transportation and land use integration (Figure 2) was obtained on the transit routes and stops along with the number and variety of land uses in the half-mile radius areas (Figure 2 was labelled with the top three land-use types) from DART and the North Central Texas Council of Governments (NCTCOG).

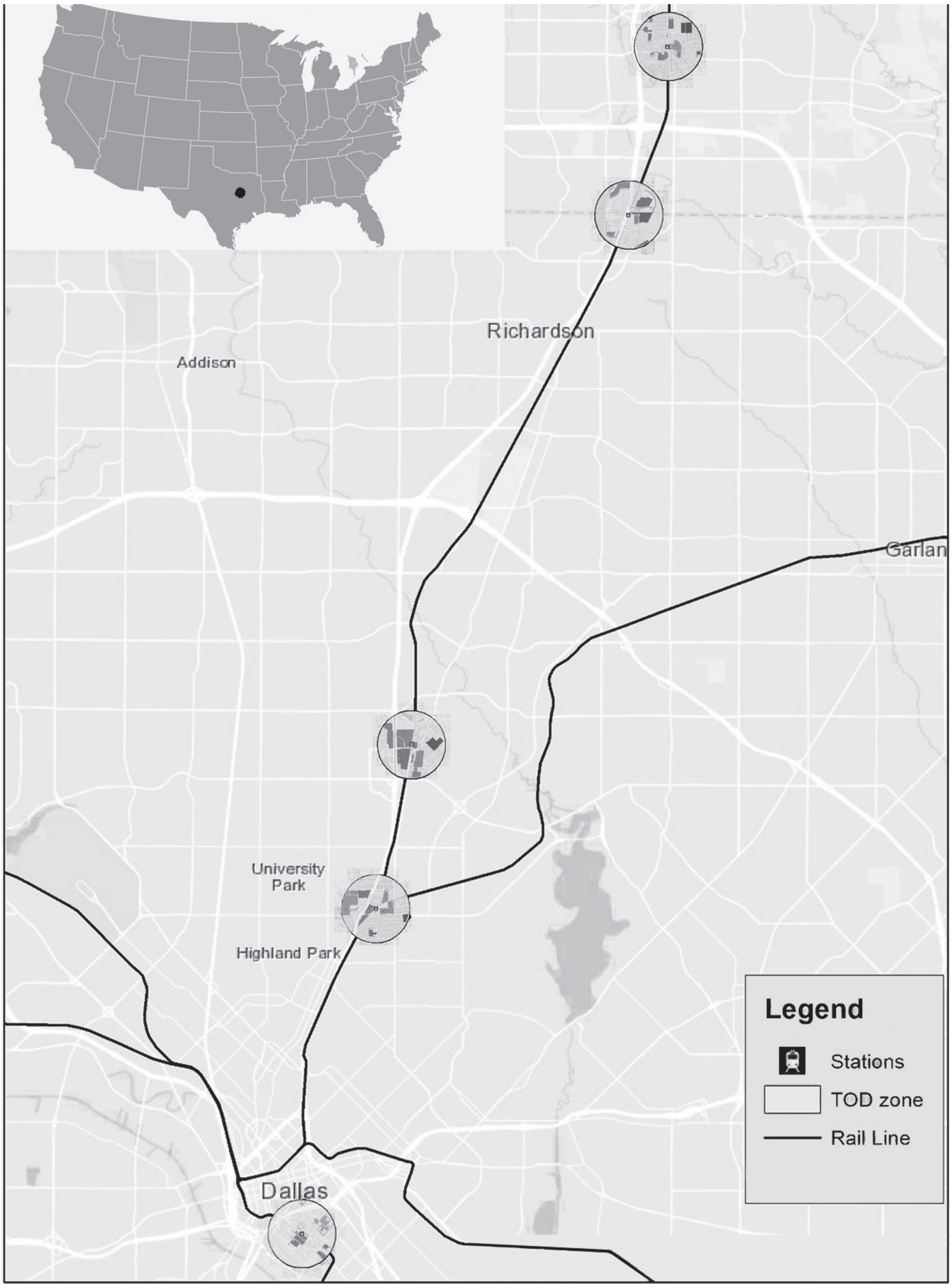
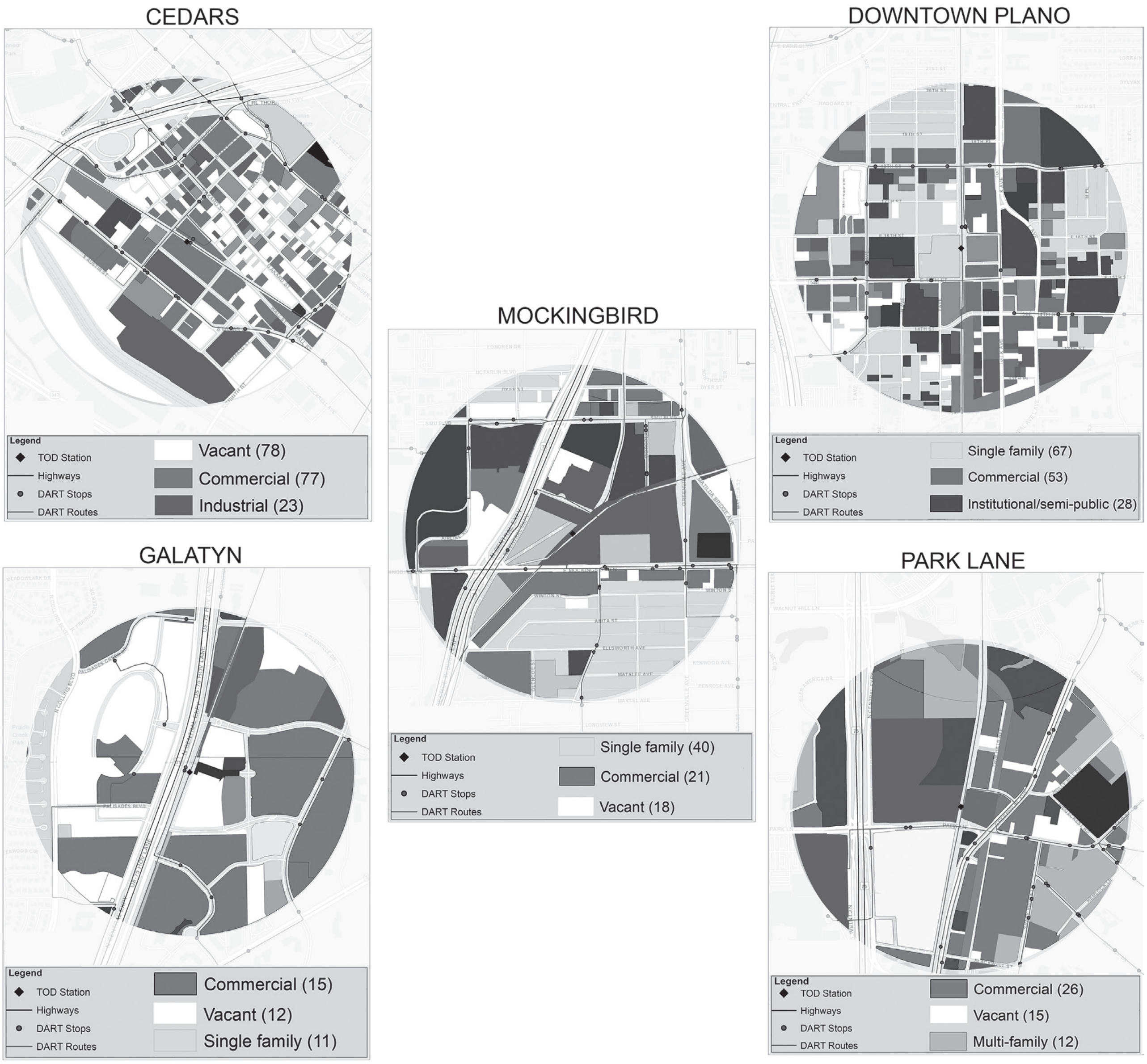


Figure 1. Study locations.

After collecting information on TODs, established techniques for the data collection on sound sampling were adapted to examine the relationship between sound and urban form characteristics. The sound sampling technique measured quantitative sound pressure levels using a method adapted from 'grid sampling' (King *et al*, 2012; Morillas *et al*., 2011). While the grid sampling method divides areas evenly into nodes on a virtual grid overlaid on a plan, this research model applied a virtual linear route to investigate buildings, plots and



Category	Cedars	Downtown Plano	Galatyn	Mockingbird	Park Lane
Number of land use types	15	16	16	14	13
Number of land uses	243	235	62	119	79
Number of transit routes	95	49	36	112	70
Number of transit stops	41	24	12	32	27

Figure 2. Morphological review of the TODs in terms of transport and land uses.

streets. Previous studies have demarcated grid lines between 300 ft (approximately 100 m) and 5000 ft (1,500 m) (Escobar *et al*., 2012; King *et al*., 2012). In this study, measurements were taken ranging from 660 ft (approximately 200 m) to 1320 ft (approximately 400 m) apart based on feasibility and avoiding obstacles such as walls and highways.

Since buildings are the smallest urban form features in the study, the researchers began

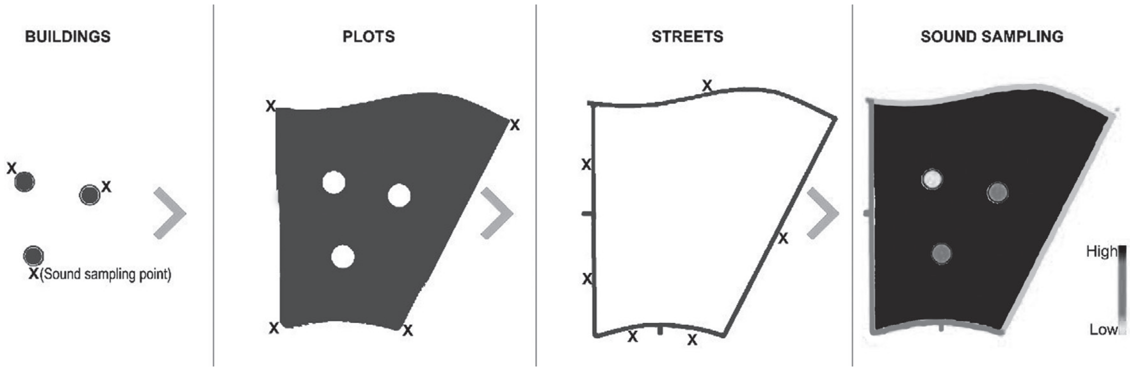


Figure 3. Sound sampling measurement approach for urban morphology characteristics.

Table 1. Sound sampling points for each TOD

	Cedars	Downtown Plano	Galatyn	Mockingbird	Park Lane	Total
Buildings	14	15	10	14	18	71
Plots	55	58	38	52	72	275
Streets	80	31	36	37	36	220

by identifying buildings. To this end, buildings within a half-mile radius of the stations were identified using an NCTCOG building database. To collect the sound samples using a standardized method, the key buildings with 25,000 or more square feet in each TOD were collected as building measurement points (Table 1). The next phase examined plots (Table 1). Sound sampling points were selected based on plots that surround and include the buildings. The sound levels were sampled from each of the plots' corner points (up to four corners) (Figure 3).

Streets were selected following the same selection criterion as plots. The sound sampling methodology, however, differed slightly different due to the linear nature of the streets (Figure 3). In order to apply a standardized approach, measurements were taken at the midpoints of streets on which the sampled buildings and plots are located (Table 1). Sound pressure level (SPL) measurement, taken at a standard 1.5 m distance from the ground, used a Landtek Instruments Professional Digital Sound Level meter 30–130 dB. All values were recorded in decibels with the A-weighting dB(A) model of SPL meter. For reference, average quiet residential areas measure at 50 dB, freeways at 70 dB, heavy traffic at 85 dB, and car horns at 110 dB sound pressure levels (Center for Hearing and Communication, 2018). Following ISO standards (ISO, 1996), Leq one-minute sample period was adopted for this research. SPL measurements were performed twice in each sampling location, on both weekdays and weekends, at the off-peak hours of 10 a.m., 1 p.m. and 4 p.m. The measurements were taken in periods that did not coincide with extreme weather conditions such as strong winds or heavy rain.

Analysis and findings

Table 2 illustrates SPL measurements for each selected building, plot, and street segment of the TODs. The buildings of the Cedars TOD had the quietest SPLs, with a mean L_{eq} of 65.3 dB(A). The buildings of Park Lane TOD had the highest sound levels, with mean L_{eq} values of 72.3. The sound measurements of plots and streets also demonstrate this pattern, with Cedars having the quietest SPLs and Park Lane having the loudest.

Table 2. Measured sound levels in TOD buildings, plots and streets

L_{eq} (dBA)		Cedars	Downtown Plano	Galatyn	Mockingbird	Park Lane
Buildings	Min	56.8	57.6	62.1	59.3	62.5
	Max	72.6	76.9	75.9	76.2	77.6
	Mean	65.3	70.5	68.4	71.0	72.3
	STD	3.91	4.08	3.04	3.58	3.55
Plots	Min	55.1	55.1	58.3	58.3	56.8
	Max	76.9	77.3	76.9	77.0	77.1
	Mean	66.0	69.8	67.8	71.1	71.6
	STD	4.31	4.37	3.52	3.51	4.05
Streets	Min	55.1	55.1	59.3	58.9	58.3
	Max	76.9	76.9	77.0	77.3	77.6
	Mean	65.4	70.0	67.9	71.5	71.6
	STD	4.08	4.24	3.31	3.53	4.31

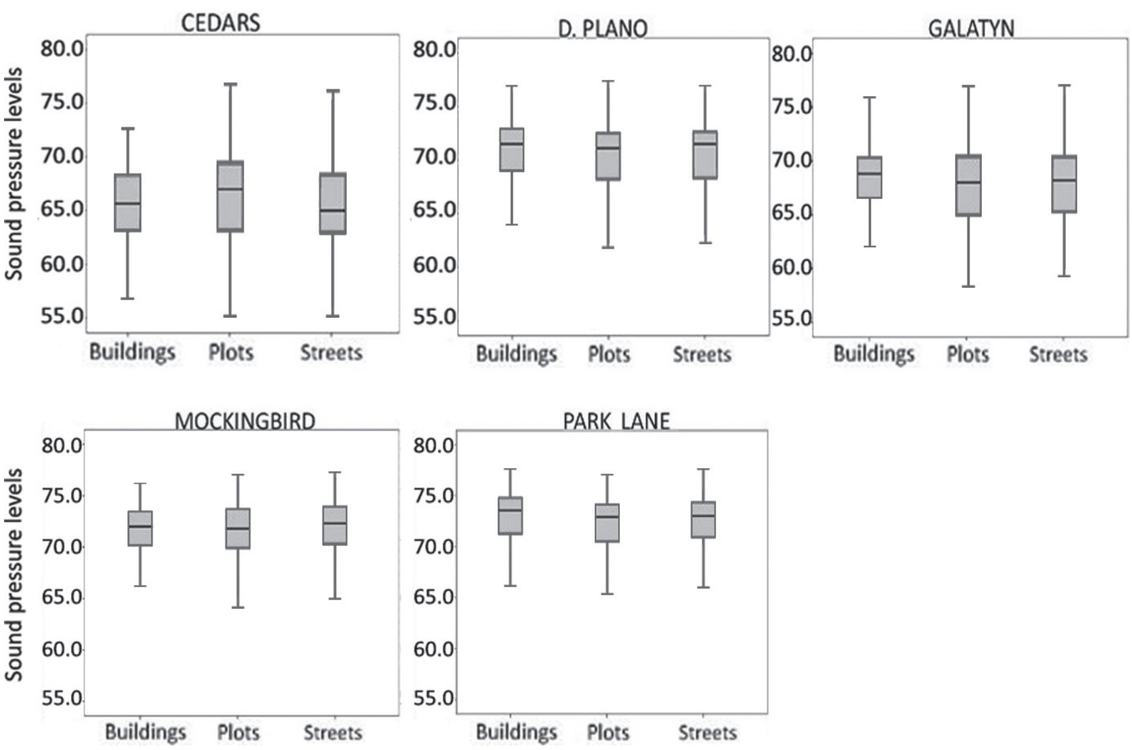


Figure 4. Sound variation for buildings, plots, and streets in TODs.

Sound variation at each TOD was also examined according to each characteristic (Figure 4). At the building level, Galatyn showed a lower sound variation (13.8 dBA difference), while Downtown Plano showed the highest (19.3 dBA). The same pattern emerged for plots, albeit with a smaller gap; Galatyn showed the lowest sound range (18.6 dBA) while Downtown Plano displayed the highest (22.2 dBA). Streets showed a similar pattern; Galatyn had the lowest range (17.7 dBA), while Downtown Plano and Cedars each produced 21.8 dBA, the highest range. When the overall means of urban form characteristics are considered, Downtown Plano and Cedars TODs show the highest sound ranges with 21.1 dBA and 19.8 dBA respectively.

Since the research aims to analyze all urban form characteristics within the selected TODs, normality of distribution was tested using the test of homogeneity of variances (Table 3). For Levene's test, which checks variances (Glen, 2020), all study locations showed a significant difference as the sound samples were not normally distributed, except for the means of Galatyn TOD. Therefore, the study followed the ANOVA method for Galatyn and the Kruskal-Wallis H test, a non-parametric procedure to test more than two factors by assuming all factors have equal distribution as the null hypothesis (McDonald, 2009), for the other measurements of TODs. From these analyses, the TODs show a significant difference with various degrees and some urban form characteristics. For instance, there is a significant difference in the Cedars TOD between streets and plots, as well as buildings and plots. However, there is no significant difference between the sound levels of buildings and streets. In addition, Downtown Plano TOD shows a significant difference in the relationship between buildings and plots. Since the test of normality of sound samples in Galatyn showed a significant level of homogeneity of variances, the data followed the ANOVA, *post hoc* test that examines which group (Allen, 2017), in this case, buildings, plots and streets, differs in terms of means (Levene's test statistic of the p-value is 0.059>0.05). Based on the results of this test, there is a significant difference between the sound of streets and plots, as well as buildings and plots. Mockingbird TOD showed a different pattern compared to other TODs and showed a significant difference between streets and plots. The sound sample comparisons of Park Lane TOD also show different patterns from the other TODs, with significant differences between streets and buildings as well as buildings and lots.

Results and discussion

This section incorporates the importance of urban form characteristics and urban design approaches in a discussion of sound implications in a TOD environment.

Urban form and the urban design of TODs

The TODs that were more balanced in terms of transport and land use integration showed higher overall sound levels compared to TODs in the unbalanced place category of Bertolini's node-place model (1999). The average overall sound levels amongst all urban form characteristics of balanced Park Lane and Mockingbird were 72.1 dBA and 71.2 dBA, respectively, while those of Cedars and Downtown Plano were 65.6 dBA and 70.2 dBA respectively. This may be due to the integration of transportation and land use producing a synergy of numerous other activities, increasing the TOD environment sounds.

Considering the urban form characteristics individually, balanced TODs – Park Lane and Mockingbird – had higher sound levels at the building scale, with 72.3 dBA and 71.0 dBA respectively. The unbalanced place TODs, Downtown Plano and Cedars, had relatively lower sound levels, with 70.5 dBA and 65.3 dBA respectively. Galatyn's TOD form is between the dependence and integrated levels, and had relatively low building sound levels of 68.5 dBA. Regarding plots, the pattern between integrated, dependence, and unbalanced place was the same, while the sound variation between integrated and unbalanced place TODs was lower. The sound levels of integrated TODs are 71.7 dBA and 71.1 dBA, while the unbalanced TODs are 69.9 dBA and 66.0 dBA. At the street level, the same pattern continues with the lower mean of sound levels for each study area. Integrated TODs include 71.7 dBA and 71.1 dBA sound levels and unbalanced TODs have 70.0 dBA and 65.4 dBA.

To illustrate how a particular configuration may help to explain the interaction between urban design and sound, the study also examined the context and scale of the urban fabric and sought to identify spatial patterns regarding sound (see Figures 5–9). Considering overall noise levels, the highest three sound level locations are depicted in the plan at the top and in street views on the left side of these Figures. The sound level measurements were

Table 3. Test results of mean comparisons in buildings, plots, and streets of TODs

		Kruskal-Wallis Test/ANOVA Test				Test of Normality/Homogeneity of Variances			
		Test Statistic / Mean Difference	**Std. Error**	**Sig.**	**Adj. Sig.**		**Statistic**	**df**	**Sig.**
Comparisons (Cedars)	Street Building	12.744	61.051	0.835	1.000	Street	.110	336	**0.000**
	Street Plot	-194.766	36.913	**0.000**	**0.000**	Building	.062	1920	**0.000**
	Building Plot	-182.022	63.083	**0.004**	**0.012**	Plot	.110	1320	**0.000**
Comparisons (Downtown Plano)	Street Building	85.535	46.262	0.064	0.193	Street	.161	360	**0.000**
	Street Plot	27.569	32.725	0.400	1.000	Building	.166	744	**0.000**
	Building Plot	113.105	42.607	**0.008**	**0.024**	Plot	.169	1392	**0.000**
Comparisons (Galatyn)	Street Building Plot	-.52382 .14399	.24654 .16041	.085 .642	-	Levene's Statistic	Df1	Df2	Sig.
	Street Plot Building	-.66781* -.14399	.24512 .16041	**.018** .642	-	2.829	2	2013	0.059
	Building Plot Building	.66781* .52382	.24512 .24654	**.018** .085	-				
Comparisons (Mockingbird)	Street Building	-92.269	45.710	0.044	0.131	Street	.160	336	**0.000**
	Street Plot	109.525	31.332	**0.000**	**0.001**	Building	.118	888	**0.000**
	Building Plot	17.256	43.863	0.694	1.000	Plot	.116	1248	**0.000**
Comparisons (Park Lane)	Street Building	127.933	51.441	**0.013**	**0.039**	Street	.165	432	**0.000**
	Street Plot	46.665	36.374	0.200	0.599	Building	.200	864	**0.000**
	Building Plot	174.598	46.959	**0.000**	**0.001**	Plot	.171	1728	**0.000**

* The mean difference is significant at the 0.05 level.

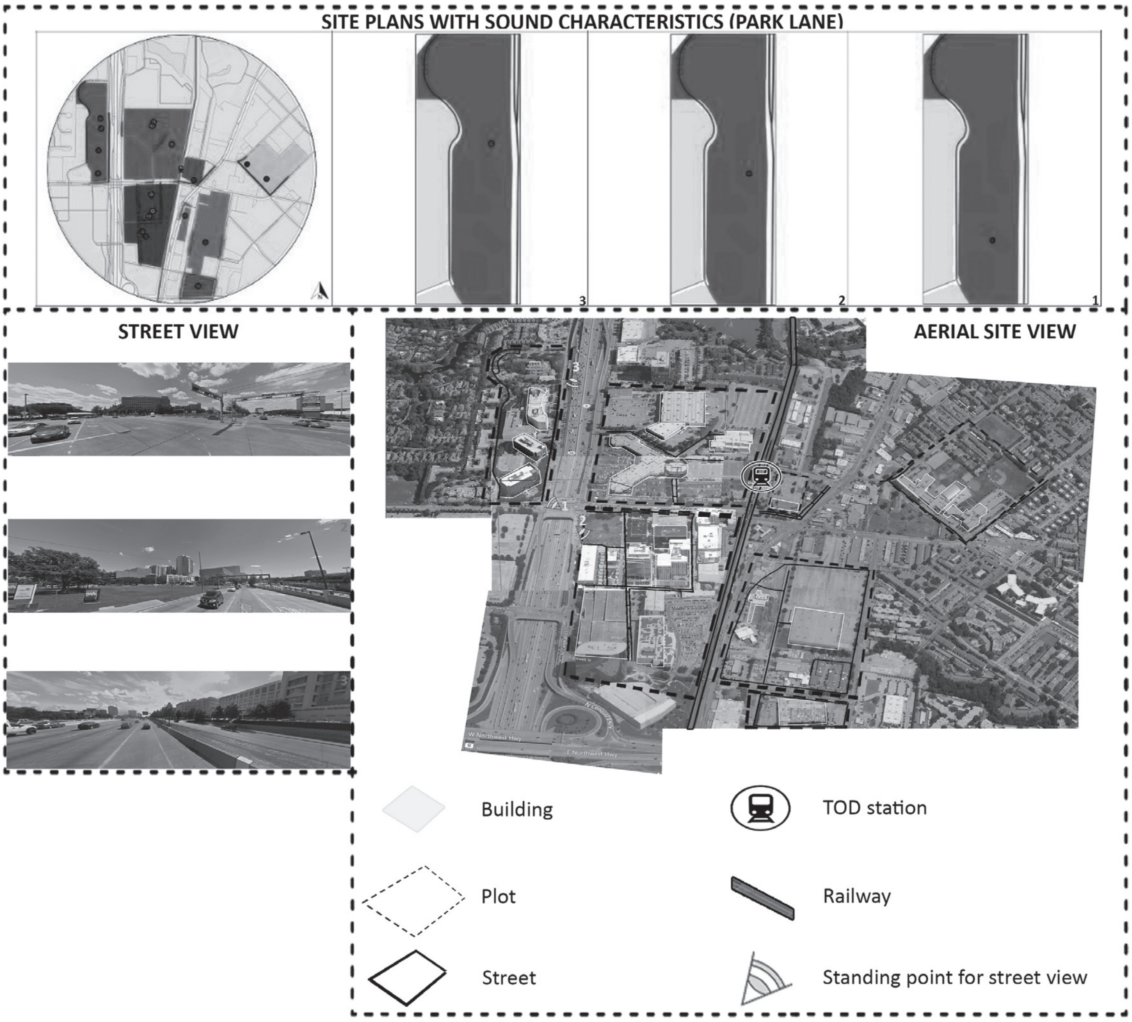


Figure 5. Images of the urban fabric with spatial sound representation (Park Lane).

analyzed and digitized based on buildings, plots, and streets using ArcMap functions. The mapping process portrays the buildings as points, the plots as polygons, and the streets as axial linear lines.

The noisiest TODs – Park Lane and Mockingbird – have stations that are elevated and below-ground (reverberation effects), respectively, as opposed to the other stations that are at ground level. This could be one reason for the production of higher sound levels. In addition to the station positioning, the width of nearby streets arguably affects sound levels, as both Park Lane and Mockingbird stations are near U.S. Central Expressway (U.S. Highway 75), a 10-lane freeway. Many study locations for Park Lane were selected between U.S. Highway 75 and the rail line corridor (Figure 5).

Mockingbird station shows similar characteristics to Park Lane except for including single-family houses and university buildings in the TOD-proximate (Figure 6). Nonetheless, the core station area includes several mixed-use buildings with retails, restaurants, entertainment options, and loft apartments.

Looking at the quietest TODs, Cedars and Galatyn, the most noticeable pattern is the existence of several vacant plots, which is reflected in a quieter acoustic environment in these TODs. While several high-rise buildings are located near the Cedars, such as South Side residential apartments on Lamar and the Dallas Police Headquarters (Figure 7), overall

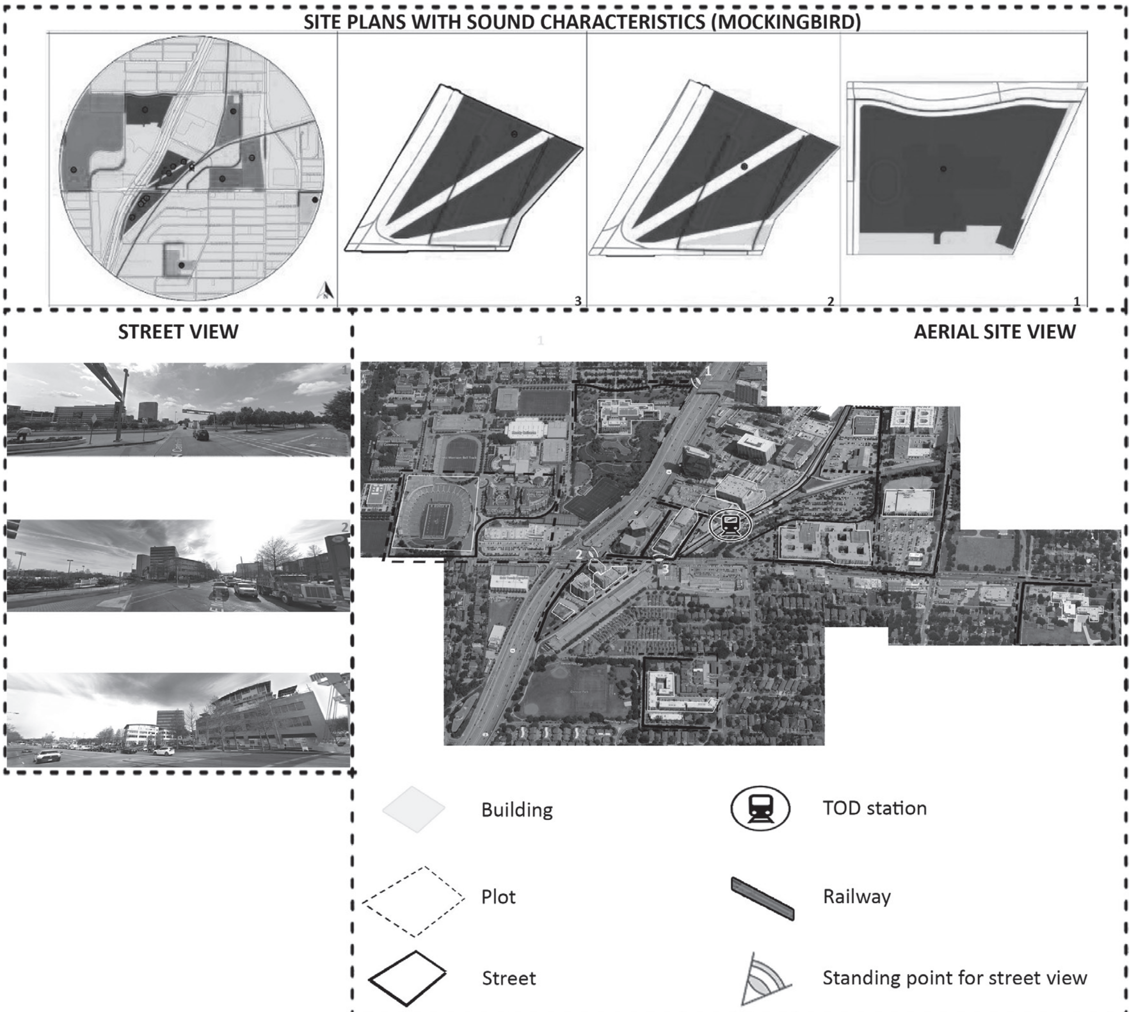


Figure 6. Images of the urban fabric with spatial sound representation (Mockingbird).

building heights are lower with single-storey single-family and commercial buildings.

Another relatively quiet TOD, Galatyn (Figure 8) also includes many vacant plots, and U.S. Highway 75 also bisects the study area. Additionally, the area includes few high-rise buildings such as the Blue Cross and Blue Shield office park and Hyatt House Hotel. This mix of urban elements has resulted in a relatively quiet acoustic environment.

Downtown Plano station can be considered as a moderate-level acoustic environment. The urban fabric of the station and surroundings is slightly different from other stations (Figure 9). Notably, the station is adjacent to the historic downtown of the City of Plano. The Plano Municipality and Police Department Buildings are located close to the station. In addition, the mixed-use Eastside Village fronts the station, with three- and four-storey buildings and a five-storey parking structure. While these developments within the grid street configuration produce a noisy environment, nearby low-rise single-family structures and public open spaces decrease the overall noise levels.

Buildings and sound levels

Since the sound sampling of the buildings is not normally distributed, the researchers performed non-parametric tests for the buildings (the Shapiro-Wilk, which checks whether

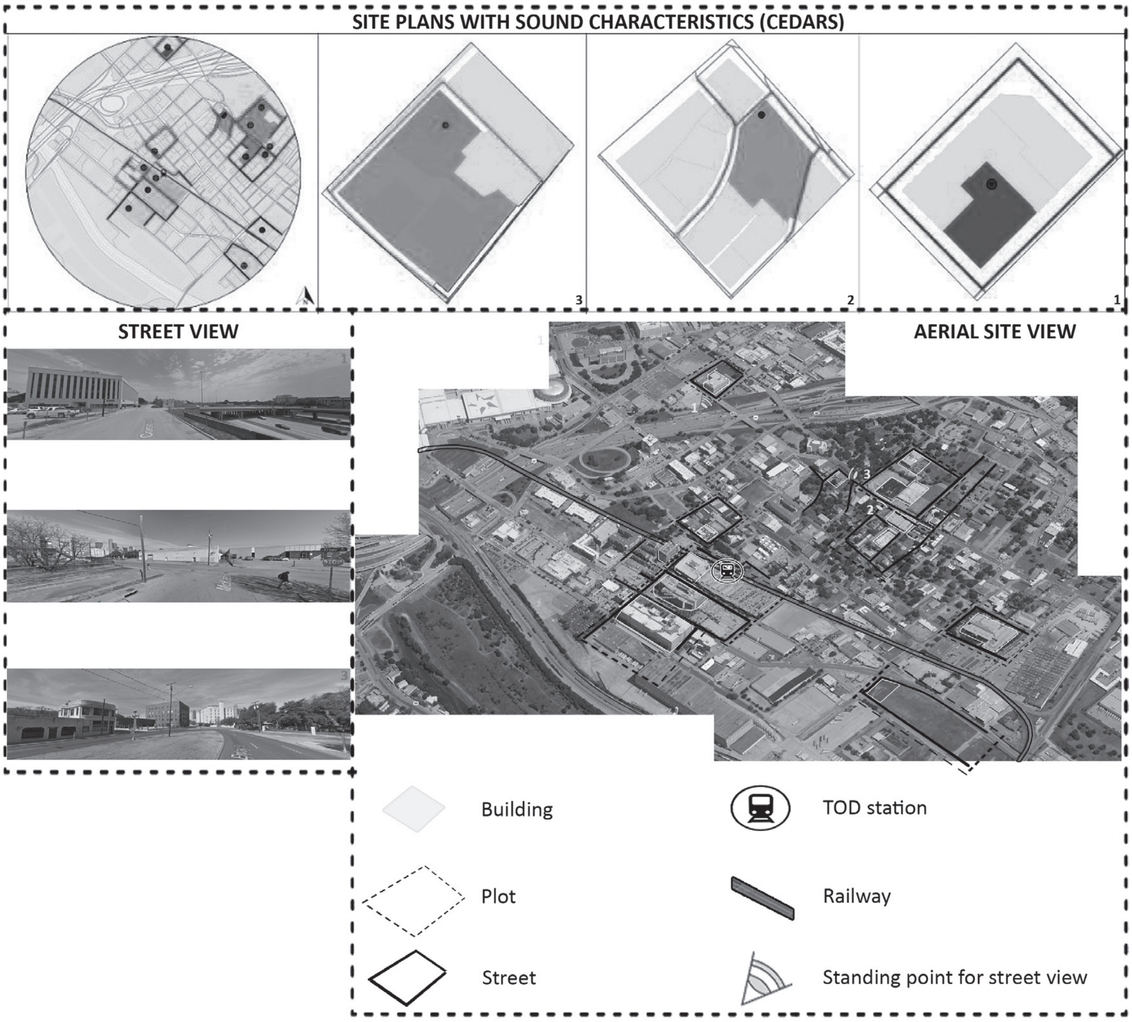


Figure 7. Images of the urban fabric with spatial sound representation (Cedars).

samples are distributed normally; the test is 0.00<0.05). As a null hypothesis, it was assumed that the distribution of sound levels would be the same among building features. After running a series of Kruskal-Wallis H tests, the statistical model showed a statistically significant difference in sound level and the building height, $\chi^2(5) = 13.628$, $p = 0.018$. Thus, building height affects the sound level – the higher the building, the greater the sound level (Figure 10A). Similarly, there is also a statistically significant difference between sound level and the building width, $\chi^2(5) = 23.855$, $p = 0.000$, which means that the wider the building, the greater the sound level (Figure 10B). The research also compared the sound levels among TODs by grouping the buildings. Considering building use (Figure 10C), all buildings were classified into four categories; apartment, business, school and other (such as police headquarters and hospital). The test also shows a statistically significant difference among building uses, $\chi^2(3) = 9.433$, $p = 0.024$. The ‘other’ category had the highest mean value followed by the business-related buildings. Based on the same analytical test, there is also a statistically significant difference among TODs, $\chi^2(4) = 26.661$, $p = 0.000$. TOD stations with the most integration of transportation and land use, Park Lane and Mockingbird, showed the highest mean ranking (Figure 10D). Perhaps this integration creates various activities that contribute to a noisy acoustic environment.

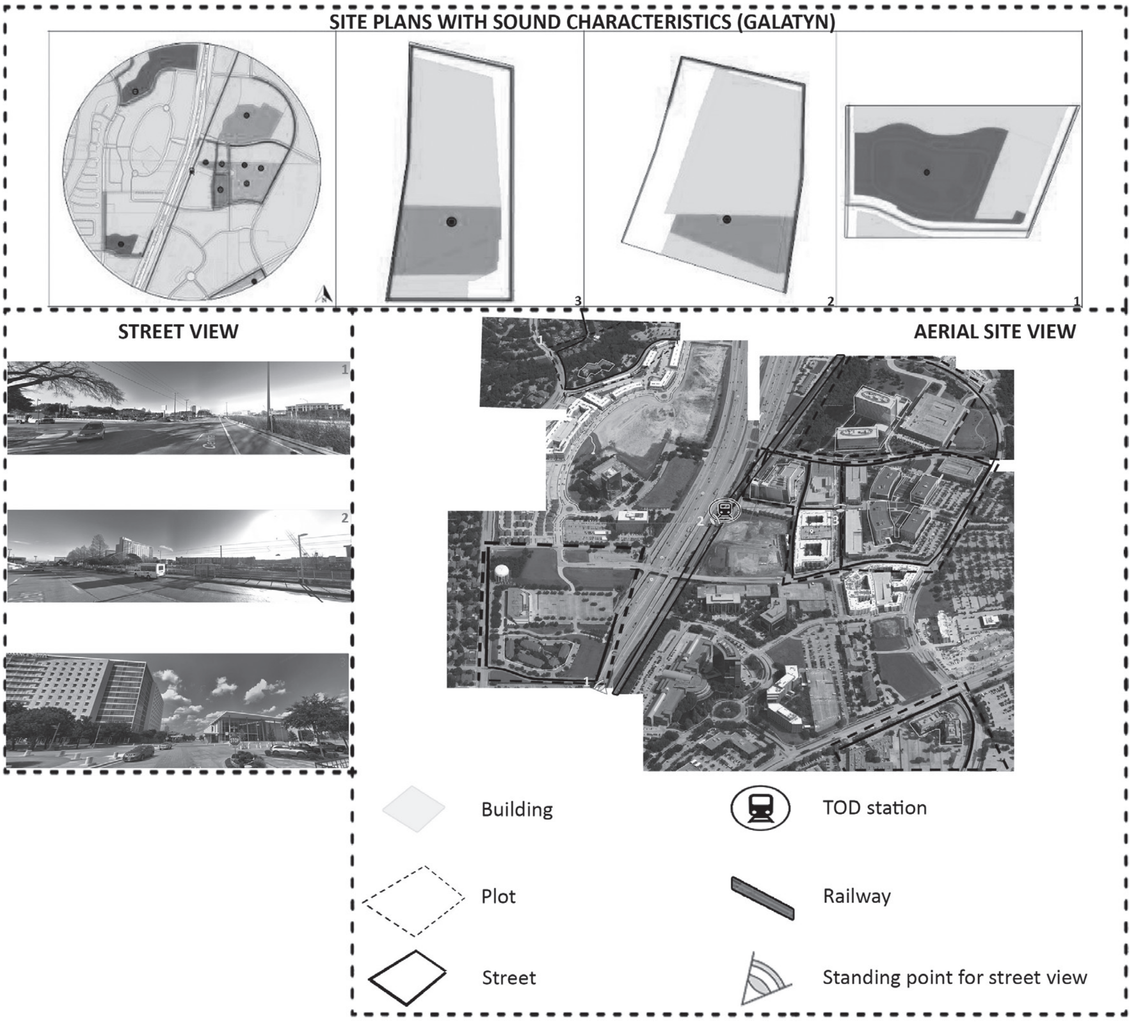


Figure 8. Images of the urban fabric with spatial sound representation (Galatyn).

Plots and sound levels

As a hypothesis, it was assumed that the distribution of sound remains the same among plot characteristics. A series of Kruskal-Wallis H tests showed that plot size does not indicate any significant difference among sound levels, $\chi^2(3) = 1.701$, $p = 0.637$. So, even though moderately sized (1.1–5.0 acres) plots and the largest plots (10.0 or more acres) have the highest mean values, this does not show any significance level (Figure 11A). There is also no significant difference in plot use and sound relationship, $\chi^2(4) = 2.899$, $p = 0.575$ (Figure 11B). The test of the relationship between sound and TOD stations shows a significant difference among TODs, $\chi^2(4) = 16.365$, $p = 0.003$. The plots of Park Lane and Mockingbird stations are the loudest while those of Cedars and Galatyn stations are the quietest (Figure 11C).

Streets and sound levels

It was hypothesised that the distribution of the sound level would not be affected by the street characteristics, which was not the case. For instance, the longer the street, the higher the sound level with Kruskal-Wallis H test indication, $\chi^2(4) = 21.065$, $p = 0.000$ (Figure 12A). Similar patterns are shown by street widths (Figure 12B), as the sound increases with increased street width, and there is a

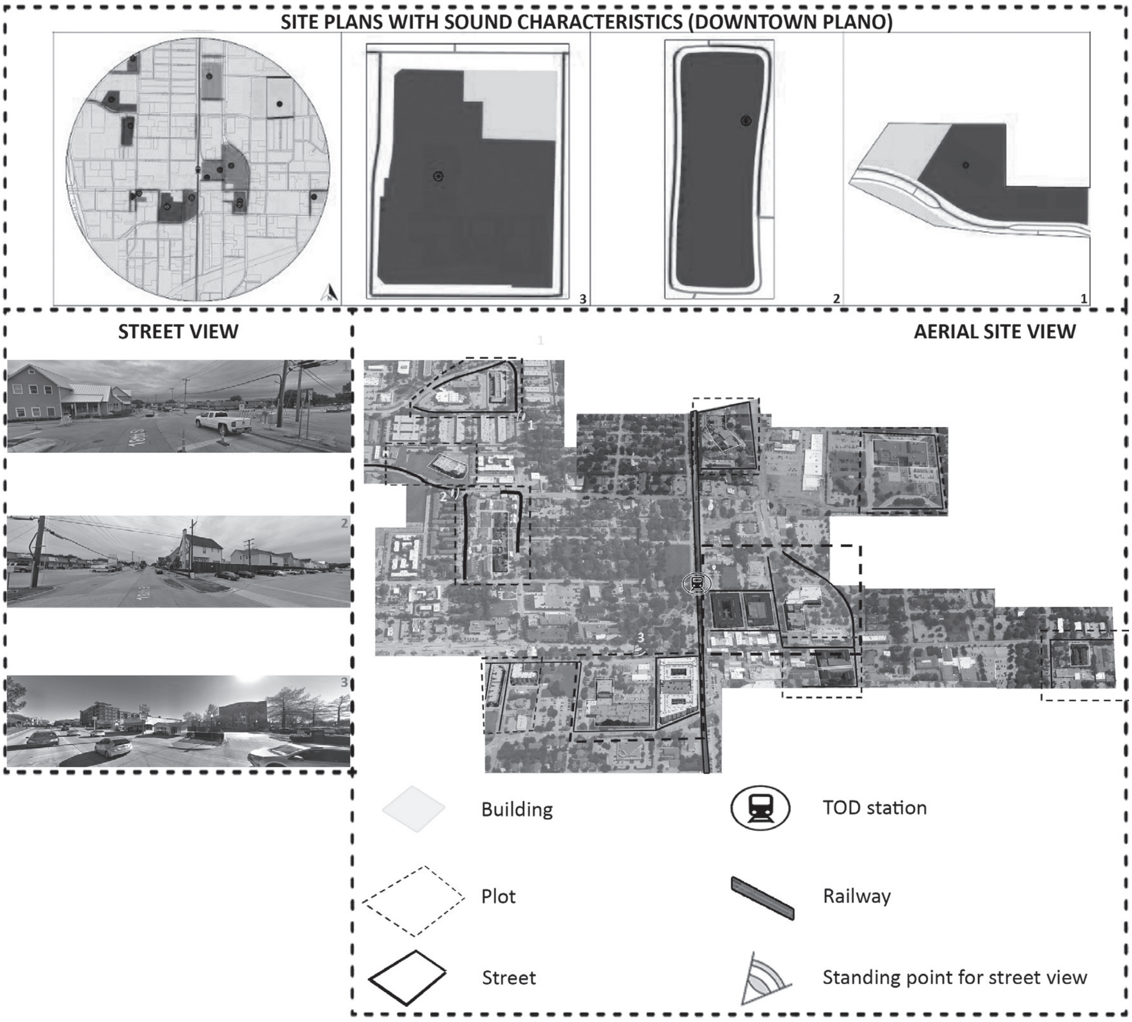


Figure 9. Images of the urban fabric with spatial sound representation (Downtown Plano).

significant difference among street widths, $\chi^2(2) = 101.688$, $p = 0.000$. The speed limits of the streets were also considered, and there is a significant difference between the speed limit and sound levels, $\chi^2(3) = 57.583$, $p = 0.000$. The pattern is very similar to street length and street width in terms of increasing speed limits corresponding to louder sound levels (Figure 12C). Finally, the sound levels of streets were assessed through clustering at the TOD level. The analysis shows a significant difference among TODs, $\chi^2(4) = 72.509$, $p = 0.000$. The sound levels of streets show a similar pattern to plots and buildings, with higher sound levels in Park Lane and Mockingbird and lower sound levels in the Cedars (Figure 12D).

Harnessing urban form characteristics to ultimately produce good urban design requires an understanding of sound. Some areas of the selected TODs included subdivisions with car-oriented urban layouts, while others were more affected by high building densities and surrounded by heavy traffic. Since the core concept of TOD attempts to offer mass transit and also to create pleasant communities for residents, this transformation becomes more challenging for sound implications, particularly within the existing car-dominated culture. The original development of these study areas gave primary consideration to vehicles, which is reflected in the big-box retail institutions, drive-through restaurants and pharmacies, strip shopping

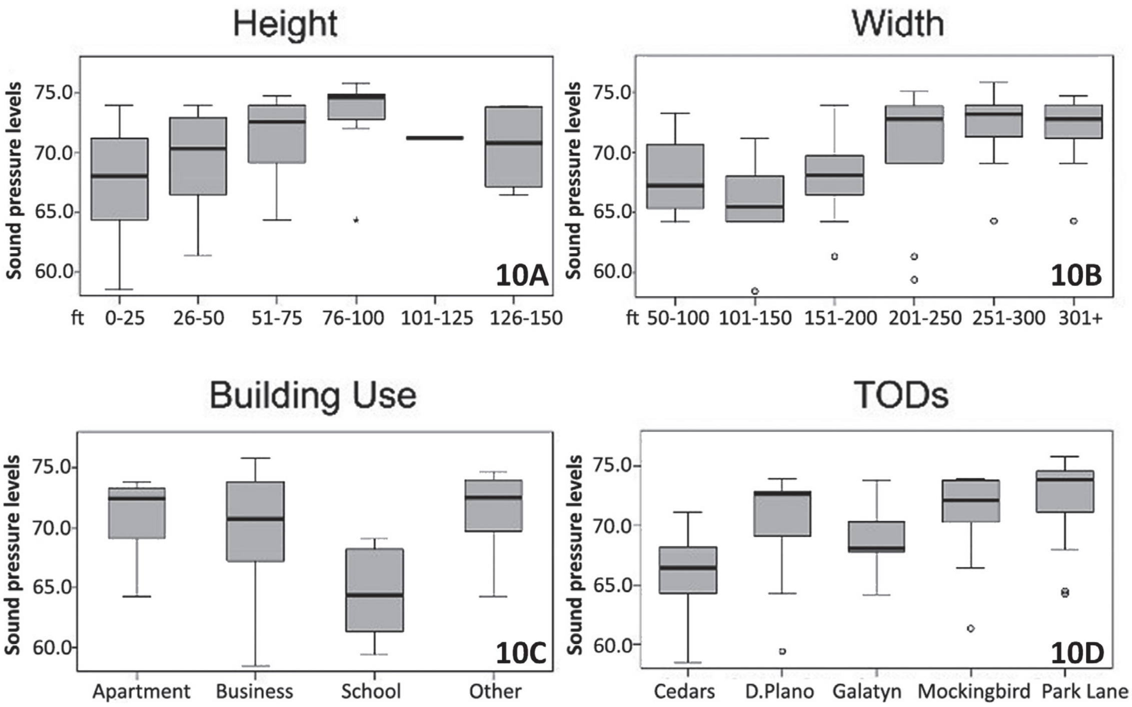


Figure 10. Building characteristics and sound level comparisons.

plazas, and large office buildings, all of which contribute to vehicle-related sounds. Many of these uses were developed with large parking lots with multiple entrances and exit points, and these building types also affect street configurations. The sheer scale of these morphological features and the traffic they generate should be considered as potential noise factors. In addition, building types such as hotels are linked to vehicle-related systems, including food, cleaning, construction, and rubbish facilities as well as customer and staff movement. Such building uses and plot configurations have a notable effect on noise levels. Medical uses and institutional buildings also generate higher sound levels. Buildings and land-use forms with dense business concentrations also increase the magnitude of sound levels, as a number of other studies demonstrate (Yu *et al*., 2010; Lu *et al*., 2014).

The arterial road street segments that serve these TODs are generally wide and winding rather than a grid layout. Since roads also carry huge amounts of traffic, including public transportation services such as buses and streetcars, they produce high sound levels. Furthermore, increased numbers of street intersections correspond to higher sound levels. On top of that, almost all noisy TODs are located adjacent to a highway. Therefore, heavy traffic circulation on TOD roads during most of the day also hinders pedestrian and bicycle activity. This illustrates a tension in TODs between automobile-dependent versus TOD-related forms, and development that supports multi-modal transportation is likely to reduce the noisy environments.

The presence of major arterials was the most significant factor affecting the spatial distribution of sound levels. This also confirms the findings of numerous other studies (Guedes *et al*., 2011, Han *et al*., 2018). Higher sound level measurements occurred adjacent to primary highways due to vehicle flow. Correspondingly, road speed limit affects sound levels, and proximity to primary highways with a speed limit higher than 40 mph resulted in noisier urban form elements compared to minor arterials with 20 and 25 mph speed limits.

Spatial arrangements of the sound level measurements for each urban form element

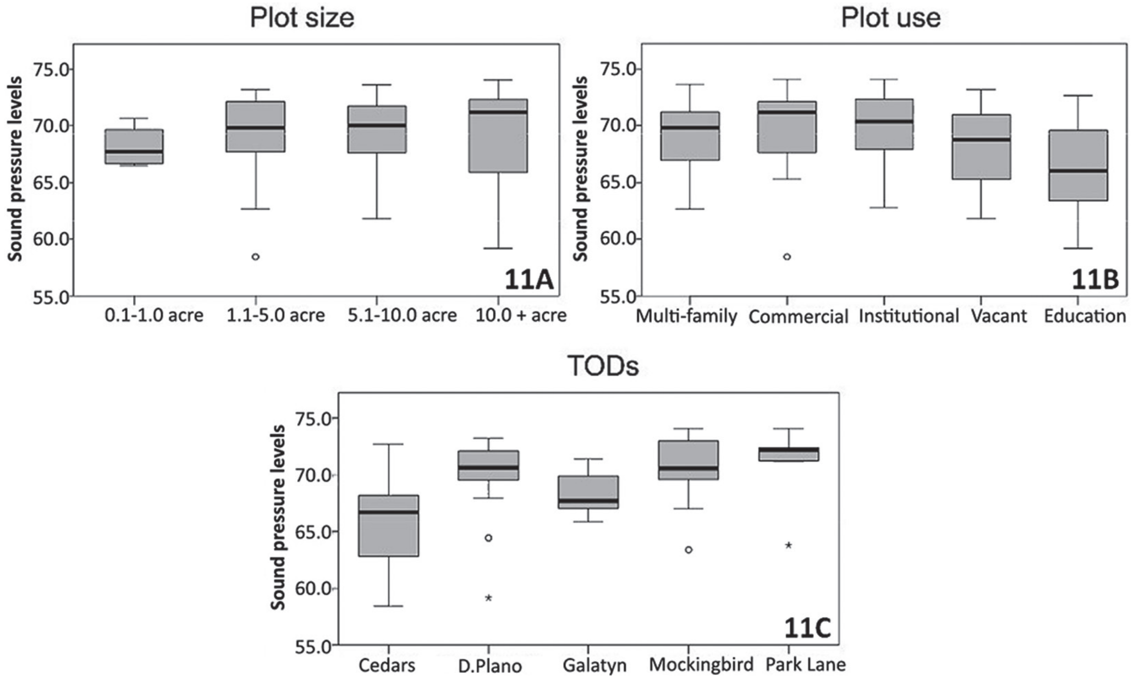


Figure 11. Plot characteristics and sound level comparisons.

also illustrate a hierarchical pattern, indicating that when sound level measurements are at peak level in streets, there is a greater likelihood of higher sound levels in buildings and plots. In some cases, however, the buildings may exhibit altered sound levels depending upon height, width, and building use, while the characteristics of plots have lesser implications on sound level compared to building and street segments.

Conclusions

This study sought to investigate the nexus between urban form elements – buildings, plots, and street segments – and sound levels in TODs. These elements were analyzed using spatial and statistical techniques, and the research indicated that sound levels vary amongst the urban form elements. Streets are the most dominant noise sources, especially those with heavy traffic, greater lengths and widths, and higher speed limits. Plots with mixed, commercial, and institutional uses (also highly related to building types) also tend to generate noisy environments. It is noteworthy that any change in urban form elements affects other elements in a transactive relationship; for instance, distinct street characteristics affect plots and buildings.

These results suggest that rethinking design guidelines and zoning policies on noise may be relevant. While robust urban design guidelines are always advisable, specific implications could include noise barriers or (in the U.S. at least) excluding train horns for point-sourced concerns as Bunn and Zannin (2016) suggested. However, as Scheer (2010) emphasized, design guidelines and zoning policies are insufficient and inferior retreats from the real-world experience if they lack understanding of the significance of urban form characteristics. Thus the continuing education of urban morphologists, planners, urban designers, and decision-makers is imperative. The integration of urban living and transit stations offers a wide range of opportunities for urban designers to engage with and consider existing and potential sounds. This is a 'nitty-gritty' and practical challenge for urban design approaches such as form-based codes. Incrementally refining urban form elements through urban design can improve the

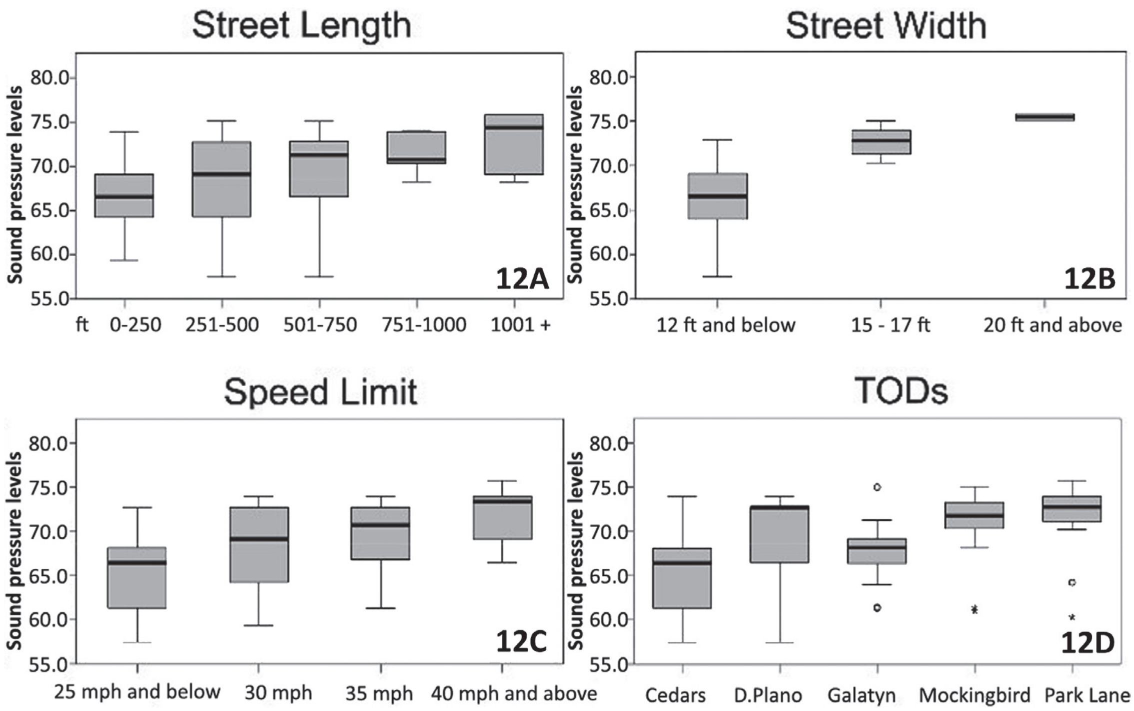


Figure 12. Street characteristics and sound level comparisons.

urban fabric at the station scale and also in terms of a wider integration of neighbourhoods (Loukaitou-Sideris *et al*., 2013). Urban designers can consider sound alongside visual aspects of a place, including building façades, plot sizes, and streetscapes.

Urban morphology spans several fields and disciplines; however, as Conzen (2001) and Whitehand (2012) highlighted, the use of the term 'urban morphology' has been ambiguous. This circumstance thus urges a variety of efforts to enhance the rigour of the urban morphology debate (Whitehand, 2014). This study contributes to the call for further research from an urban morphology perspective on sound. Therefore, investigating sounds in and amongst TODs provides an application that consolidates assessments of urban morphological patterns. This study may also prompt initial evaluations of the TODs, urban design guidelines, and policymaking fixtures that affect the quality of life of urban residents, and perhaps even the design of new districts through a greater understanding of the importance of urban morphology and sound.

Acknowledgments

The authors would like to thank the anonymous reviewers for their insightful comments and suggestions and also the DART, NCTCOG, the City of Dallas, the City of Plano, and the City of Richardson for providing the data.

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