DO VISUALLY PERCEIVED DESIGN QUALITIES INFLUENCE DOCKLESS BIKESHARE CYCLING ROUTES?

A Case Study of Ithaca Using GPS Trajectories

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Abstract. Understanding the influences of the built environment (BE) characteristics on the dockless bike-sharing system (DBS) is crucial for supporting and developing sustainable transportation mode. Previous studies on DBS cycling have primarily investigated the effects of macro-level BE characteristics (e.g., land use) or limited street features (e.g., greenery), overlooking that of perceived street design qualities such as enclosure. To better understand whether and how street-level environment characteristics, especially perceived street design qualities, influence DBS cycling routes, we calculate cycling volume based on GPS trajectories in Ithaca, a small town in New York State, and then quantify visual features and perceived design qualities using street view imagery (SVI) and computer vision (CV). Our analysis, employing linear regression and spatial regression models while controlling macro-environmental attributes as covariates, reveal the significant association between perceived design qualities and DBS cycling trip volume, confirming the significance of considering design qualities in DBS cycling studies. Geographically Weighted Regression (GWR) model explains the spatially heterogeneous effects of street-level attributes, offering practical suggestions for informing spatially varying policies and interventions for creating a cycling-friendly environment.

Keywords. Dockless Bikeshare, Street-level Characteristics, Urban Design Quality, Street View Imagery, Semantic Segmentation.

1. Introduction

Metropolitan cities have witnessed a remarkable expansion in bike-sharing systems globally over the past decade, mobilised by its diverse benefits from public health improvements to transportation and environmental sustainability. The latest generation

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of the DBS system has overcome the drawbacks of the docked system concerning accessibility and fleet size, thus serving as a catalyst for encouraging cycling and advancing bike-sharing systems (Shen et al., 2018). The rising popularity of the DBS system, coupled with the growing demand for cycling-friendly environment, warrants further research to identify specific environmental design factors affecting bike-sharing cycling behaviour (Song et al., 2023). An essential stride toward comprehending the interaction between DBS cyclists and built environment is to determine how BE characteristics may have spatially affected the cyclists' preferences.

Previous studies on linking DBS cycling to BE characteristics have typically relied on surveys or field observations, which are time-consuming and labour-intensive. Fortunately, the real-time data collected from the built-in GPS devices on the DBS system during rides offers new research opportunities to investigate the impacts of BE characteristics on cycling behaviour and route choice at a finer granularity (Qiu & Chang, 2021). Nevertheless, several research gaps remain under addressed.

On the one hand, most previous literature has focused on the influence of macro-level BE characteristics (e.g., street connectivity), with little attention paid to the role of street-level characteristics, which directly interact with cyclists (Shen et al., 2018). More importantly, these studies have mainly used remote sensing techniques to proxy such characteristics, which only reflects an overhead view while neglecting the cyclist's experiences at the street level. While the utilization of SVI has recently rendered it more efficient and accurate to study the street environment as perceived by humans, existing studies on cycling behaviour has primarily focused on view index to capture individual visual features along streets. For instance, Lu et al. (2019) investigated the effect of the eye-level greenness on aggregated cycling patterns in Hong Kong. Nevertheless, whether the perceived street design qualities affect DBS cycling routes is still largely unknown. In fact, urban design qualities (e.g., enclosure and openness) are important environment characteristics affecting various activities (e.g., walking and urban vitality), as they represent the collective effects of various visual elements that individuals experience at the street level (Ewing & Handy, 2009). Along this vein, Ma et al. (2021) have proposed a multidimensional analytical framework for quantifying eye-level perceptions of these design qualities using SVI. In this regard, there is value in understanding how the design qualities quantified through SVI data can affect DBS cycling at the street segment level.

On the other hand, the spatially heterogenous effects of micro-level BE characteristics on DBS cycling have not been sufficiently addressed in the small North American city context (Qiu & Chang, 2021). Indeed, most of empirical evidence on DBS come from Asian metropolitan cities where the DBS system gained its wide acceptance. However, cycling behaviour may differ under different urban morphologies and environment, and impacts of micro-environmental characteristics may also vary spatially, thus resulting in variances in affecting cycling. Therefore, the spatially varying effects of micro-level BE attributes in the small North American city on DBS cycling should be further explored.

To bridge these research gaps, this study uses GPS cycling trajectories to investigate the relationship between micro-level street environment features (including both visual features and perceived design qualities) and DBS cycling volumes at street segment scale in Ithaca. This study attempts to address the following research questions: (1) Do and to what extent perceived design qualities affect DBS cycling trip volume? (2) Are their relationships spatially heterogenous across different areas? (3) Do perceived design qualities complement or conflict with macro-level BE characteristics and micro-level visual features in explaining cycling behaviours?

2. Study Area and Data Source

The study area is the City of Ithaca in Tompkins County, upstate New York, covering an area of 5.39 square miles. The raw GPS data employed in this research was provided by the DBS company Lime. The anonymised dataset contains trip IDs, GPS coordinates, and timestamps. After filtering the dataset based on multiple criteria like speed and duration, 4430 trips from Nov. 2019 to Mar. 2020 were kept.

Street view images were sampled at 50m interval along each street segment and downloaded from Google API based on the coordinate of each sample point. To maintain a uniform visual experience for all SVIs, consistent camera settings (heading: parallel to the street centreline, FOV: 120 degrees, pitch angle: 0 degrees) were applied. In total, 11, 426 valid SVIs were collected. In addition to GPS trajectories and SVI data, POI and street segment data were sourced from OpenStreetMap (OSM), while the population data was obtained from official census records.

3. Methodology

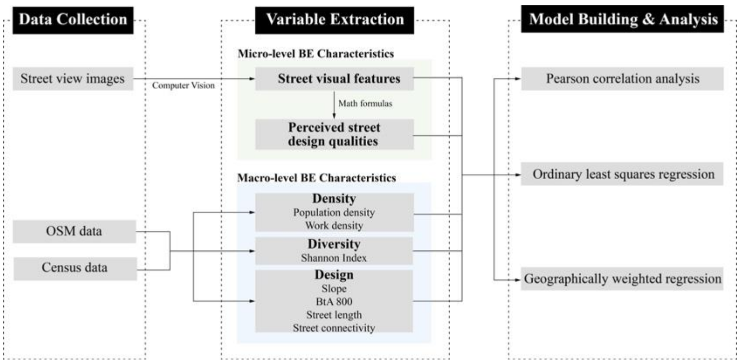

Figure 1. The analytical framework of this research

Our methodology followed several key steps (Fig. 1). First, we used actual DBS cycling trajectories collected from GPS to calculate the cycling volume for each street segment. Second, visual features were described by the percentage of pixels representing street physical elements using SVIs and CV. Simultaneously, perceived design qualities were calculated using a measurement framework that recombines the visual elements based on operational definitions of qualities. Third, following a popular 3Ds framework, we used data from OSM to calculate the macro-level BE characteristics, including density, diversity, and design, serving as covariates. Finally, Ordinary Least Squares (OLS) linear regression and GWR were applied to sampled points where the cyclists travelled along to reveal the complex relationship between micro-scale environment features and DBS cycling volume at the street level.

3.1. VARIABLES

3.1.1. Dependent Variable: DBS Cycling Trip Volume

To calculate the cycling trip volume of each road segment (Fig. 2), we first matched GPS raw points to road segments using a map-matching algorithm, and subsequently, applied the topography algorithm to create a graph structure G of all road segments. Then, we utilised Dijkstra's algorithm to identify the shortest path between two matched GPS points and generate a set of road segment IDs traversed by the cyclists. Finally, the trip volume was calculated based on the number of routes that passed by. The trip data is based on the secondary data from a previous research (Song et al., 2023).

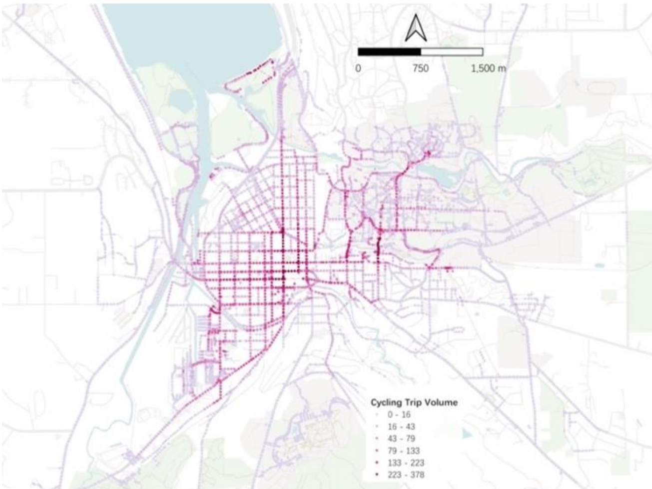

Figure 2. Spatial distribution of cycling trip volume

3.1.2. Independent Variables: Micro-level Street Environment Characteristics

Visual Features: In this study, we adopt a widely used semantic segmentation model called PSPNet with more than 93.4% prediction accuracy to extract the pixels of street elements and calculate the view index (the proportion of the pixels of a physical feature in an image) based on SVI sample points of street segments. Pre-trained on the ADE20K dataset, it allowed us to extract 31 visual features, including plant, building, and others. That said, we acknowledge that there is more recent CV development including the Vision Transformer algorithm, which has a better prediction accuracy that can be applied in future studies.

Perceived Design Qualities: Based on classical urban design theory and prior research (Ewing & Handy, 2009; Wang et al., 2022), we selected five perceived design qualities to examine their effects on cycling trip volume: (1) Greenness (DQ1_Gr), (2) Enclosure (DQ2_En), (3) Openness (DQ3_Op), (4) Street safety facilities (DQ4_SF), and (5) Walkability (DQ5_Wa). These design qualities have consistent operational definitions in previous studies. Greenness refers to the proportion of urban green space such as trees, greenbelts, and lawns. Enclosure represents how visually enclosed streets are, influenced by vertical elements, such as buildings, trees, and walls. Openness indicates the degree of the sky visibility. Street safety facilities relate to physical elements and conditions in a place that contribute to a sense of safety. Walkability refers to the degree to which the BE facilitates walking.

To measure these qualities, we built on the measurement framework of Ma et al. (2021) and modified mathematical formulas based on their operational definitions, as shown in Table 1. These formulas utilise SVI sample points on street segments to calculate each perceived design quality by recombining relevant visual indices.

Table 1. Formulas for the five perceived design qualities

Design qualities	Formula
Greenness	$Gr_i = \sum_{i=1}^{n}(T_n + G_n + P_n)$
Enclosure	$En_i = \frac{\sum_{i=1}^{n}(B_n+T_n)}{\sum_{i=1}^{m}(R_n+Sw_n+F_n)}$
Openness	$Op_i = \sum_{i=1}^{n} Sk_n$
Street safety facilities	$SF_i = \sum_{i=1}^{n}(F_n + Sb_n + Sl_n + W_n)$
Walkability	$Wa_i = \frac{\sum_{i=1}^{n}(Sw_n+F_n)}{\sum_{i=1}^{m} R_n}$

Notes: T_n is the proportion of tree pixels. G_n is the proportion of grass pixels. P_n is the proportion of plant pixels. B_n is the proportion of building pixels. R_n is the proportion of road pixels. Sw_n is the proportion of sidewalk pixels. F_n is the proportion of fence pixels. Sk_n is the proportion of sky pixels. Sb_n is the proportion of signboard pixels. Sl_n is the proportion of streetlight pixels. W_n is the proportion of windowpane pixels. $i \in (1,2,3,\cdots,n)$

3.1.3. Other Covariates: Macro-level BE Characteristics

This study selected 3Ds framework (Ewing & Cervero, 2010) to reflect the macro-level BE characteristics in Ithaca based on available data to further control their impacts.

Density: Both population density (PopDen) and work density (WorDen) were matched from census division zones to the sampling points of the road segments.

Diversity: We divided the downloaded POI data into seven categories (e.g., agricultural, commercial, community, industrial, public service, recreation and residential) and then calculated the POI count for each street segment within the 50m buffer along each street. Finally, we measure the mixture of overall POI (Total_mix) using Shannon Index.

Design: Based on Space Syntax, we utilized line connectivity (LCon) and angular betweenness (BtA800c) within a radius of 800m (a 5-minute bike ride distance) as a measure of street environmental design attributes. The length and slope of each road segment were also calculated using GIS and taken into consideration.

3.2. REGRESSION AND SPATIAL ANALYSIS

We first conducted the Pearson correlation analysis on all variables to exclude those with insignificant correlations. Then, to address multicollinearity issues among independent variables, variables with a Variance Inflation Factor (VIF) higher than 10 were removed. For instance, among the visual features, irrelevant variables such as pier, plant and fountain were removed. Next, we applied OLS linear regression to examine the relationship between cycling trip volume and BE characteristics, given its widespread use in urban studies and better interpretability. A baseline model (Model 1) was constructed with all macro-level BE characteristics. Model 2 and Model 3 were established by adding visual features and perceived design qualities, respectively, to the baseline. However, one potential issue with cycling data is spatial autocorrelation. Such effects violate the OLS assumption and can lead to biased estimates in Standard Errors, misinterpreting effects. Furthermore, OLS assumes the effects are stationary spatially, which fails to capture the spatially heterogeneous process of variables across different locations. Therefore, Moran's I statistics was applied to test spatial effects, while a more advanced spatially varying coefficient model, the GWR model were adopted to capture spatial non-stationarity in relationships between sets of variables and minimize bias of the conventional OLS model. GWR is a local regression technique for exploring spatial heterogeneity, leveraging the spatial dependence to show an intricate spatial distribution while producing highly variable localised parameter estimates (Fotheringham et al., 1998). Map visualization and description of the GWR models' results also provide more vivid and nuanced interpretations of spatial patterns and correlations of model estimates.

4. Result

4.1. OLS RESULTS

Table 2 shows the overall OLS results. First, in comparison to Model 1, both Model 2 and Model 3 exhibit an improvement in the R^2, indicating enhanced predictive ability with the inclusion of visual features or perceived design qualities, respectively. Second, the explanatory power of adding perceived qualities (Model 3) is slightly higher than that of visual features (Model 2) by 0.004, meaning that perceived qualities have a moderately stronger relationship with DBS cycling volume than visual features. It also underscores the significant role that perceived design qualities play in affecting DBS cycling volume. Third, Moran's I of all three models are significant, signifying strong spatial effects. In other words, it suggests that utilizing the OLS models without accounting for spatial interactions would lead to biased parameter estimation. Consequently, our analysis proceeds with the results from GWR models.

Table 2. The overall performances of OLS models

OLS	Model 1	Model 2	Model 3
Attributes	Baseline (3Ds)	Baseline + visual features	Baseline + perceived design qualities
R^2	0.220	0.270	0.274
Adjusted R^2	0.220	0.268	0.273
F-statistic(sig.)	408.5***	196.6***	317.4***
Moran's I on residuals	0.899***	0.883***	0.883***

Note: *** p < 0.01

4.2. GWR RESULTS

The outcomes of the GWR models (Table 3) show that both Model 4 and Model 5 demonstrate significantly higher R^2 values compared to Model 2 and Model 3, indicating a decent fit of these models. This implies that the GWR models outperform the OLS models in the efficacy of elucidating results and their capacity to describe spatial variations of micro-environmental characteristics. Notably, incorporating visual features exhibit slightly better explanatory power than perceived design quality, contrary to the OLS findings. Moreover, the wider range of the coefficients for certain variables suggests the spatially uneven and considerably non-stationary distribution of estimated coefficients, underscoring the essential role of GWR analysis in capturing intra-city spatial interactions within the data.

Table 3. GWR results for visual features and perceived design qualities

Variable	Model 4 (3Ds + visual features) coefficient				Model 5 (3Ds + perceived design qualities) coefficient			
	Min	Median	Max	STD	Min	Median	Max	STD
Intercept	-52.5	19.9	111.1	28.5	-63.4	-0.2	32.3	16.6
PopDen	-0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0
WorkDen	-0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0
Total_mix	-23.0	1.60	43.5	10.9	-18.6	0.9	41.1	10.3
LConn	-4.0	0.0	9.0	2.3	-3.3	0.1	7.5	2.1
BtA800c	-0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0
Length	-0.1	0.0	0.2	0.0	-0.1	0.0	0.1	0.0
Slope	-3.7	-0.1	1.5	0.8	-3.0	-0.1	1.9	0.6
Micro-level Characteristics - Perceived Design Qualities								
DQ1_Gr	/	/	/	/	-122.8	-23.1	69.7	39.0
DQ2_En	/	/	/	/	-2793.8	-10.2	1086.7	355.0
DQ3_Op	/	/	/	/	-75.1	-8.9	35.9	23.5
DQ4_SF	/	/	/	/	-59.8	3.6	64.4	23.6
DQ5_Wa	/	/	/	/	-8516.4	-32.4	678.8	846.5
Micro-level Characteristics - Visual Features								
Ashcan	-8479.5	286.74	5008.2	1984.1	/	/	/	/
Awning	-4766.2	502.57	29153.8	4104.7	/	/	/	/
Bicycle	-58908.5	4.16	18322.9	7953.9	/	/	/	/
Building	-32.1	28.1	131.01	35.8	/	/	/	/
Car	-156.0	-13.1	205.6	67.0	/	/	/	/
Earth	-134.1	-10.1	52.3	33.2	/	/	/	/
Person	-1774.7	292.4	8681.9	1724.6	/	/	/	/
Railing	-1411.4	115.9	4449.1	521.6	/	/	/	/

Road	-69.2	28.3	190.9	49.7	/	/	/	/
Van	-683.5	14.4	1011.0	242.7	/	/	/	/
Wall	-581.7	10.1	517.5	167.2	/	/	/	/
Water	-2361.7	34.2	2815.4	476.8	/	/	/	/
R^2	0.670				0.645			
Adjusted R^2	0.657				0.635			

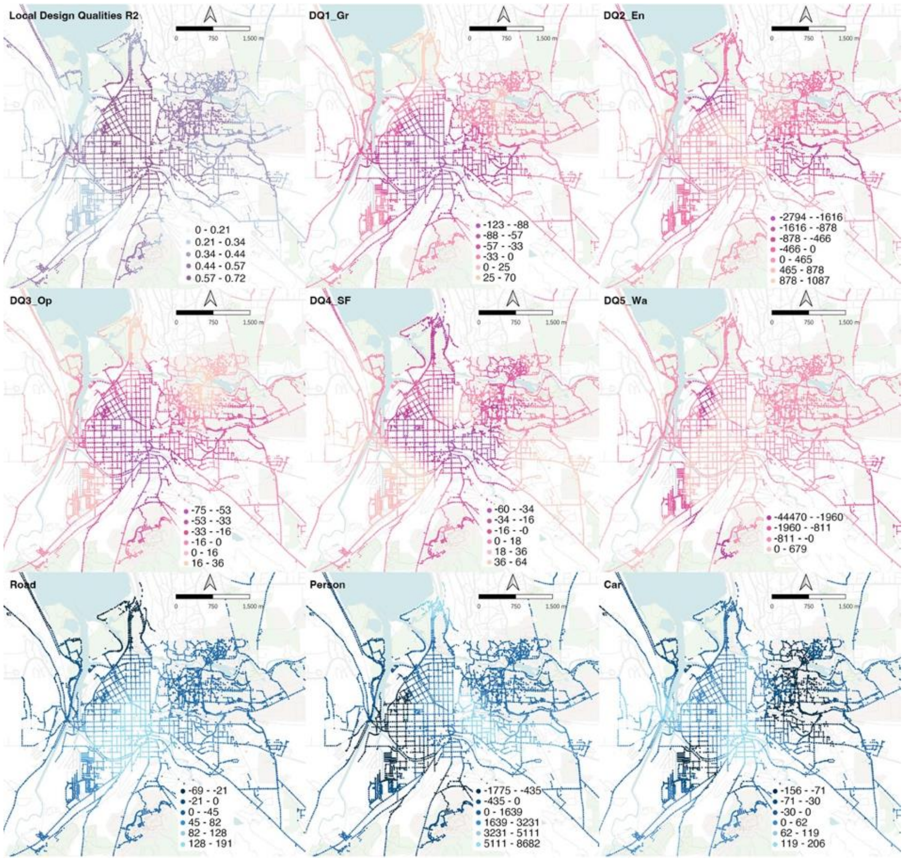

Figure 3. Spatial distribution of the local R^2 values for perceived design qualities and the coefficients of selected predictors

Figure 3 illustrates the spatial distribution of the local R^2 values for perceived design qualities in Ithaca, ranging up to 0.72. Areas with higher R^2 include Downtown, Collegetown, Cornell Campus, West End, Northside, and Fall Creek. Furthermore, the magnitudes and coefficients of perceived qualities and selected visual features have distinct spatial patterns, similar to a previous Singapore-based study showing spatially varying effects of macro-environmental characteristics on dockless bikeshare use (Shen et al., 2018). For example, in Downtown, West End, and Collegetown, greenness and openness display a negative correlation with DBS cycling volume, whereas walkability and enclosure demonstrate a reverse pattern. This demonstrates that dense vegetation and higher sky visibility in these areas will deter DBS cyclists, while enclosed streets with the pedestrian-friendly design (e.g. sidewalks and fences) will attract more DBS users. Therefore, policies and interventions for supporting cycling in these areas should prioritise vertical elements to enhance street enclosure and pedestrian-friendly design, rather than focusing on expanding green spaces. Similarly, the effect of street safety facilities is negative in Fall Creek, Northside, and the eastern part of West End, but positive in the centre of Downtown and the part of West End near Southside, implying that in these areas, the urban polices for enhancing street safety facilities should take into account spatial variations and not uniformly applied. Regarding visual features, road and person are positively associated with cycling volume in Collegetown and Cornell Campus, consistent with a prior study (Song et al., 2023), while contrary to the results of the impact of car. This suggests that a wider road allows for additional bike lanes and parking, thus encouraging cycling. However, the presence of cars poses an obstacle to cycling, possibly due to safety concerns. Overall, these results emphasize the spatial heterogeneous effects of perceived design qualities, indicating the need to tailor urban policies and interventions to different areas' BE characteristics to promote cycling.

5. Conclusion

In conclusion, we chose Ithaca, a small town in New York State, as a study area and calculated cycling volume using cycling routes collected from GPS devices on the DBS system. Employing a measurement framework based on SVI and CV, we quantified street-level design qualities and visual features. We then used OLS and GWR models to examine how these micro-environmental characteristics affect cycling volume. Although the GWR results reveal a minor yet higher strength for visual features than for perceived design qualities, the better performance of perceived qualities in both the overall OLS results and attribute groups confirms the necessity of considering design qualities in explaining DBS cycling behaviour. These results also imply that street design qualities could capture information beyond visual features and macro-level BE characteristics, thereby complementing them to some extent in explaining DBS cycling routes. Finally, the better explanatory power of the GWR models and the enhancement of OLS models after incorporating visual features and perceived design qualities prove the significant contribution of fine-grained environmental characteristics to bike-sharing cycling and provide more detailed insights into the spatially varied effects perceived design qualities. For instance, certain features and qualities might play a bigger role and positively influence the cycling volume in the downtown area, but not in Southside. Such nuances and variations in effects underscores that urban designers and planners should expand the scope of investigation from macro-level BE characteristics to micro-level ones but interpret the effects in a non-stationary approach. Such method could be used further as an effective reference to propose site-specific policies and micro-level street environment interventions.

Nevertheless, there are several limitations warranting further exploration in future research. First, we only explored the individual impacts of visual features and perceived design qualities on DBS cycling volume. However, the collective effects of these factors were not included in our analysis. Second, SVIs analysed in the study are one-directional, but since this is a conceptual test study, additional attempts to use 360-degree SVIs in the analysis process are desirable. Third, this study only focuses on objective measures of street-scene perceptions. However, given that human perception is a subjective and subtle human-environment interaction and that (Song et al., 2022) have predicted subjectively-measured qualities based on SVI, for future studies, effects of subjective perception of qualities might explain more nuance and complex user-environment relationships. Forth, due to the data anonymization and availability constraints, the personal information about cyclists (i.e., gender, age, and trip purposes) was lacking in our research. Yet, these factors are closely related to bike share usage and behaviour. Therefore, future studies should consider them in examining the relationship between bikes-sharing cycling behaviour and micro-environmental characteristics if data becomes available. Fifth, despite Lime's GPS timestamps, we neglected the temporal dimension. In fact, bike-sharing cycling behaviour can vary over time and different periods of the day (Shen et al., 2018), and thus future research should consider temporality for a more comprehensive analysis.

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