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Nonlinear influences of landscape configurations and walking access to transit services on travel satisfaction

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ABSTRACT

Walking, as a form of active travel, has played a significant role in facilitating sustainable transport and the development of the built environment. A growing number of studies have examined the relationships between the built environment and active travel trips around transit stations. However, travellers' propensity to walk to transit stops and their travel satisfaction with doing so, particularly for first-mile trips, and its relationship with the built environment, in developing countries, have so far received little attention in the literature. Thus, this paper examines the nonlinear influences of landscape configurations, walking access to transit services and the interactions between them on travel satisfaction. Gradient boosting decision tree models are used to control for trip attributes and factors related to the built environment both in residential areas and business/commercial districts where a lot of transit stations are located. We combine street view data and individual survey data for the Beijing metropolitan area to document that improving walking access to transit services has significant effects on travel satisfaction. The results show that landscape configurations tend to have nonlinear associations with walking access to transit services as well as having pronounced interaction effects on travel satisfaction. The findings of this study demonstrate the importance of planning the spatial placement of stations to make them more convenient and improve people's travel satisfaction with first-mile journeys made on foot.

1. Introduction

Travel satisfaction reflects the individuals' moods and emotions related to travel experiences, which is an important domain of overall well-being (Ye et al., 2022). Achieving public satisfaction with travel is a key focus of planning policies aimed at coordinating sustainable transportation and land use in the 'new urbanism' era (Ye et al., 2022). In this context, planning policies, including transit-oriented development (TOD), have frequently combined maximising transport efficiency with attempts to make transport services

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more equitable (Cao and Hickman, 2019; Wu et al., 2020b), based on the assumption that better access to transit can help to mitigate congestion and the related adverse environmental effects (Ibraeva et al., 2020; Van Wee and Handy, 2016), and increase people's levels of travel satisfaction (Li et al., 2022; Mokhtarian, 2019; Wu et al., 2023a). However, the development of rail transit is often poorly integrated with other forms of travel in many developing countries (Knowles et al., 2020). Indeed, walking distance to transit stations is a key component of rail access with important implications for transit users' total travel time (Akbari et al., 2018; Hsiao et al., 1997). Transit users may feel inconvenienced and become less satisfied with their travel if transit stations are beyond the range of easily walkable distances and are too far away from residential and workplace locations (Lang et al., 2020; Loutzenheiser, 1997; Zhao et al., 2003). As the Coronavirus pandemic of 2019 (COVID-19) may have decreased people's willingness to travel, there is a need to better understand how to increase people's travel satisfaction and the use of public transit during the post-pandemic period (Wang and Gao, 2022).

Previous studies have documented the importance of built environment characteristics and demonstrated the correlation between the built environment and travel satisfaction independently (Liu et al., 2024; Tao et al., 2020a,b; Wang et al., 2022d; Wu et al., 2020a, a; Yang et al., 2022b; Ye and Titheridge, 2017, 2019; Zhao et al., 2023) and through the interaction effect with travel attitudes or behaviours (Cao and Ettema, 2014; Mao et al., 2022; Wang et al., 2024). For example, Ye and Titheridge (2017) showed that the availability and accessibility of amenities (e.g., rail stations) were positively associated with travel satisfaction in Xi'an, China. Ta et al. (2021) suggested that exposure to green space during a journey also contributes to travel satisfaction. In addition, Cao and Ettema (2014) found that there were interaction effects between the built environment and both travel attitudes and behaviours on travel satisfaction in the Twin Cities, USA. Finally, Mao et al. (2022) examined the effect of the interaction between the built environment and travel attitudes (but not travel behaviour) on travel satisfaction in Shanghai, China. These studies are relevant in their own right and offer insights into planning interventions designed to improve subjective well-being. However, most existing research has largely assumed that there is a pre-determined or linear relationship between the built environment and travel satisfaction. Recent work has shifted the focus towards assessing the nonlinear associations between built environment characteristics and travel behaviour (Ding et al., 2018; Zhang et al., 2020) and the relationships between service attributes and transit rider satisfaction (Abenoza et al., 2019; Sun et al., 2020), which suggests that nonlinearity patterns vary over space. Neglecting this nonlinearity is likely to cause the associations with built environment characteristics to be overestimated or underestimated and lead to erroneous planning and policy implications (Wu et al., 2020b,a). In addition, landscape configurations involving natural features, buildings and physical infrastructure densify the built environment and are expected to sustain human activity and social interactions (Cao and Porter-Nelson, 2016; Shaer et al., 2021; Ye et al., 2017; Wu et al., 2022b; Wu et al., 2023b). This is especially the case in areas around stations where spatial disparities in a landscape with a mix of amenities create a more attractive setting for walking access to transit services and play a critical role in sustaining the vibrancy of the area (Jacobs, 1961; Shao et al., 2020; Sung and Lee, 2015; Yang et al., 2012). Consequently, the interactive associations between landscape configurations and walking access to transit services with travel satisfaction constitute an important issue that requires further exploration.

This study represents a first attempt to assess the interactive effects of landscape configurations and walking access to transit services on travel satisfaction. It addresses the following research questions: (1) How important are different dimensions of landscape configurations for travel satisfaction? (2) Are there nonlinear associations between walking access to transit services and travel satisfaction? (3) How do landscape configurations influence travel satisfaction both independently and through the interaction effect with walking access to transit services? We controlled for the main built environment characteristics and explicitly tested for whether walking longer distances to transit stations may diminish the influence of landscape features. Using a combination of street view data and individual survey data collected from the Beijing metropolitan area, we quantified evidence regarding the efficacy of shaping land use policies to improve people's perceived travel experiences and prioritise optimising landscape designs, in order to answer the first question. Our findings regarding questions two and three are pertinent to identifying whether the association is nonlinear in the presence of interaction effects; it is expected that landscape and transportation policies would have synergistic implications for people's travel satisfaction.

This study makes a threefold contribution to the literature. First, it enriches existing knowledge by relaxing the assumption of linearity that has plagued earlier work, by leading to the conclusion that the relationship is pre-determined and static (Yang et al., 2022a). We therefore attempt to demonstrate the nonlinear and interactive associations of landscape configurations and walking access to transit with travel satisfaction. Second, our work contributes to the empirical literature on walking access to transit services (Tao et al., 2020a). We measure walking access to transit services based on the walking distance to the nearest subway station from the participants' residential neighbourhood via the available road networks. Our analysis quantifies new evidence regarding decisions about walking access to transit services and offers potential channels for identifying perceived benefits of transit services. Third, previous studies have made substantial efforts to investigate the effects of various aspects of built environment characteristics on travel behaviour and satisfaction outcomes (Ta et al., 2021). However, limited evidence has been offered about the role of landscape configurations involving physical infrastructure, natural features, and buildings, obtained from street view data. This study fills the gap by using evidence from street view data collected in Beijing. The transferability of our approach provides a basis for estimating landscape configurations at fine spatial scales in developing countries where there is a lack of traditional built environment census data.

This paper is organised as follows: Section 2 presents the theoretical framework for the analysis. Section 3 describes the data and the methods used. Section 4 explains the results. Section 5 offers conclusions and discusses implications for planning policies.

2. Theoretical considerations

Travel satisfaction is a measurable and subjectively perceived state that affects people's subjective well-being and usually refers to how happy people are with their experience of travel (Cao and Ettema, 2014; De Vos and Witlox, 2017). It is empirically measured using 'satisfaction with travel' scales and other Likert-based scales designed to assess people's cognitive evaluations of their travel experiences (De Vos et al., 2015; Ettema et al., 2011; Friman et al., 2013; Wang et al., 2020a). Understanding more about the determinants of travel satisfaction has implications for planners, in terms of helping them to identify rail transit development policies and types of landscape design that can improve the quality of transit services and generate substantial benefits for people's subjective well-being.

Travel satisfaction is mainly influenced by three groups of factors. First, travel attributes are predictive of travel satisfaction. For instance, travel mode is an important determinant of travel satisfaction and active travellers are generally more satisfied with their travel than those travelling by car or public transit (Olsson et al., 2013). In line with the literature on consumer satisfaction (Harreman-Fernandes et al., 2021), the service attributes of public transport have also been found to influence transit riders' levels of travel satisfaction (Rong et al., 2022). Trip duration is another determinant of travel satisfaction (Higgins et al., 2018; Morris and Zhou, 2018), although travel is not necessarily a derived demand (Wang et al., 2020b). Second, the built environment may interact with travel behaviours and they can jointly influence travel satisfaction (Cao and Ettema, 2014). For example, both accessibility to transit services (Mao et al., 2022) and network accessibility between metro stations (Zhai et al., 2021) are significantly associated with travel satisfaction. For instance, the condition of the waiting area and the walking environment are predictive of travel satisfaction for both transit riders and pedestrians (Manaugh and El-Geneidy, 2013) Kim et al., 2014; Park et al., 2021). Characteristics of urban form such as compactness, neighbourhood density and distance to the city centre are also associated with travel satisfaction (Mouratidis et al., 2019). Third, personal characteristics influence travel satisfaction too. For instance, personal attitudes (Mao et al., 2022) and preferences (Ma et al., 2021; Wu et al., 2022a) are important predictors of travel satisfaction. Sociodemographic and socioeconomic characteristics may also be associated with travel satisfaction and are usually controlled for in modelling.

However, the literature can be extended in three directions. First, subway stations are often located in places with potential demand (Giuliano, 2004), and are associated with perceived satisfaction outcomes (Cao, 2013), so more attention should be paid to the links between walking accessibility to transit services and travel satisfaction. Hence, existing studies have pointed out that ignoring the influence of accessibility to transit services may lead to serious bias when modelling travel satisfaction (Ye and Titheridge, 2017; Zhai et al., 2021). Notably, transit trips can usually be split into the following: walking and on-board travel (Park et al., 2021). Similarly, rail transit accessibility can be divided into two categories: accessibility between stations within the rail transit network (by-transit accessibility) and walking access to transit facilities (to-transit accessibility or the first-/last-mile experience) (Delbosc, 2012; Ettema et al., 2011; Taniguchi et al., 2014). Walking is the most common way of reaching transit facilities and gaining ridership benefits and thus is an important predictor of the convenience of transit use in a spatial context (El-Geneidy et al., 2014; Wang and Cao, 2017). It also influences people's travel experiences and choices about how to get to transit stations (De Vos et al., 2022). However, existing studies have largely explored the association between the perceived accessibility of public transit services and travel satisfaction or measured the accessibility of public transit services based on the straight-line distance, while only limited attention has been paid to the role of walking access to transit services based on available road networks (Mao et al., 2022).

Second, traditional methods have mainly measured the built environment based on the 5Ds (density, diversity, design, distance to transit and destination accessibility) model (Cervero et al., 2009), which highlights the influence of the environment from an overhead perspective. Recent studies have tried to shed more light on landscape configurations, which can reflect people's visual exposure to different elements of the built environment (e.g., green space) from a human-centric perspective (Wang et al., 2021, 2022a–c). Therefore, more effort needs to be expended in investigating how landscape configurations around the transit station area influence travel satisfaction. The new urbanism and healthy city movements have had implications for planning and policy in terms of shaping urban landscape design by promoting mixed land use and walkability (Abraham et al., 2010; Corburn, 2009). The literature on exploring the correlates of travel satisfaction is substantial (Ye et al., 2022) and asserts that mixed land use plays a role in explaining variations in travel satisfaction (Zhao and Li, 2019). It can be argued that travel satisfaction is likely to be directly influenced by the landscape design at stations and the surrounding areas, particularly if the land use is mixed and there are favourable built environment characteristics. A mixed and well-designed station area can save daily travel time by offering opportunities for social interactions, business and leisure and thus reducing demand for travel to other destinations (Cao and Ettema, 2014; De Vos and Witlox, 2017; Ye and Titheridge, 2017). For example, people are generally less satisfied with their travel experience if access to transit services and opportunities for activities are limited (Cao and Ettema, 2014). Manaugh and El-Geneidy (2013) posit that the landscape configurations of amenities have direct impacts on travellers' emotions and feelings, which in turn affect their perceived evaluation of their travel experience. A transit station offering various additional facilities may attract more transit riders and encourage the transit provider to improve the quality of public transportation services. Furthermore, the landscape configurations in the area around transit stations may moderate the effects of walking access on travel satisfaction. As noted by Bertolini (1999), accessibility is not only about access to a transportation node but is also related to the diversity of activities available within that location. For example, transit stations that can offer better rail access in terms of potential travelling time along the rail transit network are likely to be preferred by transit users (Alshalalfah and Shalaby, 2007; O'Sullivan and Morrall, 1996), and may be perceived by travellers as offering greater benefits. Similarly, people may find it more stimulating to walk along streets with diverse facilities and activities.

Third, our work is related to the growing body of literature dealing with the nonlinear effects of the built environment on transit usage. Along with emerging studies exploring the non-linear effects of built environment correlates of walking access to transit services (Wang and Cao, 2017) and the non-linear effects of transit services on travel satisfaction (Abenoza et al., 2019; Sun et al., 2020; Wu et al., 2020), walkability to transit stations and landscape configurations of the transit station area may also be expected to have non-linear impacts on travel satisfaction. Indeed, conventional planning wisdom has tended to assume that residents will be willing to walk to a transit station if they live within a certain catchment area or radius of it, but such an association may still be conditional on the distances to transit (Gutiérrez and García-Palomares, 2008; Hsiao et al., 1997; Zhao et al., 2003). Similarly, the effects of other built environment correlates on travel satisfaction may also be non-linear, such relationships may vary based on these factors and even become insignificant when the value is beyond the acceptable range. For example, Yin and Shao (2021) found that both green space and land use mix had non-linear association with satisfaction.

3. Data and method

3.1. Data

The survey data for this study were collected in 2013 in Beijing using a multi-stage stratified probability proportionate to population size sampling (PPS) method. First, residential neighbourhoods were randomly selected from the main urbanised districts (Dongcheng, Xicheng, Chaoyang, Fengtai, Haidian and Shijingshan) in the Beijing metropolitan area. Second, households were randomly chosen from neighbourhoods and districts to be part of the sample. Finally, one adult from each household who was in full-time employment was randomly selected to be a participant using the Kish Household Sampling Method (Binson and Catania, 2000). A total number of 5,116 valid respondents were invited to participate; of these, 3,843 individuals were included in the modelling analysis after data cleansing (the test indicated that there was no significant difference in travel satisfaction between the omitted sample and the final sample). These samples were representative of the local population of Beijing based on 2010 Census information (Zhang et al., 2015). In 2010, the total population in Beijing was about 19 million, and 52 % were males. About 82.7 % of the population was aged between 15 and 64 years, while 53 % had an educational attainment above high school level. In this study, we mainly focused on the subway which is one of the most important forms of public transit. In 2013, there were 13 subway lines (lines 1, 2, 4, 5, 6, 8, 9, 10, 13, 14, 15, airport, and Changping) operating in the research area, which yielded a total of 236 subway stations that were analysed in the study (Fig. 1).

3.2. Variables

3.2.1. Travel satisfaction

Following previous studies (De Vos and Witlox, 2017; Mouratidis, Ettema, and Næss, 2019; Zhai et al., 2021), travel satisfaction was measured by asking the following survey question: 'How satisfied are you with your daily travel?'. Participants were required to rate their satisfaction using a five-point scale ranging from 'very dissatisfied' to 'very satisfied'.

3.2.2. Landscape configurations

We used street view data to calculate street view-based landscape configurations in residential neighbourhoods and around subway stations. The street view images were obtained from Tencent Map[https://map.qq.com/] (2013–2014) which has been widely used for transportation research in China (Wang et al., 2020; Yang et al., 2022). We constructed the sampling points to be used for collecting the images along the major roads in the research area (at 100-m intervals) based on OpenStreetMap[1] (Haklay and Weber, 2008). For each sampling point, four images were downloaded to reflect the environment from the four cardinal directions (0, 90,180, and 270 degrees). Following previous studies (Wang et al., 2021, 2022a,b), we used a fully convolutional neural network (FCN-8 s) (Long et al., 2015) and the ADE20K training data set (Zhou et al., 2019) to calculate landscape configurations from the images. Both the training and testing datasets achieved a high rate of accuracy (>80 %) in identifying ground objects. We included four landscape configuration metrics in the analysis, namely: nature index (natural features including vegetation such as trees and grass, and bodies of water); road and pavement index (roads and pavements reflect the horizontal landscape configuration); building index (buildings reflect the vertical landscape configuration); and the entropy index (which was calculated based on the entropy of the former three indices and indicates how mixed the landscape configurations are). The number of landscape configurations per sampling point was then calculated by taking the proportion of pixels per image for each of the landscape configurations totalled over the four cardinal directions, to the total number of pixels per image summed over the four cardinal directions. Last, the landscape configurations of residential neighbourhoods and subway stations (the nearest subway station from the participants' residential neighbourhood) were calculated by averaging the landscape configurations of all the sampling points within the 1000-m circular buffer.

3.2.3. Walking access to transit

Walking access to transit was measured by calculating the walking distance to the nearest subway station from the participants' residential neighbourhood based on the available road networks, derived from Gaode Map (https://ditu.amap.com/) – similar to Google Maps – which is widely used in China.

3.2.4. Covariates

Following previous studies (Guan and Wang, 2019a, 2019b; Smith et al., 2017), we controlled for a series of individual and built environment covariates. We also controlled for several socio-demographic characteristics, including respondents' age, sex, marital

[1] OpenStreetMap is a free, open geographic database updated and maintained by a community of volunteers that includes data about roads, buildings, addresses, shops and businesses, points of interest, railways, transit, land use and natural features.

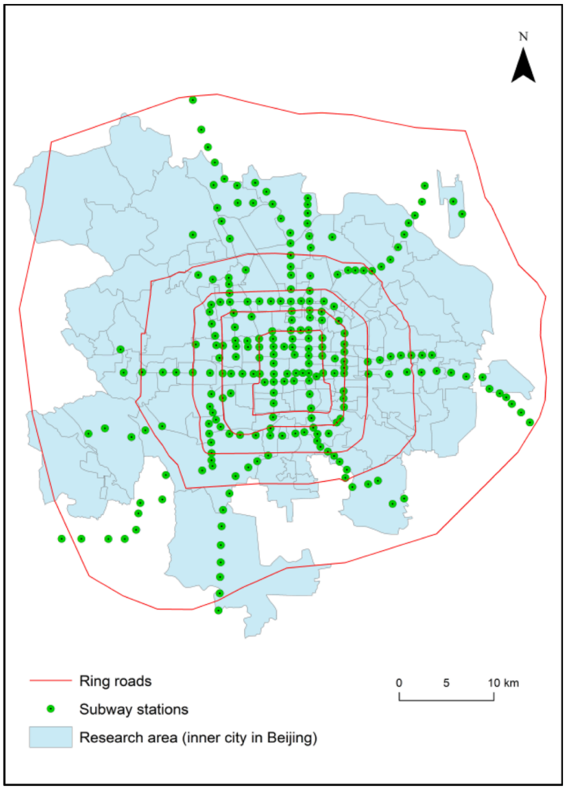

Fig. 1. The location of the research area.

status, educational attainment, monthly household income (Chinese Yuan[2]), and car ownership. Hence, subway usage was controlled for as an indicator of travel behaviour. We then included the following built environment characteristics. First, as transport-related infrastructure plays an important role in transportation mode choice (Townsend and Zacharias, 2010), we included the density of bus stops (number/km^2), and the density of parking lots (number/km^2) based on the 2013 infrastructure records. Second, based on the '3D' theory (Frank et al., 2006), population density (persons/km^2), land use mix (0-1) based on the entropy algorithm (Jost, 2006), and intersection density (number/km^2) were included to reflect land use density, diversity, and design respectively based on 2015 Tencent Points of Interest (POI) data. Table 1 provides a summary of the variables.

3.3. Method

We used a gradient boosting machine (GBM) (Friedman, 2001) modelling approach. This approach has been widely used to examine the nonlinear effects of built environment characteristics on travel behaviours (Ding et al., 2018; Ding et al., 2022). Tree-based GBMs tend to have good predictive accuracy and provide information about the shape of the associations between predictors and the outcome (Hagenauer and Helbich, 2017). When using the GBM method, the residuals are calculated using a gradient boosting algorithm which means that the loss function of the model is iterated and minimised to produce the lowest residuals for each tree. The overall residuals are calculated by adding up the results of all the trees (Ding et al., 2018). The GBM aggregates many different forms of simple models (trees) into one complex model in a sequential procedure (Elith et al., 2008), which enables the model to give a nonlinear prediction. It is superior to traditional regression models used in transportation-related research for several reasons (Yang et al., 2022a,b). First, the GBM is based on a combination of multiple trees, so it can achieve a high rate of predictive accuracy by constructing a complex relationship between the predictors and the outcome (Friedman, 2001). Second, because the GBM does not assume that the predictors and outcome are linear, any multicollinearity issues between the predictors, outliers and/or missing values will result in less bias than would be the case with linear regression models. Third, the GBM shows the relative importance of predictors, thus allowing different predictors to be compared even if they are quantified in different units.

We used two approaches to interpret the results, namely, calculating the relative importance of each of the predictors, and drawing a partial dependence plot (PDP). The relative importance of a predictor is calculated as its mean contribution to predicting the overall outcome of all the trees. It was measured by the proportion of the improvement in the overall goodness of fit (%R^2). A PDP shows the

[2] 1 Chinese Yuan is approximately equal to 0.12 Pounds sterling.

Table 1
Descriptive statistics of samples (3,843 individuals).

Variables	Definition	Numbers (proportion)/Mean (S.D.)
Travel_satisfaction	Travel satisfaction (1–5)	3.50(0.72)
Subway_commuter	Subway commuter	876(0.23)
	Non-subway commuter	2967(0.77)
Age		
Age_0	Aged below 30 years	1711(0.45)
Age_1	Aged between 30 and 49 years	1885(0.49)
Age_2	Aged above 49 years	247(0.06)
Male	Males	2029(0.54)
	Females	1814(0.47)
Married	Married	2286(0.59)
	Other	1557(0.41)
Education		
Edu_0	Educational attainment below high school	290(0.07)
Edu_1	Educational attainment equivalent to high school	953(0.25)
Edu_2	Educational attainment above high school (e.g., college)	2600(0.68)
Income		
Income_0	Monthly household income below 10,000 Chinese Yuan	2370(0.62)
Income_1	Monthly household income between 10,000 and 20,000 Chinese Yuan	1186(0.31)
Income_2	Monthly household income above 20,000 Chinese Yuan	287(0.07)
Car_ownership	With a car	1432(0.37)
	Without a car	2411(0.63)
Bus_density	Bus stop density (numbers/km2)	18.55(14.07)
Parking_density	Car park density (numbers/km2)	10.27(13.73)
Pop_density	Population density (persons/km2)	19125.01(8521.01)
Land_use_mixed	Land use mix (0–1)	0.05(0.05)
Intersection_density	Road intersection density (numbers/km2)	23.44(9.09)
Distance_subway	Walking distance to the nearest subway station (m)	1590.52(1560.01)
Nature	Street view-based nature index in the residential neighbourhood	0.14(0.05)
Entropy	Street view-based entropy index in the residential neighbourhood	0.83(0.05)
Road_pavement	Street view-based horizontal index in the residential neighbourhood	0.24(0.03)
Building	Street view-based vertical index in the residential neighbourhood	0.18(0.06)
Subway_nature	Street view-based nature index at the subway station	0.14(0.05)
Subway_entropy	Street view-based entropy index at the subway station	0.18(0.04)
Subway_road_pavement	Street view-based horizontal index at the subway station	0.19(0.06)
Subway_building	Street view-based vertical index at the subway station	0.02(0.01)

predicted value of the outcome when a certain value is assigned to a specific predictor (Hastie et al., 2009). After controlling for covariates, the PDP was used to show the nonlinear and threshold associations between landscape configurations, walking access to subway stations and travel satisfaction. The analysis was conducted via R version 3.6.3 using the “gbm” package (Ridgeway, 2007).

4. Results

Table 1 summarises the characteristics of the study population. Nearly 54 % of the respondents were males and 59 % were married. In terms of age, about 45 % of the respondents were below 30 years and 6 % were above 49 years. Only 7 % of the respondents had a level of educational attainment below high school, while 62 % of the respondents had monthly household incomes below 10,000 Chinese Yuan. Approximately one-fifth (23 %) were subway commuters, and 37 % had a car. Variance inflation factors (VIF$<$3) suggested there were no serious multicollinearity issues between the independent variables.

Following previous studies (Ding et al., 2018; Tao et al., 2020a,b), we set the shrinkage rate λ as 0.001 and started with 50,000 iterations (trees). The depth of each tree was set at values ranging from 1 to 49, and a five-fold cross-validation was used to find the optimum number of iterations which would produce the lowest root mean square error (RMSE). Generally, as the tree depth increases, both the RMSE and the number of iterations decrease (Fig. 2). The lowest RMSE was found to occur when the tree depth was set at 36, and the model was converged after 3,692 iterations with an RMSE of 0.55. The final Pseudo R^2 value was 0.35. The five-fold cross-validation also indicated that there was no significant difference in goodness-of-fit between the training and testing data set which means our model does not suffer from overfitting or underfitting issues.

Table 2 shows the relative importance of each independent variable in explaining travel satisfaction. Overall, distance contributes most (11.90 %) to predicting travel satisfaction, followed by land use mix (10.59 %), and the road and pavement index at the residential neighbourhood level (9.73 %). Overall, built environment factors account for 46.07 % of the total importance (average importance = 7.68 %) of all the variables, street view-based metrics at the residential neighbourhood level account for 31.24 % (average importance = 7.81 %), street view-based metrics at the subway station constitute 15.84 % (average importance = 3.96 %), and individual variables account for only 6.85 % (average importance = 0.69 %).

The PDP illustrates the relationships between the landscape configurations and travel satisfaction. Fig. 3a, 3b, 3c and 3d present the association between the landscape configurations in residential neighbourhoods and travel satisfaction after controlling for individual-level and neighbourhood-level covariates. When the nature index in a residential neighbourhood is less than 0.13, it is positively

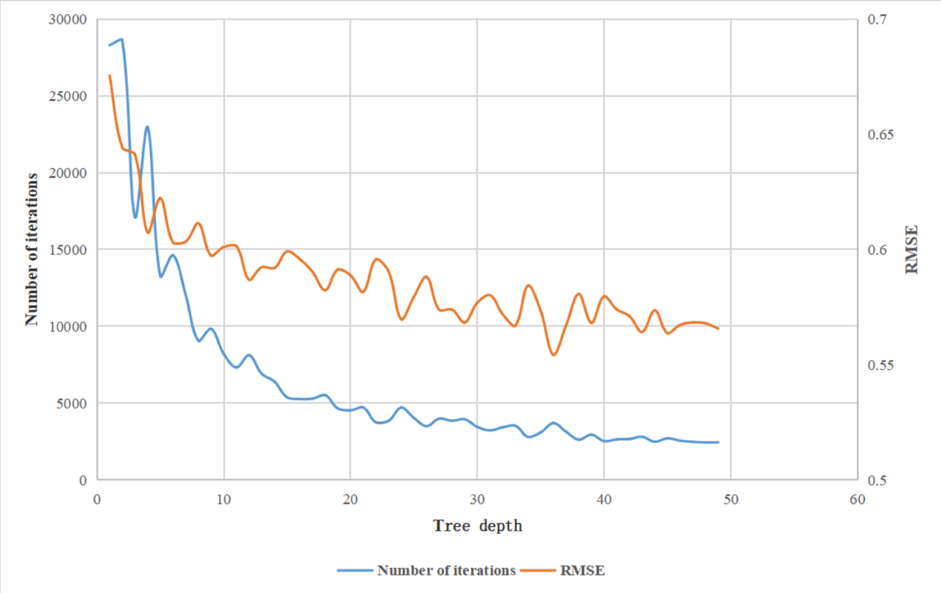

Fig. 2. RMSE and number of iterations versus tree depth.

Table 2
The relative importance of all the variables.

Variables	Relative importance (%)	Total (%)	Mean (%)
Individual variables		6.85	0.69
Subway_commuter	0.91		
Age_1	0.9		
Age_2	0.27		
Male	0.98		
Married	1.01		
Edu_1	0.47		
Edu_2	0.51		
Income_1	0.78		
Income_2	0.18		
Car_ownership	0.84		
Built environment variables		46.07	7.68
Bus_density	5.85		
Parking_density	5.04		
Pop_density	7.48		
Land_use_mix	10.59		
Intersection_density	6.02		
Distance_subway_walk	11.09		
Street view-based metrics in the residential neighbourhood		31.24	7.81
Nature	7.12		
Entropy	8.06		
Road_pavement	9.73		
Building	6.33		
Street view-based metrics at the subway station		15.84	3.96
Subway_nature	2.85		
Subway_entropy	4.47		
Subway_road_pavement	4.18		
Subway_building	4.34		

associated with travel satisfaction. However, it also has a positive effect between the range of 0.13–0.27, but the effect becomes negative again between the range of 0.27–0.30. Finally, the effects reach saturation point when the index is over 0.30. The entropy index has no significant effect in a residential neighbourhood between the range of 0.50–0.70. However, when it exceeds 0.70, the association with travel satisfaction becomes positive. Similarly, the road and pavement index has no significant effect in a residential neighbourhood between the range of 0.05–0.12. However, when it exceeds 0.12, it is positively associated with travel satisfaction. The building index is negatively associated with travel satisfaction when it is less than 0.1, but once the ratio exceeds the cut-off point, it has a positive association with travel satisfaction. The saturation point is reached when the index is over 0.35.

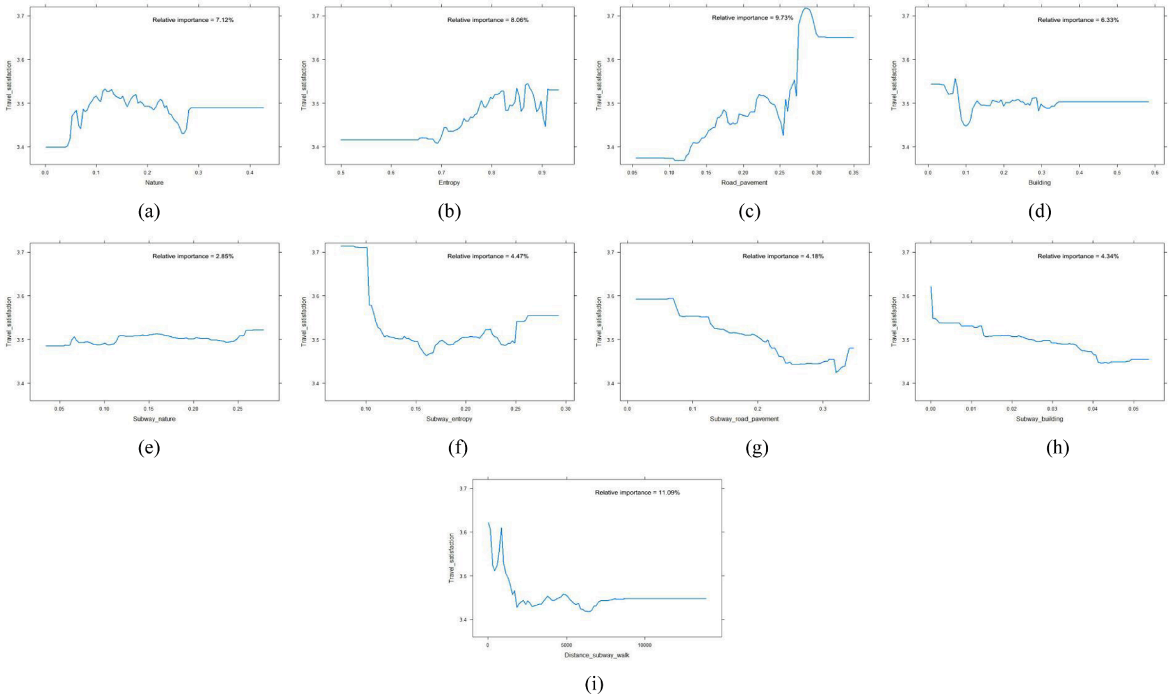

Fig. 3. Nonlinear relationships between street view-based attributes and travel satisfaction. Distance_subway = Walking distance to the nearest subway station; Nature = Street view-based nature index in the residential neighbourhood; Entropy = Street view-based entropy index in the residential neighbourhood; Road_pavement = Street view-based horizontal index in the residential neighbourhood; Building = Street view-based vertical index in the residential neighbourhood; Subway_nature = Street view-based nature index at the subway station; Subway_entropy = Street view-based entropy index at the subway station; Subway_road_pavement = Street view-based horizontal index at the subway station; Subway_building = Street view-based vertical index at the subway station.

Fig. 3e, 3f, 3 g and 3 h illustrate the association between the landscape configurations at subway stations and travel satisfaction after controlling for the covariates. The association between the nature index at subway stations and travel satisfaction generally follows a ‘W’ shape pattern with turning points of 0.09, 0.16, and 0.24. The entropy index is negatively associated with travel satisfaction when it is less than 0.16 and the association becomes inverted after the cut-off point. Both the road and pavement index and the building index are negatively associated with travel satisfaction. Finally, Fig. 3i displays the association between the distance

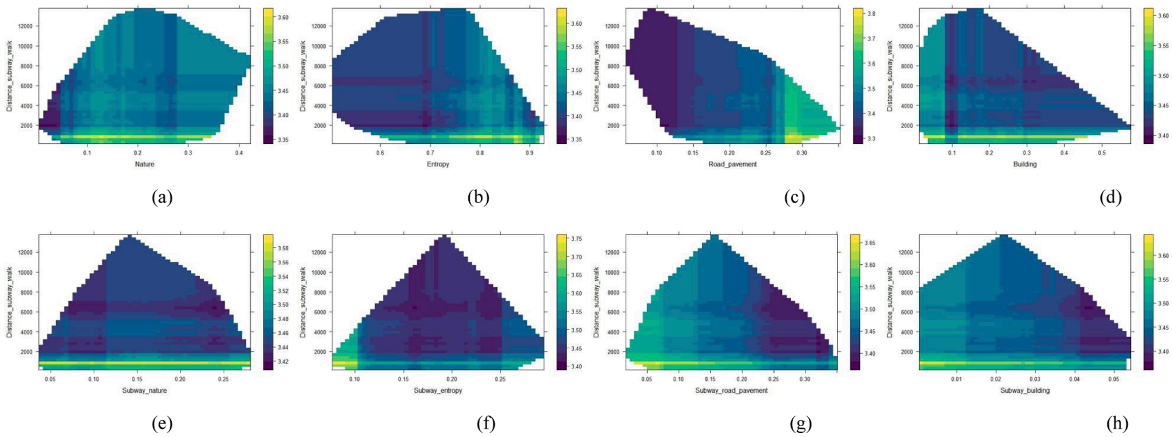

Fig. 4. Nonlinear relationships between street view-based attributes and travel satisfaction (moderation effects by the distance to the subway station). Distance_subway = Walking distance to the nearest subway station; Nature = Street view-based nature index in the residential neighbourhood; Entropy = Street view-based entropy index in the residential neighbourhood; Road_pavement = Street view-based horizontal index in the residential neighbourhood; Building = Street view-based vertical index in the residential neighbourhood; Subway_nature = Street view-based nature index at the subway station; Subway_entropy = Street view-based entropy index at the subway station; Subway_road_pavement = Street view-based horizontal index at the subway station; Subway_building = Street view-based vertical index at the subway station.

from each participant's residential neighbourhood to the nearest subway station and travel satisfaction. Overall, the results indicate that it is negatively associated with travel satisfaction. However, the effects reach the point of saturation when the distance is over 6 km. We further stratified the results between subway commuters and non-subway commuters (Fig S1 and Fig S2). In the case of non-subway commuters (Fig S1), the results remained similar to the pooled samples. However, for subway commuters (Fig S2), most of the results remained similar for landscape configurations in residential neighbourhoods: there were some significant variations in the entropy index at subway stations and distance from each participant's residential neighbourhood to the nearest subway station. For example, the entropy index at subway stations was generally positively associated with travel satisfaction in subway commuters. In addition, the distance from each participant's residential neighbourhood to the nearest subway station was positively associated with travel satisfaction at first, but the association became inverse when the distance was above 1,000 m.

Because the distance to the nearest subway station influences people's willingness to travel and experience of the journey (Wu et al., 2022), it may also affect the association between landscape configurations and travel satisfaction. We produced two-dimensional PDPs to illustrate the interaction effect of the distance to the nearest subway station and landscape configurations on travel satisfaction (Fig. 4). The x-axis shows the value of each landscape configuration, while the y-axis shows the value of walking distance to the nearest subway station. The lower the value, the higher the level of travel satisfaction. Overall, the results indicate that the effects of landscape configurations on travel satisfaction decrease as the distance to the nearest subway station increases, which means that the distance to the nearest subway station weakens the effect of landscape configurations on travel satisfaction. For example, in Fig. 4(a), when the walking distance to the nearest subway station is low, nature-related travel satisfaction seems to be stronger (the colour changes from green to yellow).

5. Discussion

5.1. Major findings

According to the results of the GBM models, the landscape configurations (both in residential neighbourhoods and around subway stations) and walking access to subway stations are much more important in terms of predicting travel satisfaction than individual-level variables. Thus, this study confirmed that landscape configurations (both in residential neighbourhoods and around subway stations) and walking access to subway stations play a crucial role in influencing travel satisfaction in high-density cities in developing countries. Furthermore, we found that the three most important variables in predicting participants' travel satisfaction were: the walking distance to the nearest subway station, mixed land use, and the road and pavement index in a residential neighbourhood. Unlike previous studies that have used the Euclidean distance measure (Yang et al., 2022a,b), we measured walking access to the nearest transit station using the available street network, and the results showed that this factor is the most important, relatively speaking, in terms of predicting travel satisfaction. Walking access to the transit station is related to the use of public transit and is therefore important in terms of influencing people's overall experience of travel (Delbosc, 2012; Ettema et al., 2011; Taniguchi et al., 2014). Land use mix indicates the diversity of (one of the 3D indicators) the street amenities and is associated with walkability (Lu et al., 2017), so it is also important in predicting travel satisfaction. The road and pavement index in a residential neighbourhood reflects the maintenance and design of the street, which is also related to the travel experience (Wang, Liu, et al., 2022).

This study has shown that the association between landscape configurations, walking access to transit services and travel satisfaction is nonlinear. Specifically, walking distance to the nearest subway station was generally negatively associated with travel satisfaction, and its effect gets weaker as the distance increases. A possible explanation for this decay is that people are less likely to travel by public transit as the distance increases (Zhai et al., 2021). Therefore, as the walking distance to the nearest subway station increases, its marginal effect on travel satisfaction decreases. In the case of residential neighbourhoods, the road and pavement, nature, and entropy indices were generally positively associated with travel satisfaction, while the building index was negatively associated with travel satisfaction. The nature index measures the quantity of visible green space in an area, which can help pedestrians to feel more relaxed, while the entropy index reflects the diversity of the street from a human perspective, both of which have been proven to be positively associated with a better walking experience (Yang et al., 2022b). As mentioned above, the road and pavement index gives an indications of the quality of the road and pavement networks, and a better road infrastructure should be positively associated with a more pleasant walking experience (Wang et al., 2022c). However, a higher building index may be associated with a sense of being too enclosed within a dense environment, which may make people feel stressed (Lu et al., 2017). Around the subway station, the road and pavement, building, and entropy indices were generally negatively associated with travel satisfaction, while the nature index had a 'W' shaped association with travel satisfaction. Higher values for the entropy, road and pavement, and building indices around the subway station may be associated with a dense and crowded environment, which is negatively related to the travel experience (Lu et al., 2017). The nature index also evaluates exposure to green space, and it has been shown to have a dose–response effect on people's perception of the environment in previous studies (Jiang et al., 2015). Furthermore, similarly to the effect of walking distance to the nearest subway station, their effects become weaker as the values of these indices grow. Existing evidence suggests that people's eyes are more sensitive to changes in landscape configurations when these only occupy a small proportion of their visual sense, but perceptions of such changes become weaker when the proportion of configurations becomes too large (Burian et al., 2018; Li et al., 2020).

Overall, the results indicate that the effect of landscape configurations on travel satisfaction decreases as the distance to the nearest subway station increases, which means that the distance to the nearest subway weakens the effect of landscape configurations on travel satisfaction (interaction effect). There are several potential explanations for such a finding. First, existing studies have pointed out that having to travel a longer distance to the nearest transit station is negatively associated with the use of public transit (Zhai et al., 2021), which may result in less exposure to landscape configurations both in the residential neighbourhood and around the transit station. For example, Ta et al. (2021) found that pedestrians have greater visual exposure to landscape configurations than people who choose to travel by other transport modes, and people making trips of shorter duration also have more visual exposure to landscape configurations. Second, when people have to travel a longer distance to get to the nearest transit station or to get back to their residential neighbourhood on the way home, they may feel tired and pay less attention to the surrounding environment, including its landscape configurations (Yang et al., 2022b). The effect of visual landscape configurations is strongly dependent on the extent to which people are paying attention to their environment (Suppakittpaisarn et al., 2019), so when the distance to the nearest transit station becomes longer, people may be too preoccupied with the lengthy and tiring nature of the trip to notice much about the surrounding landscape configurations.

5.2. Policy implications

Assessing the nonlinear influences of landscape configurations and walking access to transit services on travel satisfaction in Beijing has implications for urban planning and policy-making. First, it is important to improve the accessibility to transit stations from residential neighbourhoods. Not only do the findings indicate that poor access to the nearest subway station is negatively associated with travel satisfaction, but also that walking access to the nearest transit station has the highest relative importance in predicting travel satisfaction, so it is also necessary to improve the walkability of the pavements and routes that pedestrians have to use to get to the subway station through policies aimed at improving people's travel satisfaction. Second, landscape configurations both in residential neighbourhoods and around subway stations have a significant influence on travel satisfaction, so it is important to target both of these contexts through planning interventions designed to improve landscape configurations. Our findings suggest that the landscape configurations in residential neighbourhoods are relatively more important than those around subway stations, so policy interventions should prioritise making improvements in residential neighbourhoods. Third, the nonlinear influences of landscape configurations and walking access to transit stations on travel satisfaction should be taken into consideration; for example, if the quantity of landscape configurations can be optimised in line with the peak travel satisfaction points, as shown on the PDP plot. Last, the interaction analysis suggests that the effect of landscape configurations depends on the walking access to transit stations. Therefore, as well as improving the accessibility of transit stations, policymakers could also consider taking measures to locate transit systems closer to residential areas.

5.3. Limitations

This study is based on cross-sectional data, which may prevent us from inferring causality between landscape configurations, walking access to transit services and travel satisfaction. Hence, we were unable to disentangle the effects of residential self-selection (Cao et al., 2009). For example, participants' unobserved attributes relating to their choice of residential location may influence landscape configurations, walking access to transit services and travel satisfaction, so the associations that we observed between these variables could contain some bias. Second, although we included four different types of landscape configurations in this research, that still might not be enough to fully reflect all the characteristics of local landscape configurations. In addition, street view data is usually static and cannot reflect variations in temporal changes, thus making it difficult to understand the effects of seasonal changes in landscape configurations. Third, existing studies have pointed out that landscape configurations should be evaluated in 3 dimensions (3D) to enable their features to be assessed more accurately (Qi et al., 2022). Thus, although we measured people's visual exposure to different landscape configurations using street view data, we were unable to assess their 3D features. Hence, some covariates may be temporally mismatched with the survey data, and this could lead to bias in our results. Fourth, travel satisfaction was measured by a single self-reported answer to a question, which means we were unable to assess participants' travel satisfaction with a specific travel mode or journey, but could only reflect participants' general experience of travel. Last, previous studies have also suggested that the built environment can influence travel satisfaction indirectly via travel behaviour (Ye and Titheridge, 2017). However, we only distinguished between subway commuters and non-subway commuters, and omitted other attributes due to data availability. This prevents us from identifying the pure effect of the built environment on travel satisfaction. Additionally, although travel attitudes can both confound and interact with the effects of the built environment on travel satisfaction (Cao and Ettema, 2014), we did not include information on travel attitudes due to data availability. Future studies should therefore consider the role of both travel attitudes and behaviours in the relationship between the built environments and travel satisfaction.

6. Conclusion

Our study is among the first to investigate the nonlinear effects of landscape configurations and walking access to transit services on travel satisfaction both in residential neighbourhoods and around transit stations. The results suggest that the relative importance of landscape configurations and walking access to transit facilities in predicting travel satisfaction is much higher than individual attributes. The results also clearly demonstrated the nonlinear effects of the landscape configurations and walking access to transit services on travel satisfaction. The interaction analysis indicates that walking distance to the nearest subway station weakens the effect of landscape configurations on travel satisfaction. These results clarify the importance of considering non-linear and interactive associations of landscape configurations and walking access to transit services in generating perceived travel satisfaction benefits.

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CRediT authorship contribution statement

Wenjie Wu: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Mengqiu Cao:** Writing – review & editing. **Fenglong Wang:** Writing – review & editing. **Ruoyu Wang:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2024.104232.

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