*Research Paper*

# Street Sky Openness Estimation Based on Deep Learning

## Case Study of Hakata Station Area, Fukuoka

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### Abstract

*The sky view factor has been recognized as an important indicator in the urban landscape and it is closely related to the physical and mental health of urban residents. In the past studies, the calculation of sky openness and the calculation of measurement indices were still mostly done manually, which was time-consuming and laborious. Meanwhile, Walk Score is widely used to measure the accessibility of surrounding amenities, often considering the physical characteristics of streets. In this study, we provided a method to calculate the sky openness of street-based on semantic segmentation processing of street view images. Based on a deep learning model, this study semantically segmented the streetscape images of roads around the Hakata station area in Fukuoka, Japan. The results could be compared with the Walk Score. The correlation analysis between the street sky openness and Walk Score would also be conducted. The findings showed that there is a negative correlation between street sky openness and Walk Score. This study is based on the estimation of street view images; therefore, it can more truly reflect the current situation of the street, and the model's high efficiency also makes it more suitable for large-scale urban research.*

### Keywords

*Sky view factor, Walk Score, Urban planning, Semantic segmentation, Deep learning*

## 1. Introduction

In the process of urban development, the uncontrolled expansion of urban land has caused traffic congestion, insufficient public space, and environmental pollution (Chen et al.,2019). Streets, as an important component of urban landscapes, can reflect the image, life quality, and vitality of public space (Tang et al.,2022). Streetscape also plays an important ecosystem function. Creating good walking conditions in the streets contributes to a better living environment for people (Schroeder&Cannon,1983) and helps some patients to recover after surgery (Pazhouhanfar&Kamal,2014). In addition, the geometry of the street valley affects the daily experience of pedestrians. The openness of the street directly influences the amount of solar radiation on the ground (Carrasco-Hernandez et al.,2015), which in turn affects the thermal comfort of pedestrians, a point that requires particular public attention in the hot summer months. Conversely, streets with too much enclosure tend to create a sense of oppression for pedestrians, which affects their perception of their surroundings and reduces their willingness to walk in the streets (Asgarzadeh et al.,2014).

The sky view factor (SVF) has been used to be discussed the association with the physical and mental health of urban residents (Xia et al., 2021). In Japan, the sky view factor of the street is an important indicator of landscape design. In the past studies, the calculation of SVF and the calculation of measurement indices were still mostly done manually, which was time-consuming and laborious. In recent studies, researchers have simulated urban landscapes through high-resolution remote sensing data, but the data analysis from an overhead angle can hardly reflect the experience and perception of the streetscape by pedestrians on the ground (Li et al.,2015).

Walk Score is widely used to measure the walkability of streets as a reflection of the urban structure, often taking into account the distribution of amenities within walking distance. Lots of studies have been conducted on the Walk Score by researchers from different countries and regions. For example, Walk Score could be used as a method to quantify the accessibility of facilities in a neighbourhood and to analyse the relationship between public transportation accessibility and Walk Score (Carr et al.,2010,2011; Duncan et al.,2013). In addition, Walk Score has been used to predict the walking potential of neighbourhoods (Cole et al.,2015) and to assess the walkability of adults (Hajna et al.,2015).

Existing street images can capture the spatial form of the street and have a similar angle to that of a pedestrian, prompting an intuitive perception of the surrounding landscape environment. Simple visual analysis in the past usually used pictures to quiz the investigators and tally the results. With the continuous development of artificial intelligence technology, it's possible to apply training models to parse semantic information from street images, and this research process has become significantly more automated. This study processes the streetscape with a model from the perspective of computer vision analysis to quantitatively assess the impact of the sky view factor in the streetscape on walk score in urban area. The sky view factor can reflect the structural characteristics of a street by reflecting the street sky openness. Through exploring the relationship between street sky openness and Walk Score, we aim to analyse the influence of street environment on walking behaviour in urban centre areas.

## 2. Deep learning and street view images

With the development of computer science technology, many challenging computer vision topics are being effectively addressed by various types of deep neural networks, such as convolutional neural networks, recurrent networks, etc. (Ghosh et al., 2019). There is a lot of research in the field of object detection and recognition, but at the same time, many new deep learning techniques have been involved in image segmentation. Researchers have begun to use the deep learning model to collect specific information from varieties of street view pictures. For example, image segmentation analysis can be used to identify the plants or even the green ratio to evaluate the urban green visual level (Dong et al.,2018). U-Net, as a popular deep convolutional neural network module, is applied for semantic segmentation to extract architectural footprints from high-resolution multispectral satellite images (Li et al.,2019). Another domain where applied image segmentation is essential is surveillance. Many occasions, such as pedestrian detection (Leibe et al.,2005) and traffic surveillance (Friedman&Russell,1997), have required the segmentation of objects (e.g., cars or bicycles). Deep learning techniques have advanced new classes of image segmentation algorithms. Earlier studies (Zhao et al.,2017) have shown the potential of deep learning-based methods. And there are also studies (Geng et al.,2018) covering several approaches and comparing them based on their reported performance. Garcia-Garcia et al. (2017) listed various deep learning-based segmentation techniques. They tabulated the performance of various state-of-the-art networks in several modern challenges. The literature is very useful to understand the state of the art in this field.

Recently, the number of literatures on street view images (SVIs) has risen exponentially (Xu et al.,2021). SVIs such as Google Street View images (Yin&Wang,2016), Baidu Street View images, and Tencent Street images are widely used to symbolize the street environment in cities and can be used to calculate the sky view factor, green view index, and other street environment estimation factors. Researchers led by Carrasco-Hernandez (2015) have demonstrated that the sky view factor could be calculated based on Google Street View images, while Liang et al. (2017) provided proof-of-concept research to estimate the sky view factor based on street panorama images. Li et al. (2018) also demonstrated by examples that Google Street View images can be applied to the study of street openness. In addition, street-level images have been used to measure physical activity on the street (Lu,2019), map urban perceptions (Zhang et al.,2018), visually assess neighbourhood walkability (Zhou et al.,2019), and understand social sensing. There has also been some recent research work that has turned to the use of street-level image data to assess the association between streetscapes and the mental health of residents (Bader et al.,2015). However, this kind of literature has focused on empirical studies in North American and European cities, and few studies have been conducted in Asian cities (Rzotkiewicz et al.,2018). With the development of big data applications, street view images will continue to have greater potential in environmental landscape research, as Google Street View images can cover most major urban areas in the world, providing unprecedented opportunities for a survey.

## 3. Study area and methodology

### 3.1. Case study

The area around the Hakata Station in Fukuoka City is selected as the study area. Fukuoka is the capital city of Kyushu, Japan, which is built along the shores of Hakata Bay and has been a centre of international commerce since ancient times. In addition, Fukuoka is the largest city and metropolitan area west of Keihanshin with a population of 1,603,543. Hakata Station is a major railway station located in Hakata-Ku, Fukuoka. It's the largest and busiest railway terminal on Kyushu Island, regarded as a gateway to other cities in Kyushu for tourists. For the sake of research rigor, this study hopes to analyse areas that span a wide range of functions rather than a single functional area. The location and scope of the study area are shown by the red dotted line in Figure 1, which consists of mixed land use and its area is 2.46km$^2$. The study area is a functional area with major transportation points, commercial areas, residential areas, and scenic riverfront areas.

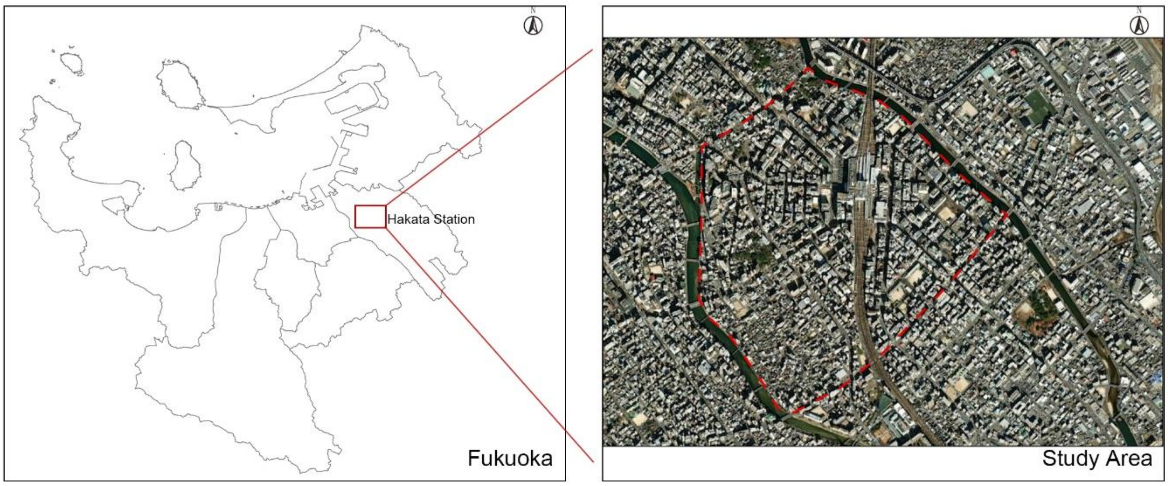
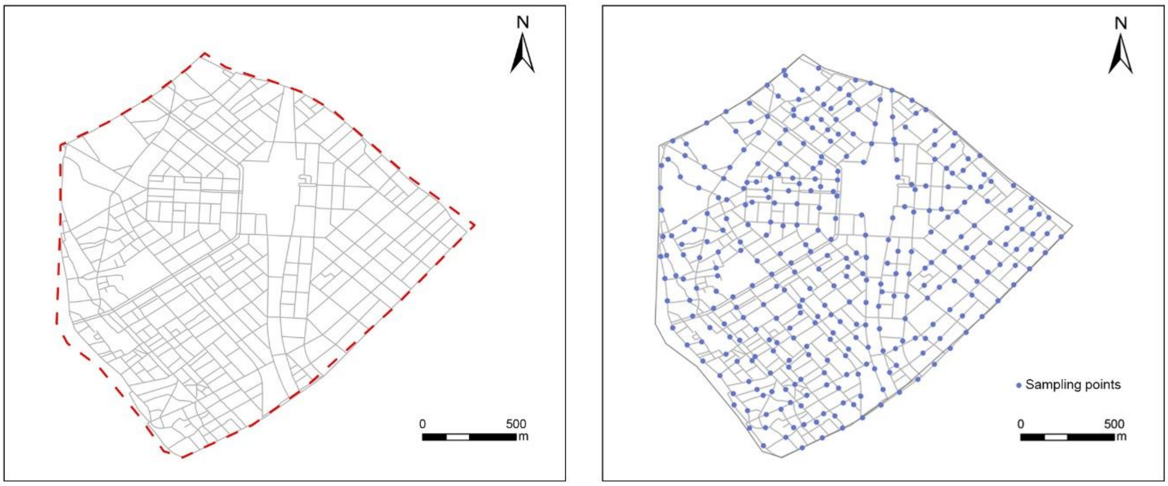



**Figure 1. Location of the study area. Source: MILT of Japan, Google Map**

### 3.2. Data source

We obtained the street network of the study area from the Open Street Map website, and we set sampling points along each main road at 100-m intervals (Figure 2). Google Street View (GSV) has provided public application programming interface (API) services that enable applicants to request and download static panoramic street view images using the APIs. The timing of the images should be chosen in spring and summer to avoid the lack of leaves in autumn and winter that would affect the accuracy of the sky view factor calculation. In total, 334 sampling points with coordinates were set in the study area and we downloaded the panoramic street view images of these sampling points.

In addition, for the data of POI required for the Walk Score calculation, we crawled the geographic data (including name, latitude, and longitude) of different facilities in the study area from the Mapfan website (https://mapfan.com/).




(a) (b)

**Figure 2. (a) The street map and (b) sampling points distribution map of the study area. Source: Open Street Map; self-drawn**

### 3.3. Methodology

#### 3.3.1. Semantic image segmentation

Image segmentation is defined as an image processing technique that can be used to divide the image into several meaningful regions. Semantic segmentation is regarded as the most classic version (Garcia-Garcia et al.,2017). In this study, the main image processing method is semantic image segmentation based on a python deep learning model, which is an image processing method in computer vision whose goal is to assign a category label to each pixel in an image. It can locate specific objects in the image and classify discrete categories that describe the image. The prediction model is deeplab v3+ based on PyTorch to train the model. The cityscape dataset is used, with a training dataset of 3475 street images and a validation set of 1525 images. In the training of the model, the number of iterations is set to 30,000, and the loss value finally converges to 0.0301. The accuracy of this deep learning prediction model is 0.721.

We used semantic segmentation to automatically extract the sky area from the collected street view images. Based on the cityscape dataset, we could extract the sky type from the original 19 categories, namely road, sidewalk, building, wall, fence, pole, traffic light, traffic sign, terrain, vegetation, sky, person, rider, car, truck, bus, train, motorcycle, and bicycle (Table 1).

**Table 1. Segmentation items in the recognition of images in the cityscape dataset**

| Number | Category | Type |
|---|---|---|
| 1 | Road | Flat |
| 2 | Sidewalk | Flat |
| 3 | Building | Construction |
| 4 | Wall | Construction |
| 5 | Fence | Construction |
| 6 | Pole | Object |
| 7 | Traffic light | Object |
| 8 | Traffic sign | Object |
| 9 | Terrain | Object |
| 10 | Vegetation | Object |
| 11 | Sky | Sky |
| 12 | Person | Human |
| 13 | Rider | Human |
| 14 | Car | Vehicle |
| 15 | Truck | Vehicle |
| 16 | Bus | Vehicle |
| 17 | Train | Vehicle |
| 18 | Motorcycle | Vehicle |
| 19 | Bicycle | Vehicle |

Then we used python to calculate the proportion of pixels in the sky classification to the total pixels in the original image, to calculate the sky view factor in streets based on the perspective of the street view images taken. The specific calculation formula is as follows.

$$SVF = \frac{Area_s}{Area_t} * 100\%$$

*SVF: sky view factor; $Area_s$: the total number of pixels representing the sky in the image; $Area_t$ : the total number of pixels in the image.

### 3.3.2. Estimation of Walk Score

In the calculation of Walk Score, we reclassified the POI data obtained from Mapfan and assigned corresponding weights to the POI data of different types of facilities. Based on the classified results, and the simplified and topologically processed road network (from Open Street Map), the network dataset was constructed to calculate the service range of 400m, 800m, 1200m, 1600m, and 2400m for each type of POI data. The service range of each type of POI data was multiplied by the corresponding decay coefficient, and then the evaluation results of the service level of the facility were obtained by weighted superposition. We performed simplifications for Walk Score in two aspects. On the one hand, this study focused on the functional mix of facilities instead of considering the distribution density of facilities. For example, there was one restaurant or two restaurants within 400 meters that were given the same weight. We were more concerned with the diversity of facilities, as having one facility within the service range could be sufficient to meet the needs of daily life. Long and Zhou (2016) have demonstrated that the functional mix of streets has a higher impact on street vitality that the functional density of streets. Referring to the Walk Score method of classifying facilities and assigning weights, we have modified the selection of the facilities according to the local conditions of Japanese cities. Drinking bars and coffee shops were classified as restaurants. As post offices in Japan handle banking services and they were included in the facilities of banks along with ATMs. The classification of facilities and their weights are shown in Table 2. On the other hand, we used a piecewise function for the calculation (Table 3), taking into account the walking distances of people. We set the service without attenuation for facilities within 400 meters, with an attenuation coefficient of 0.9 in the range of 400-800 meters, 0.55 for 800-1200 meters, 0.25 for 1200-1600 meters, and 1600-2400 meters with an attenuation coefficient of 0.08, and facilities beyond the range of 2400 meters would not be considered to have service level.

**Table 2. Categories and weighting of facilities**

| Category | Weight |
|---|---|
| Catering（restaurant, drinking bar, coffee shop） | 3 |
| Supermarket, convenience store | 3 |
| Park | 2 |
| Education Facility (kindergarten, school, university) | 2 |
| Shopping mall | 2 |
| Medical Facility | 1 |
| Financial Facility (bank, post office, ATM) | 1 |
| Bookstore | 1 |

**Table 3. Decay coefficient of the piecewise function**

| Distance(m) | Decay coefficient |
|---|---|
| 0-400 | 1.00 |
| 400-800 | 0.90 |
| 800-1200 | 0.55 |
| 1200-1600 | 0.25 |
| 1600-2400 | 0.08 |
| >2400 | 0.00 |

### 3.3.3. Pairwise Pearson Correlation analysis

The relationship between different things is the objective existence. Thus, the analysis of the relationship between variables is an essential part of this research work. It can help researchers to judge the related variables and improve their level of knowledge. Correlation analysis is a statistical research method. Correlation is the external performance level of the object, and it can reflect the similarity between the phenomena displayed in the process of development (Xu et al.,2019). Here, Pairwise Pearson Correlation was used to analyse the correlation between the street sky openness and Walk Score for every sampling point in the study area. The Pearson Correlation coefficient can be used to quantify the linear relationship between distributions (or features) in a single metric. It ranges from -1 to 1, -1 being a perfect negative correlation and +1 being a perfect positive correlation.

## 4. Results

### 4.1. Results of street sky openness estimation

Figure 3 shows the visual recognition results of semantic segmentation. The different coloured markers represented the different elements in the panoramic street view image as well as those that were identified and classified. The calculation of the SVF showed that the overall average sky ratio within the study area was 24.38%, with a maximum of 41.25% and a minimum of 2.77%. The SVF value ranges from near 0, indicating little sky openness, to 1.0, indicating total sky openness. The resulting CSV file was then used to correspond with the sampling points in ArcGIS pro to add the SVF attribute, and Figure 4 shows the spatial pattern of its visualization. In cities, the SVF is lower in areas with high-density development and vice versa. The area around Hakata Station in Fukuoka City is surrounded by high-density housing, and overall, the SVF in this area is low. This is because the sky view is blocked by high-density buildings and narrow streets or excessive vegetation landscape. In the study area, the SVF is higher along the main road and the riverside scenic path because the sky view is not blocked to a large extent due to the wide road and landscape view along the river.

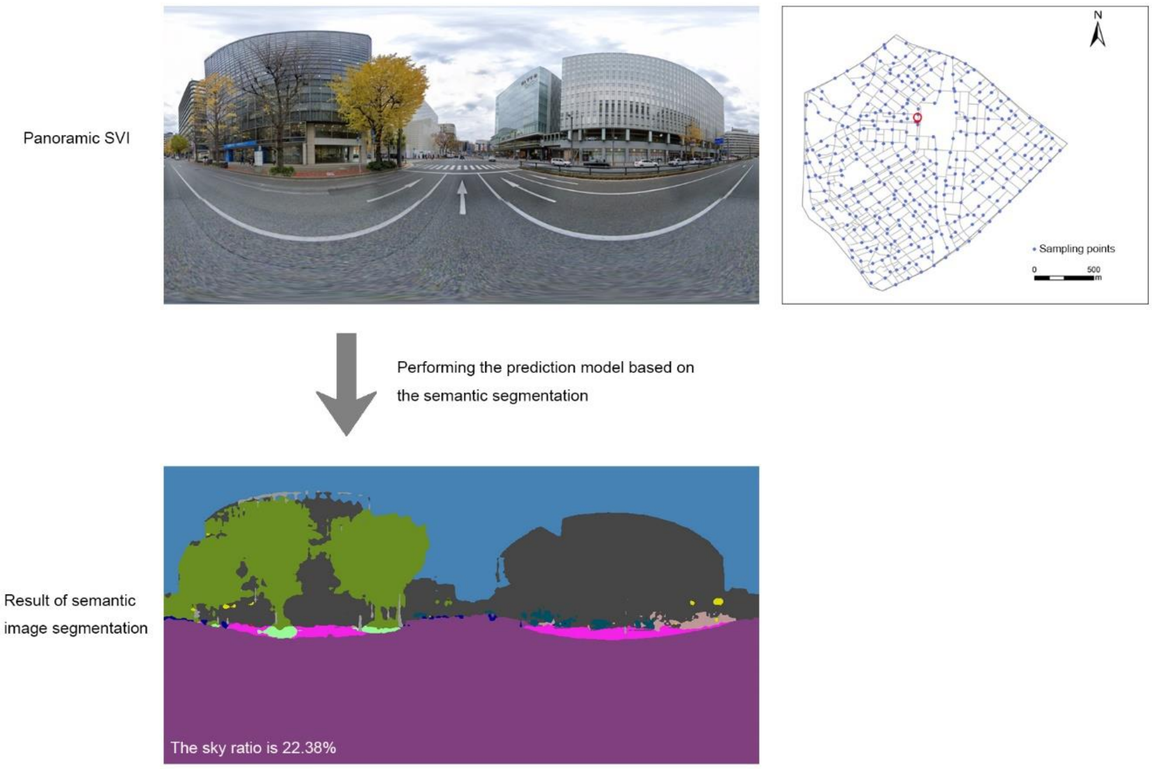



**Figure 3. The location of the point in the study area and the example of extracting sky view factor from SVIs.**

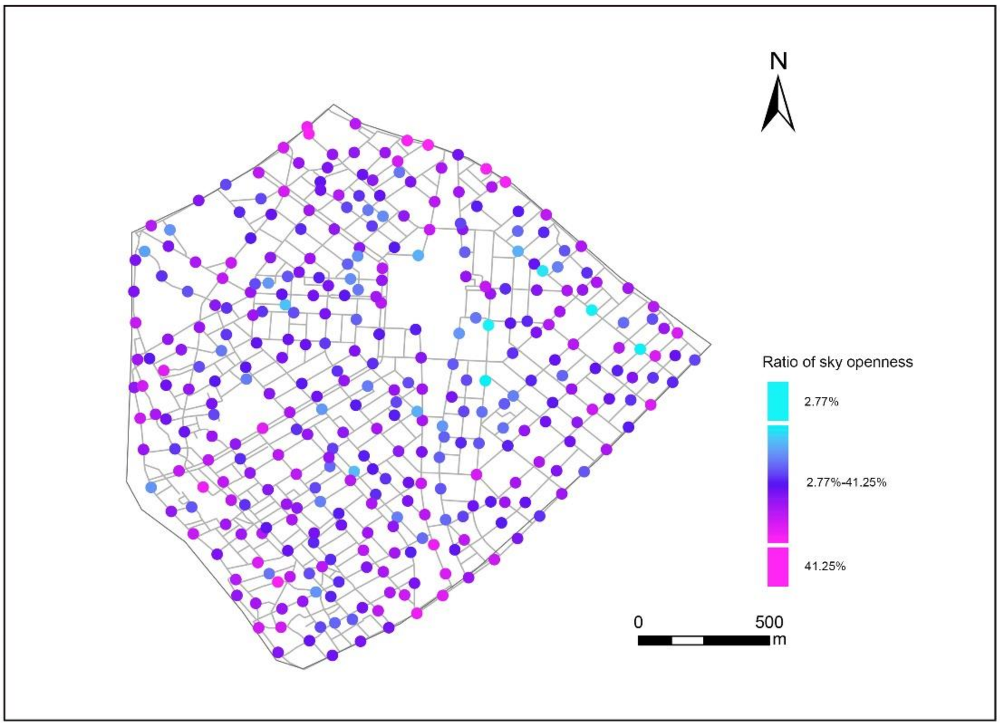



**Figure 4. Spatial pattern of sky openness in the study area**

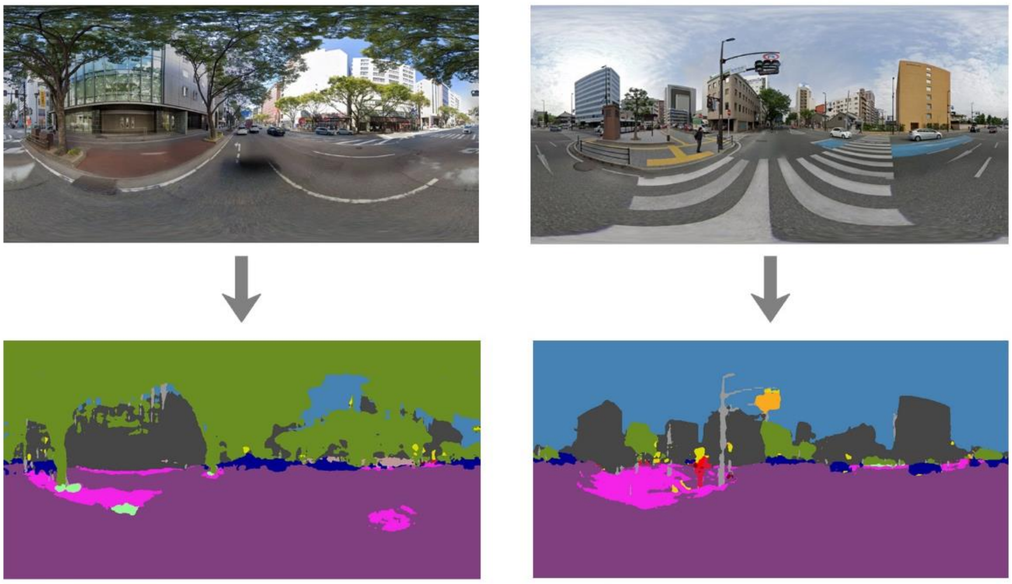



**Figure 5. Examples of the sky openness in the street**

Figure 5 shows the real view of streets with a sky ratio of 2.77% and 41.25%, respectively. It can be found that the streets with the lowest SVF have not only a higher density of buildings but also a richer green landscape in the street with a larger area shaded by trees, which makes the sky view small. This sampling point is located on the road in front of Hakata Station, which is richer in landscape and facilities. The street view image of the sampling point with the highest SVF shows that the sampling point is located on the main road and although there are many buildings, the road is wider, and the view of the sky is not blocked. It can be seen that the width of the road, the density of buildings, and the distribution of green landscape all have an impact on the openness of the sky in the street.

## 4.2. Results of Walk Score estimation

The spatial distributions of the comprehensive evaluation of the walkability of streets in the study area are shown in Figure 6. The walkability of the study area near Hakata station is significantly higher than that of the peripheral areas. With Hakata station as the centre, the Walk Score gradually decreased with increasing distance, and the Walk Score of the eastern area was higher than that of the western area. The Walk Score was divided into five levels according to the Walk Score method, and Table 4 shows the frequency and proportion of Walk Score in the study area.

Walk Score in the study area ranged from a high of 100 to a low of 84.042, with an average of 95.23. Overall, the Walk Score in the study area was high. All the sampling points in the streets have reached a very walkable level and 91% of the sampling points have reached the highest level of Walk Score. Only some of the roads along the river and the sampling points located in the annex of the main road have a lower Walk Score than the sampling points around Hakata station. The study area is located in the CBD area of Fukuoka city and has a very important transportation node, Hakata station, and a lot of commercial facilities in the surrounding area, which makes it more convenient for the residents.

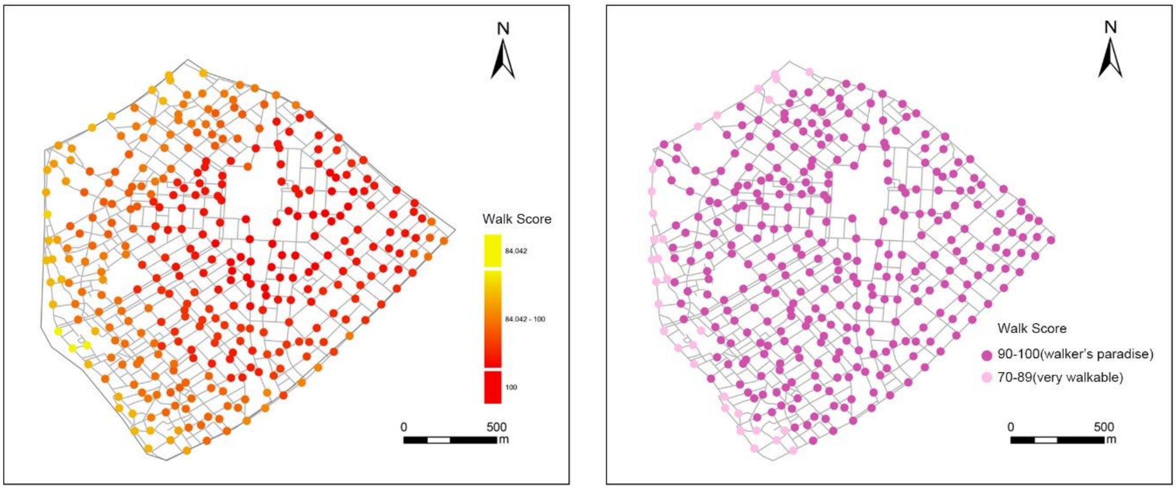



**Figure 6. Spatial distribution of Walk Score in the study area**

**Table 4. Frequency and proportion of walk score (5 levels)**

| Walk Score | Description | Frequency | Proportion |
|---|---|---|---|
| 90-100 | Walker's Paradise | 304 | 91.02% |
| 70-89 | Very Walkable | 30 | 8.92% |
| 50-69 | Somewhat Walkable | / | / |
| 25-49 | Car-Dependent (Most errands require a car) | / | / |
| 0-24 | Car-Dependent (Almost all errands require a car) | / | / |

### 4.3. Association between street sky openness and Walk Score

To determine the relationship between street sky openness and Walk Score, the Pearson Correlation was conducted between the SVF and the calculated Walk Score for each sampling point in the study area, for a total of 334 points. As shown in Table 5, the correlation coefficient between street sky openness and Walk Score was -.292 with a significance of .000, which shows a significant negative correlation at the 0.001 level, indicating that Walk Score was strongly related to the street sky openness in the study area. The lower the SVF, the higher the Walk Score, and conversely, the higher the SVF, the lower the Walk Score.

**Table 5. Correlation analysis of street openness and Walk Score**

| | | Street sky openness | Walk Score |
|---|---|---|---|
| Street sky openness | Pearson correlation coefficient | 1 | -.292*** |
| | Sig. | | .000 |
| | Number | 334 | 334 |
| Walk Score | Pearson correlation coefficient | -.292*** | 1 |
| | Sig. | .000 | |
| | Number | 334 | 334 |

*** Indicates that it correlates significantly with the level of 0.001 (p <0.001).

## 4. Discussion and conclusion

In this study, we analysed the sky view factor of streets in the area around Hakata Station in Fukuoka City and visualized the street sky openness in the study area. Deeplabv3plus neural network model was used for predictive analysis and semantic segmentation of 334 panoramic street view images. At the same time, we also introduced the research idea of Walk Score to evaluate the walkability of streets by considering the functions of streets and the street environment comprehensively. In practice, we also optimized the calculation method of Walk Score, focusing on the diversity of street functions, and used the piecewise function instead of the continuous function to calculate the distance decay coefficients of facility services, which greatly improved the calculation efficiency and facilitated the subsequent large-scale extension of the calculation. Through correlation analysis, street sky openness has a significant negative correlation with Walk Score. That is, streets with high walkability are surrounded by a denser distribution of facilities, and more buildings and landscape will be distributed in the area. In the street, the construction of buildings will block the view of the whole street, making the sky ratio (sky view factor) lower. However, the sky view factor is still a very important index in the urban landscape construction, and the subsequent urban construction should consider the sky view factor to plan the building construction and landscape under the condition of ensuring the function of the area.

However, there are limitations in this study, as we have only studied the relationship between street sky openness and Walk Score for the streets in the CBD area of Fukuoka City, which is more developed and has various facilities and street construction. In the future, we will expand the study area to analyse the relationship between street landscape construction and walkability in other less developed areas. In addition, pedestrian perception of walking on urban streets is less considered in the calculation of Walk Score. Pedestrians' perception of the street environment is very important, and the street environment affects pedestrians' moods and further influences their willingness to walk. Street sky openness, as visual perception, can be introduced into a psychological questionnaire for street walkers to more comprehensively evaluate the perception of walking in the streets.

## 5. Acknowledgement

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