Web-based spatio-temporal data visualization technology for urban digital twin

Qing Yu[1,2], Wen-long Shang[3], Jinyu Chen[4], Haoran Zhang[4]

[1] Department of Computer Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China

[2] The Key Laboratory of Road and Traffic Engineering, Ministry of Education, Tongji University, College of Transportation Engineering, 4800 Cao'an Road, Shanghai 201804, People's Republic of China

[3] Beijing Key Laboratory of Traffic Engineering, College of Metropolitan Transportation, Beijing University of Technology, Beijing 100124, People's Republic of China

[4] Center for Spatial Information Science, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8568, Japan

Email: 1810514@tongji.edu.cn

Abstract: The digital twin technology is a fast-growing research topic, but it is still in its infancy. The organic combination of urban digital twin and web-based visualization of spatio-temporal big data is one of the important directions for future smart city decision-making, planning, and management. This chapter introduces the potential of web-based visualization technology for enhancing the visualization of massive spatio-temporal data. The advantages, key technologies, and common tools of web-based visualization, as well as the common form of visualization for different data. This chapter also presents an example of a web-based digital twin project called 3D UrbanMOB, including its feature, design concepts, and development details. This field is becoming increasingly important as researchers become more conscious of the necessity to use urban digital twin for monitoring, modeling, and assessment of urban events in the development of next-generation smart cities.

Key Words: Spatio-temporal big data, Digital twin, Data visualization, Web-based visualization

1. Introduction

With the wide usage of smart mobile devices and the fast development of the Internet of Things (IoTs) technology in recent years[1], GPS Positioning Data generated by individual users are collected began to grow explosively. Also known as "spatio-temporal big data" or "Track &Trace data"[2], these data are widely considered as a powerful source to support the construction of the next-generation smart city and have already triggered and motivated a large number of scientific research in relevant fields[3-9]. These spatio-temporal big data typically require three aspects of information [10, 11]: Who? When? Where? They can completely capture individuals' everyday activities and travel behavior in both temporal and spatial dimensions[12].

The emergence of large-scale spatio-temporal big data has also brought about the demand for data visualization[13]. Data visualization figures can be used by researchers to express their perspectives and notion and have grown in importance as a tool for academics to extract relevant information from their data. Data-driven research may give valuable insights for comprehending the present situation of the urban system and assisting with urban management in the field of transportation[14, 15], energy[16, 17], human mobility[18], urban sustainablility[19, 20], emergency management[21, 22], etc.

As a part of the Industry 4.0 wave, the concept of Digital Twin(DT) is emerged, which is defined as a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making[23-25]. In urban areas, an urban D.T. is a digital version of a smart city that may be used to replicate and visualize real-world occurrences. It is frequently presented in the form of interactive platforms that can record and display real-time 3D spatio-temporal data in order to model urban settings and data flows[26]. In fact, an urban D.T. can be regarded as a higher level of data visualization system with the integration of multiple interactive applications.

The emergence of web-based visualization technology has brought a new way to visualize spatio-temporal big data. Meanwhile, the web-based application with the D.T. system deploying on a web page creates easy access dynamic and interactive experience for users. The organic combination of urban D.T. and visualization of spatio-temporal big data is one of the important directions for future smart city decision-making, planning, and management[27].

In this chapter, we seek to address specific research questions regarding web-based visualization for spatio-temporal big data:

- What are the advantages, key technologies, and common tools of web-based spatio-temporal big data visualization?
- How to use web-based visualization technology to properly visualize spatiotemporal big data?

The rest part of this chapter is organized as follows: Section 2 introduces the advantages, key technologies, and common tools of web-based visualization; Section 3 introduces the common form of spatio-temporal data visualization; Section 4 introduces an example of spatio-temporal data visualization using web-based technology; Section 5 draw the conclusions of our discussions.

2. Web-based data visualization technology

2.1. Advantages of Web-based data visualization

The following difficulties exist in the visualization of spatio-temporal big data:

- **Massive data:** Spatio-temporal big data usually involve a massive amount of data[28]. Real-time dynamic and interactive data visualization will occupy considerable computation resources and generates high requirements for visualization.
- **Various characteristics:** Spatio-temporal big data involves multiple types of data with different characteristics (taxi GPS data, bicycle-sharing data, bus GPS data, etc.). Flexible visualization approaches are also required to show diverse types of data in a suitable manner.
- **GIS-based:** The spatial information of the data is the most important part, which means that the data visualization should be GIS-based, and a large part of data presentation and interaction should be on the map application.
- **Responsive interaction:** Spatio-temporal big data contains information in multi-dimensions. A better way to present the data is in the form of responsive interaction, which can help users perceive data.

To deal with these challenges, Web-based visualization technology have the following features that can well solve the above difficulties. The highlight advantages of Web-based visualization technology include follows:

- Web-based visualization technology can be built upon Web Map Service (OpenStreetMap, mapbox, etc.), which supports rendering large geospatial data sets with interactive events. Also provides highly customizable and flexible APIs to present multiple forms of data visualization.
- Web-based applications are with high compatibility that can be easily accessed by any device by visiting the web page, which is helpful to promote among users.
- Web-based applications are based on JavaScript programming language, which has superior performance and great potential to integrate popular industries or algorithms like Machine Learning, Data Analysis, and Spatial data processing.

The above advantages make web-based data visualization become one of the most suitable technology for developing urban D.T. applications.

2.2. The key technology of Web-based data visualization

2.2.1. HTML5 webpage standard

In recent years, web-based data visualization has become the mainstream of data visualization technology. It visually exhibits data figures on a web page so that users may readily access visualization figures via a web browser. Web-based data visualization is a type of webpage that is powered by the HTML5 standard[29]. HTML5 is the fifth version of HyperText Markup Language (HTML) for delivering website content on the World Wide Web, and it is regarded as one of the Internet's basic technologies.

The HTML5 webpage is usually supplemented by the Cascading Style Sheets (CSS) and JavaScript to support the animation and interactivity of webpage elements. In general, HTML determines the overall structure of the page; CSS determines the presentation style of the webpage contents, including layout, colors, and fonts; JavaScript provides the engine to enable programming and execute the code on the web page. Compared with Adobe Flash (the traditional way of webpage interaction), the HTML5 standard is safer, more efficient, and compatible[30, 31].

2.2.2. WebGL 3D graphics rendering

Web Graphics Library (WebGL) is a standard that serves as a bridge between JavaScript and OpenGL (Open Graphics Library), allowing JavaScript to generate 3D graphical objects[32]. It also supports GPU-accelerated rendering of 3D scenes and models as part of the web page canvas in web browsers[33].

With the help of WebGL, web developers are able to present 3D objects (3D models, buildings, terrain, etc.) with live effects(sunlight, shadow, fog, etc.) on WebGL map to construct a highly realistic 3D city on the website. These features make WebGL becoming one of the most suited technology to build urban D.T. and visualize large-scale spatio-temporal data.

2.2.3. JavaScript framework

A JavaScript framework is a pre-written collection of code designed to assist applications and provide features that plain JavaScript does not deliver on its own. JavaScript frameworks are designed to perform numerous functions and serve as the foundation of a web application[34]. The JavaScript framework allows for expanded functionality without the need to write code from scratch.

React, Angular, and Vue are the three most popular JavaScript frameworks[35-37]. Taking React as an example, it employs JSX rather than standard JavaScript to help in the handling of U.I. within the JavaScript code. One of React's benefits is that it employs the virtual document object paradigm (DOM). When a change is made to a React app, the diffing algorithm is used to compare the old DOM to the new in-memory and then update the altered part of the DOM. As a result, React is faster for web pages and applications with a lot of interactive elements.

React-based apps can only update the altered portion of the data without re-rendering the entire dataset. This mechanism enables react apps to show larger amounts of data at a faster rendering speed with a quick response, which is especially useful when dealing with vast volumes of data visualization with interactivity.

2.2.4. Interaction between frontend and backend

In web development, the web application is usually separated into the webpage displaying contents (front-end) and the server storing the data and providing data access(back-end). For web-based data visualization, the design of interaction logic between the front-end and back-end will have a significant impact on the system function and response speed of the interaction. Generally, there are two types of settings: static web page and dynamic web page (Figure 1).

Static web page: Prior to visualization, the massive dataset is computed and converted to a small dataset, keeping only the part that the user needs to visualize. It arranges all possible user interactions in advance, and all visualization results are already computed and saved. As a result, when a user conducts an interactive activity, the front-end merely needs to locate the associated data file and then update the visualization. This approach of thinking allows the data query to be completed ahead of time and eliminates the utilization of the back-end.

Dynamic web page: When the user interacts with the visualized web page, the web page (front-end) sends the operation information of the interaction to the server (back-end). When the back-end receives the request, it implements the query on the database, obtains the result, and sends it back to the frontend for visualization. Dynamic web pages allow interaction with real-time data queries. Compared to a static web page, dynamic web pages usually request data by sending query parameters to the back-end through an API. Each time a request is sent, the back-end must query the data and then deliver the data after the results have been gathered. As a result, dynamic web pages may have a longer response time than static websites, but they may accomplish more flexible data interaction.

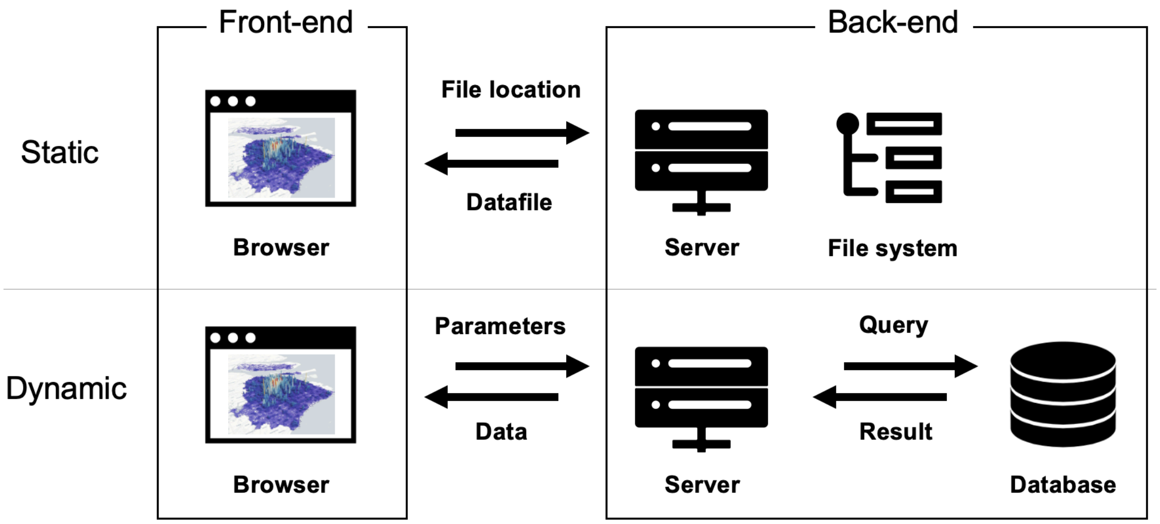


Figure 1 Static and dynamic web page

2.3. Web-based visualization tools

In JavaScript, there are already many mature libraries that can provide the integration of WebGL data visualization with web maps. Related tools are shown in Table 1. At present, these tools can be roughly divided into two categories. One is to provide the basic API interface for WebGL maps, which can display simple data information as layers on the map, such as Mapboxgl (based on Mapbox)[38], and leaflet (based on OpenStreetMap)[39]; The second category focus on the present of data, they are built upon the first category and further encapsulates the API to provide more advanced effects and visualization methods, such as Deck.gl[40], AntV-L7, ECharts.gl[41], etc.

Table 1 Popular spatio-temporal data visualization libraries on JavaScript

Library	Description
Mapbox.gl	Provides APIs for building interactive web maps and web applications on Mapbox.
React-map-gl	A suite of React components for Mapbox GL JS-compatible libraries.
Deck.gl	WebGL-powered framework for visual exploratory data analysis of large datasets.
leaflet	Mobile-friendly interactive maps based on OpenStreetMap
AntV-L7	Large-scale WebGL-powered Geospatial Data Visualization analysis framework which relies on Mapbox GL or AMap to render basemaps
Maptalks.js	An open-source javascript library to create integrated 2D/3D maps with essential features for mapping projects.

ECharts.gl	WebGL-based data visualization tools provide multiple types of charts. Also provides integration of WebGL maps powered by Mapbox or maptalks.

3. Visualization of data

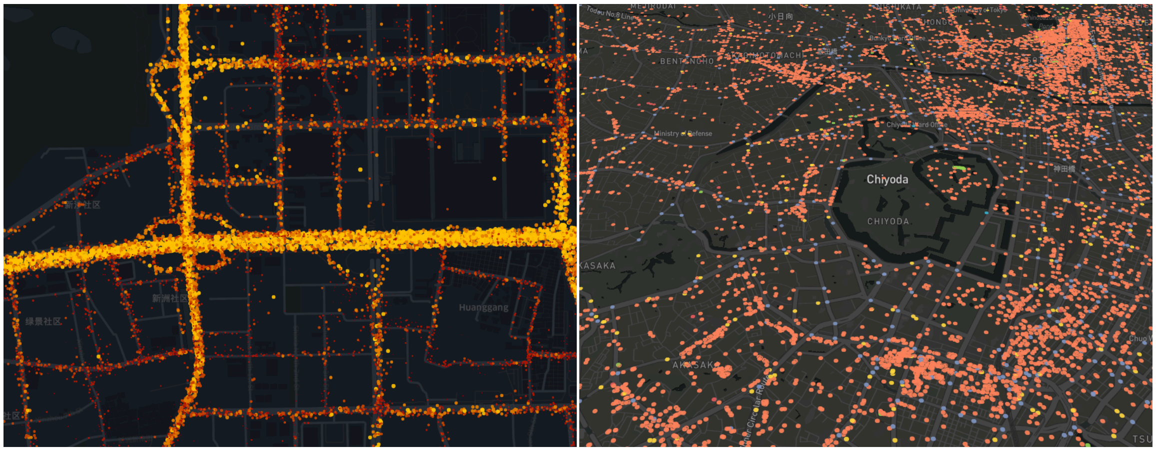
In the urban digital twin, there are many types of data that need to be presented. The previously stated Web-based visualization tools also offer several forms of visualization. These visualization forms can be roughly divided into three types: Point, Line, and Region.

3.1. Point：GPS points, Point of interests

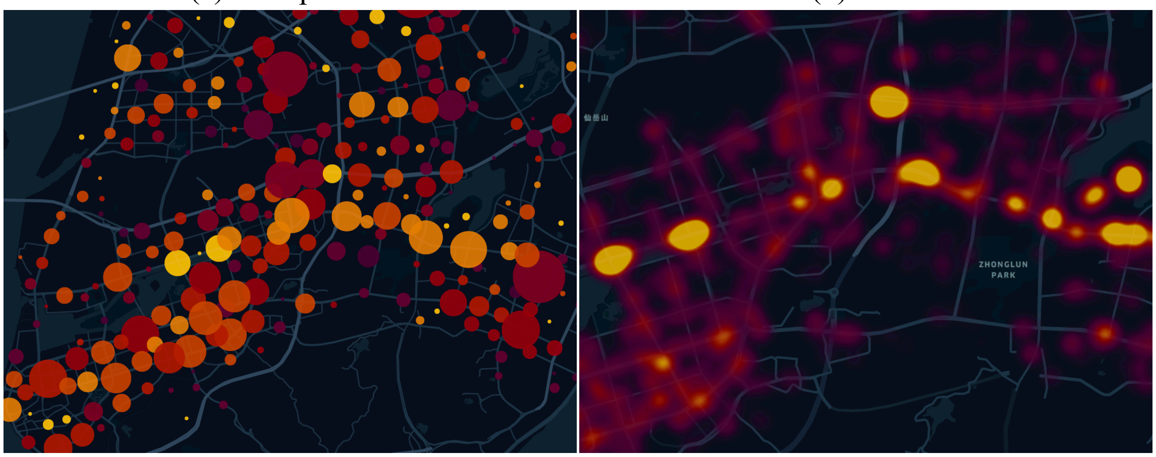
Point data (scatter plot) is the simplest form of presentation and is often used to represent GPS points or Points of interest (POI) data (see Figure 2).

In addition to spatial information, the marker size and color of the scatter plot can be used to represent additional dimensions of information (Figure 2(a) and (b)). It is also called the bubble plot if there is a difference in the size of the data points (Figure 2(c)). However, a bubble plot can only hold a limited amount of data. Too large bubbles may interfere with accurately identifying the location of the bubble center; some bubbles may also be too large to block and obscure smaller bubbles. If an extra dimension other than the location is to be displayed, color differences should be prioritized over size differences.

Point data can also be visualized with a heatmap to represent the concentration of the data distribution (Figure 2(d)). A heatmap is a thermal figure that has been smoothed and blurred. When creating a heatmap, three parameters are commonly included: point size, blur size, and colormap. The selection of parameters for a heat map can greatly affect the display; even the same dataset might be rendered substantially differently with various parameters.



(a) GPS points (b) POI



(c) Bubble plot (d) Heatmap

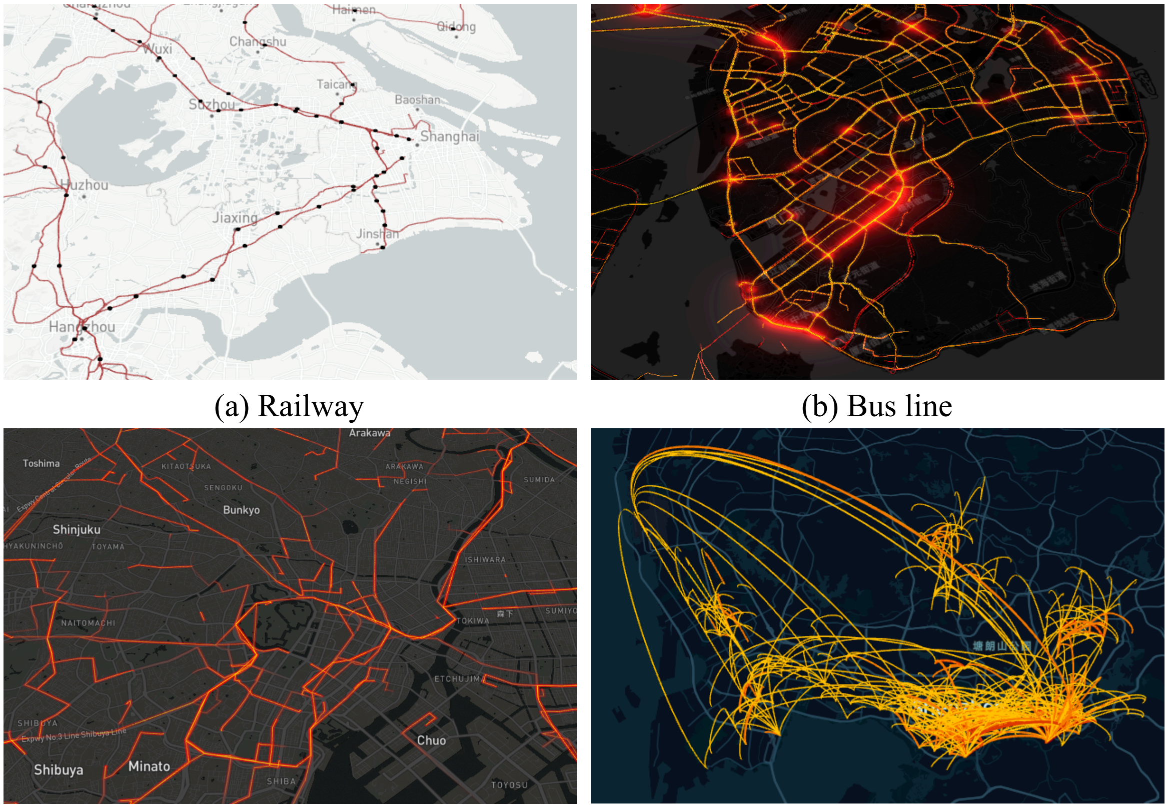
Figure 2 Visualization of points

3.2. Line: Trajectory data, Traffic line data, O.D. data

Lines are often used to represent trajectory data, traffic route data, and Origin-destination (O.D.) data (see Figure 3). Lines are divided into Line segments (only with starting and ending points) and polylines (multiple points on the line) in terms of morphology, and static and dynamic lines in terms of display in terms of how they are displayed.

Static lines are usually suitable for traffic lines (bus, subway, or roads) and O.D. flows, and for line segments with only start and end points, the curvature can be added to them for better visualization (Figure 3(d)). In some visualization tools, it is also possible to add dynamic light effects or arrows to the line to represent the direction of the flow.

Dynamic Lines are animated lines that are used to show trajectories(Figure 3(c)). Given a timestamp, the visualization tool calculates the trajectory's position and presents it with a trailing effect. It is feasible to create a time-controlled animation of the trajectory using this mechanism.



(a) Railway (b) Bus line

(c) Dynamic trips (d) OD

Figure 3 Visualization of lines

3.3. Region：AOI, Buildings, Grids, 3D bars

Region visualization is the polygon surfaces on the map, which is often used to represent polygon or multi-polygon data such as Areas of interest (AOI), administrative units, buildings, geospatial grids, 3D bars, etc. (see Figure 4).

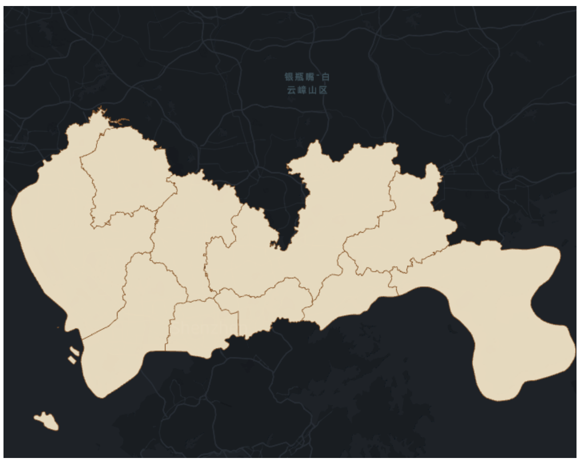
Region visualization is a common technique for geographic analysis involving location selection[6], spatial differentiation analysis[42, 43], etc. When visualizing region with areas with different size, the selection of spatial anayzing unit may have a significant impact on the visualization outcomes, which is also known as the modifiable areal unit problem[44].

One of the most common approaches to spatio-temporal big data processing is to match and aggregate it into grids with same size, as it provides a comparable and efficient way to process and present the data (Figure 4(b)). By mapping the data to various hues of warm and cool tones and displaying the data on grid-based map allowing researchers to clearly understand how the data are distributed regionally and spatially and to conduct spatially relevant data analysis and discussion[45-47]. For the task of generate, calculate, match, optimize and visualize spatial mesh grids, we developed a Python package named

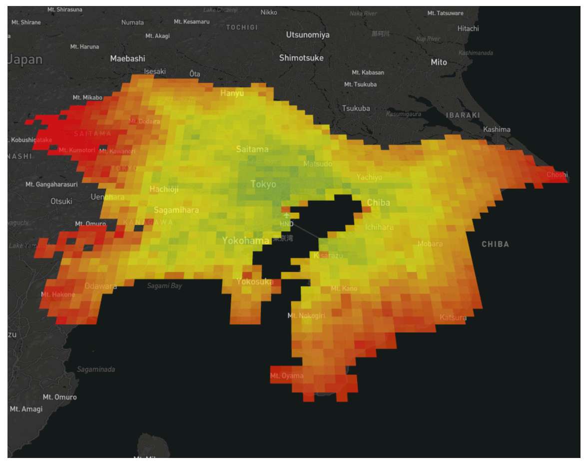
TransBigData[11], which has already been used in a number of scientific publications[48-51].

By vertically extruding the polygon on 3D maps, the region may add another dimension to convey data. Extruding the grid data, for example, may provide the appearance of a 3D barplot(Figure 4(c)), and the height of the data attribute value can be represented by the height of extruding.

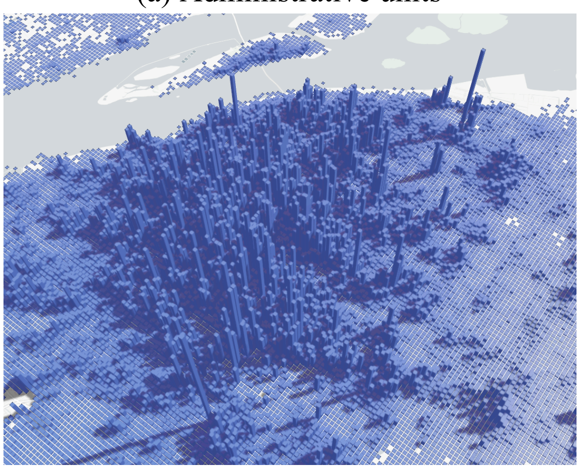
Instead of using the detailed model object, buildings can be simplified and represented by the architectural outline using polygon extrude (Figure 4(d)). This method of visualization in the urban D.T. system simplifies the building model, reduces resource consumption, and enables the visualization of large-scale buildings and the development of applications on top of them.



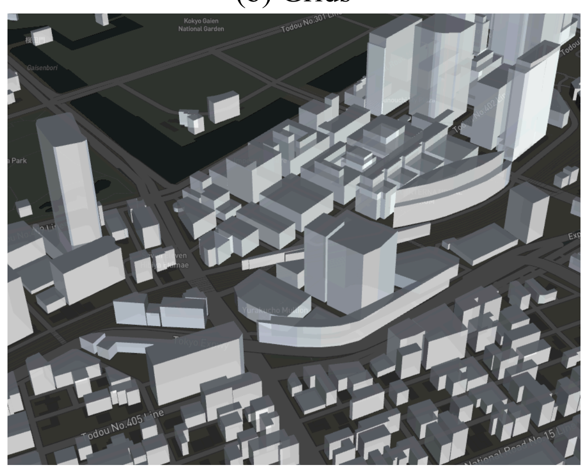
(a) Administrative units



(b) Grids



(c) 3D Bars



(d) Buildings

Figure 4 Visualization of regions

4. Case of web-based urban digital twin application: 3D UrbanMOB

This section introduces an example of a web-based urban digital twin application--3D UrbanMOB. As a sub-module of the Small World A.I. (Spatial Multimodal ALL-World Artificial Intelligence) project[52], 3D UrbanMOB is a web-based digital twin visualization system with multiple solution-oriented applications. Small World A.I. incorporates several promising technologies that together help generate a near real-world scene in real-time. In 2021, Small World A.I. received the R&D100 Award (the "Oscar of Innovation"), recognizing it as one of 2021′s 100 most innovative and disruptive technologies, and the 2021 Smart 50 Awards in recognition of innovation and its potential impact on smart city technologies.

This section presents the feature, design concepts, and development details of 3D UrbanMOB. 3D UrbanMOB is developed based on JavaScript language and runs as a web-based data visualization application. The core structure of the system is developed based on React.js framework; the geographic information processing and analysis (WebGIS) module of the system adopts the technology combination of Deck.gl, React-map-gl, and Turf.js[53]. This technology Portfolio has also been used in multiple similar interactive visualization platforms[54-56].

4.1. Trajectory visualization

Human trajectory is the most basic data source in 3DUrbanMOB. Most applications are built based on trajectory data. With the support of the trips layer from Deck.gl, 3DUrbanMOB provides dynamic visualization for trajectory data. As time changes in the system, the user's trajectory is displayed with real-time animated lines with glowing effects.

This feature is supported by the interaction between three components: the hourly distribution bar plot, the playback control tool, and the base map. When the user selects a bar in the bar plot, the corresponding trajectory will be displayed on the map with animation. At the same time, a playback control tool appears on the interface, allowing the user to control the play, pause and speed up the trajectory movement, as well as drag the progress bar to specify a certain moment to observe the location of the individuals.

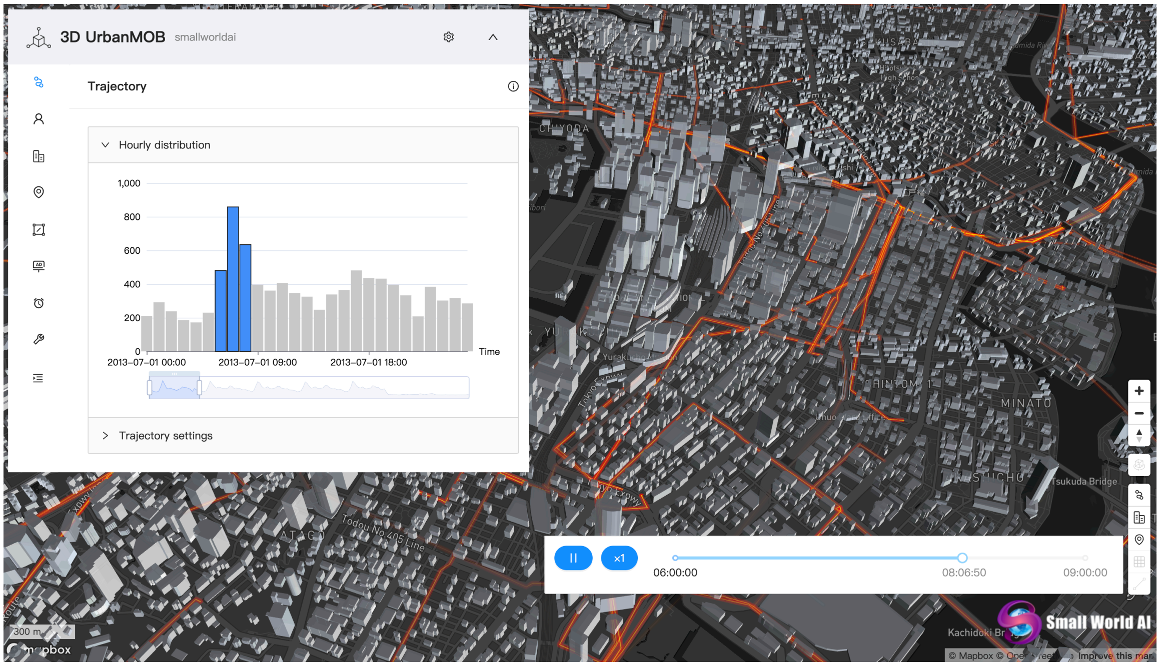


Figure 5 Dynamic trajectory visualization in 3D UrbanMOB

4.2. The active population inside a certain area

Buildings and POIs are the infrastructure data describing the city in the D.T. system. In practical applications, understanding the active population(the population generates activities or travel pass through) within a certain range of areas on the map can produce valuable information.

3DUrbanMOB provides the function of analyzing population characteristics in a certain area. By drawing an area on the map, the algorithm will extract the active population and passenger flow related to the selected area.

Methods for obtaining active population information in the region may be classified into two categories: based on key activity points and based on trajectories. Among them, the key activity point-based method is to extract the population information that has stayed and generates activities in the area, while the trajectory-based method is to filter out the trajectory passing through the area based on the spatial relationship between the trajectory and the selected area. The demographic information obtained from these two methods will have some differences with different application values.

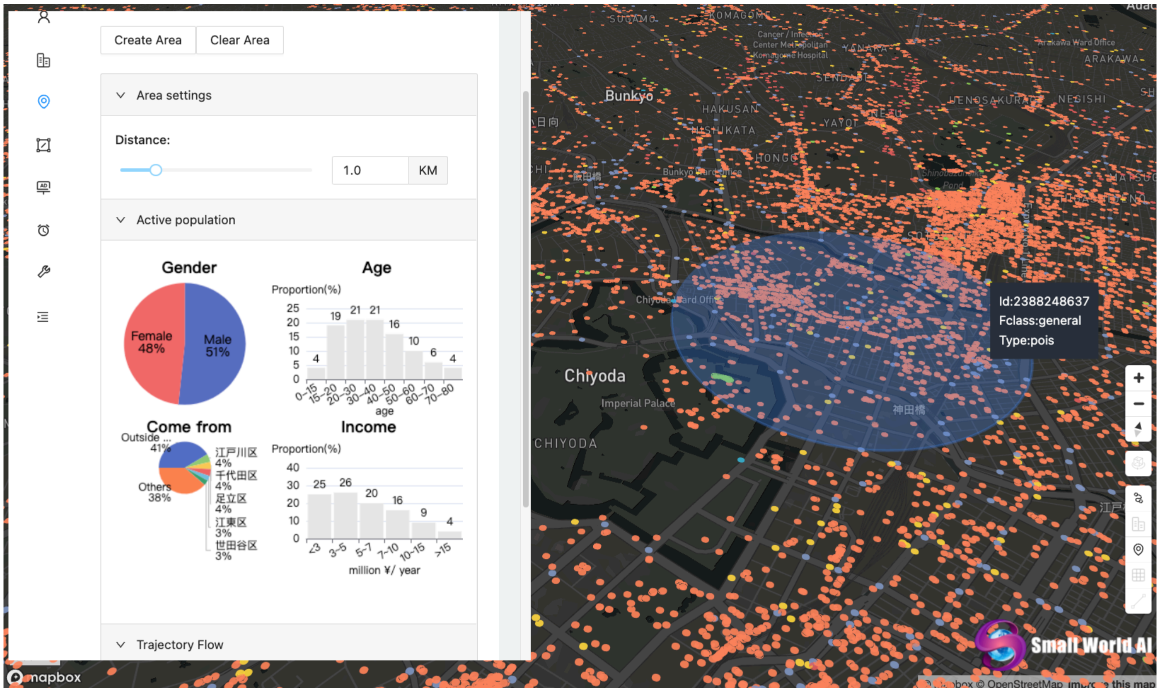


Figure 6 Demographic information of Active population inside a given area

4.3. Advertisement calculation

The selection of the proper place for offline billboards is extremely beneficial to brand promotion and the growth of the marketing market. The real-world influence of advertising models may be studied using urban building models in the D.T. system.

3D UrbanMOB provides a tool to evaluate the visibility of outdoor advertising. By using the map-drawing tool, the width of the billboard and the top and bottom boundary information can be adjusted to set up the billboard at any location on the map.

The examination of the advertisement's visibility is divided into two steps: 1. The billboard resolution and average public visual acuity are used to compute the approximate visibility range of the advertisement; 2. The buildings within this range are screened, and the building occlusion is calculated to produce the fine visibility range of the advertisement.

The precise mapping from 3DUrbanMOB may serve as a reference base and theoretical foundation for offline billboard layout and commercial site selection investigations. The audience information of advertisements may be evaluated further in conjunction with the calculation of the active population to provide a complete evaluation of the advertising effectiveness.

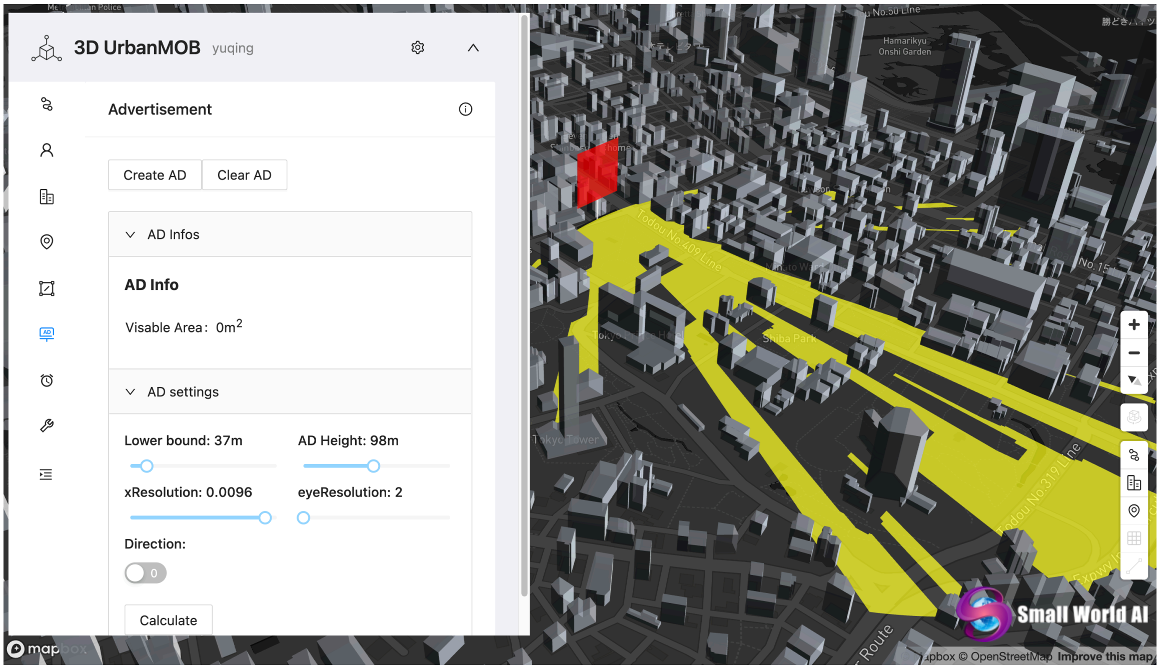


Figure 7 Visibility calculation of outdoor advertising billboard

4.4. Accessibility evaluation

The concept of accessibility is often used to measure the transportation performance of a certain geospatial region. The evaluation of accessibility is also one of the important topics in the field of urban transportation planning. 3D UrbanMOB provides a built-in Urban Accessibility Analysis System to assist decision-makers in promptly evaluating the accessibility improvements brought about by transportation infrastructure investment.

The main functions of the system are as follows:

Accessibility calculation: Compute accessibility by using the built-in traffic network topology model to easily calculate the Average Travel Time of a certain area.

Custom traffic network: It allows users to draw any traffic line on the map. It also supports deploying stations and adjusting the operation speed of the traffic lines. The system can recalculate the average travel time and evaluate the improvement of accessibility.

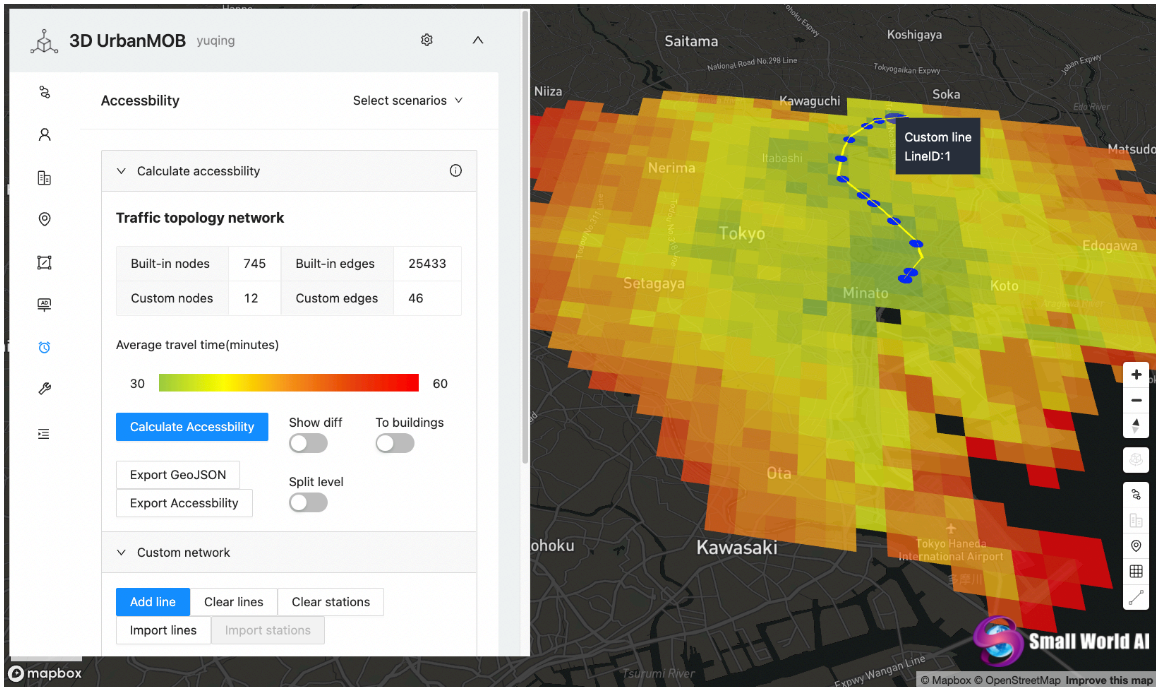


Figure 8 Accessibility evaluation with customized traffic lines

5. Conclusion

In the era of big data, the emergence of spatio-temporal data allows us to characterize a city's everyday activities in more detail. The urban digital twin is based on multi-source spatiotemporal big data, with a variety of real-world applications developed on top of data visualization technologies. The introduction of the urban digital twin can provide city planners with a brand new and powerful tool for designing next-generation smart cities.

The emergence of web-based visualization technology creates easy access to dynamic and interactive experiences to visualize spatio-temporal big data. The organic combination of urban digital twin systems and web-based spatio-temporal big data visualization is one of the important directions for future smart city decision-making, planning, and management.

This chapter introduces the advantages, key technologies, and common tools of web-based visualization, as well as the common form of visualization for different data. This chapter also presents an example of a web-based digital twin project called 3D UrbanMOB, including its feature, design concepts, and development details.

The web-based visualization technology is becoming increasingly important as researchers become more conscious of the necessity to use urban digital twin for monitoring, modeling, and assessment of urban events in the development of next-generation smart cities.

Reference

1. Yao, Y., et al., *Internet of Things Positioning Technology Based Intelligent Delivery System.* IEEE Transactions on Intelligent Transportation Systems, 2022: p. 1-15.
2. Harrison, G., S.M. Grant-Muller, and F.C. Hodgson, *New and emerging data forms in transportation planning and policy: Opportunities and challenges for "Track and Trace" data.* Transportation Research Part C: Emerging Technologies, 2020. **117**: p. 102672.
3. Chen, J., et al., *GPS data in urban online ride-hailing: A simulation method to evaluate impact of user scale on emission performance of system.* Journal of Cleaner Production, 2021. **287**: p. 125567.
4. Zhang, H., et al., *Mobile phone GPS data in urban ride-sharing: An assessment method for emission reduction potential.* Applied energy, 2020. **269**: p. 115038.
5. Zhang, H., et al., *Epidemic versus economic performances of the COVID-19 lockdown: A big data driven analysis.* Cities, 2022. **120**: p. 103502.
6. Chen, J., et al., *Roadmap to hydrogen society of Tokyo: Locating priority of hydrogen facilities based on multiple big data fusion.* Applied Energy, 2022. **313**: p. 118688.
7. Yu, Q., et al., *Mobile phone GPS data in urban customized bus: Dynamic line design and emission reduction potentials analysis.* Journal of Cleaner Production, 2020. **272**: p. 122471.
8. Yu, Q., et al., *Mobile phone data in urban bicycle-sharing: market-oriented sub-area division and spatial analysis on emission reduction potentials.* Journal of Cleaner Production, 2020. **254**: p. 119974.
9. Yu, Q., et al., *GPS data in taxi-sharing system: Analysis of potential demand and assessment of fuel consumption based on routing probability model.* Applied Energy, 2022. **314**: p. 118923.
10. Yu, Q., W. Li, and D. Yang, *Chapter 6 - Data-driven estimation for urban travel shareability*, in *Big Data and Mobility as a Service*, H. Zhang, X. Song, and R. Shibasaki, Editors. 2022, Elsevier. p. 177-202.
11. Yu, Q. and J. Yuan, *TransBigData: A Python package for transportation spatio-temporal big data processing, analysis and visualization.* Journal of Open Source Software, 2022. **7**(71): p. 4021.
12. Yu, Q., et al., *Mobile phone data in urban commuting: a network community detection-based framework to unveil the spatial structure of commuting demand.* Journal of Advanced Transportation, 2020. **2020**.
13. Yang, C., R. Jiang, and R. Shibasaki, *MaaS system visualization*, in *Big Data and Mobility as a Service*. 2022, Elsevier. p. 245-263.
14. Zhang, H., et al., *Mobile phone GPS data in urban bicycle-sharing: Layout optimization and emissions reduction analysis.* Applied Energy, 2019. **242**: p. 138-147.
15. Shekhar, S., et al., *Data mining and visualization of twin-cities traffic data.* 2001.

16. Zhang, H., et al., *Battery electric vehicles in Japan: Human mobile behavior based adoption potential analysis and policy target response.* Applied Energy, 2018. **220**: p. 527-535.
17. Zhang, H., et al., *Urban power load profiles under ageing transition integrated with future EVs charging.* Advances in Applied Energy, 2021. **1**: p. 100007.
18. Li, P., et al., *IIoT based Trustworthy Demographic Dynamics Tracking with Advanced Bayesian Learning.* IEEE Transactions on Network Science and Engineering, 2022.
19. Sui, Y., et al., *Mining urban sustainable performance: Spatio-temporal emission potential changes of urban transit buses in post-COVID-19 future.* Applied Energy, 2020. **280**: p. 115966.
20. Song, X., et al., *Mining urban sustainable performance: Millions of GPS data reveal high-emission travel attraction in Tokyo.* Journal of Cleaner Production, 2020. **242**: p. 118396.
21. Song, X., et al., *Big data and emergency management: concepts, methodologies, and applications.* IEEE Transactions on Big Data, 2020.
22. Fan, C., et al., *Disaster City Digital Twin: A vision for integrating artificial and human intelligence for disaster management.* International Journal of Information Management, 2021. **56**: p. 102049.
23. Negri, E., L. Fumagalli, and M. Macchi, *A review of the roles of digital twin in CPS-based production systems.* Procedia Manufacturing, 2017. **11**: p. 939-948.
24. Jones, D., et al., *Characterising the Digital Twin: A systematic literature review.* CIRP Journal of Manufacturing Science and Technology, 2020. **29**: p. 36-52.
25. Dou, S., et al., *Research on construction of spatio-temporal data visualization platform for GIS and BIM fusion.* The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 2020. **42**: p. 555-563.
26. Deng, T., K. Zhang, and Z.-J.M. Shen, *A systematic review of a digital twin city: A new pattern of urban governance toward smart cities.* Journal of Management Science and Engineering, 2021. **6**(2): p. 125-134.
27. Seto, T., et al. *Constructing a digital city on a web-3D platform: simultaneous and consistent generation of metadata and tile data from a multi-source raw dataset*. in *Proceedings of the 3rd ACM SIGSPATIAL International Workshop on Advances in Resilient and Intelligent Cities*. 2020.
28. Zhang, H., et al., *1.6 Million transactions replicate distributed PV market slowdown by COVID-19 lockdown.* Applied Energy, 2021. **283**: p. 116341.
29. Lawson, B. and R. Sharp, *Introducing html5*. 2011: New Riders.
30. Reyna, J., *From flash to HTML5: The eLearning evolution.* Training & Development, 2012. **39**(5): p. 28-29.
31. Ozer, J., *Video compression for flash, apple devices and HTML5*. 2011: Doceo Publishing.

32. Angel, E. and D. Shreiner, *Interactive Computer Graphics with WebGL*. 2014: Addison-Wesley Professional.

33. Parisi, T., *Programming 3D Applications with HTML5 and WebGL: 3D Animation and Visualization for Web Pages*. 2014: " O'Reilly Media, Inc.".

34. Kaluža, M., K. Troskot, and B. Vukelić, *Comparison of front-end frameworks for web applications development.* Zbornik Veleučilišta u Rijeci, 2018. **6**(1): p. 261-282.

35. Aggarwal, S., *Modern web-development using reactjs.* International Journal of Recent Research Aspects, 2018. **5**(1): p. 133-137.

36. Jadhav, M.A., B.R. Sawant, and A. Deshmukh, *Single page application using angularjs.* International Journal of Computer Science and Information Technologies, 2015. **6**(3): p. 2876-2879.

37. Kyoreva, K. *State of the Art JavaScript Application Development with Vue. js*. in *Proceedings of International Conference on Application of Information and Communication Technology and Statistics in Economy and Education (ICAICTSEE)*. 2017. International Conference on Application of Information and Communication ….

38. Kastanakis, B., *Mapbox Cookbook*. 2016: Packt Publishing Ltd.

39. Crickard III, P., *Leaflet. js essentials*. 2014: Packt Publishing Ltd.

40. Wang, Y., *Deck. gl: Large-scale web-based visual analytics made easy.* arXiv preprint arXiv:1910.08865, 2019.

41. Li, D., et al., *ECharts: a declarative framework for rapid construction of web-based visualization.* Visual Informatics, 2018. **2**(2): p. 136-146.

42. Zhang, H., et al., *A universal mobility-based indicator for regional health level.* Cities, 2022. **120**: p. 103452.

43. Chen, Z., et al., *Using mobile phone big data to identify inequity of artificial light at night exposure: A case study in Tokyo.* Cities, 2022. **128**: p. 103803.

44. Yao, Y., et al., *Modifiable Areal Unit Problem on Grided Mobile Crowd Sensing: Analysis and Restoration.* IEEE Transactions on Mobile Computing, 2022.

45. Sui, Y., et al., *GPS data in urban online ride-hailing: A comparative analysis on fuel consumption and emissions.* Journal of Cleaner Production, 2019. **227**: p. 495-505.

46. Jiang, W., et al., *GPS data in urban online ride-hailing: The technical potential analysis of demand prediction model.* Journal of Cleaner Production, 2021. **279**: p. 123706.

47. Yu, Q., et al., *GPS data in urban bicycle-sharing: Dynamic electric fence planning with assessment of resource-saving and potential energy consumption increasement.* Applied Energy, 2022. **322**: p. 119533.

48. Hui, Y., et al., *Hotspots Identification and Classification of Dockless Bicycle Sharing Service under Electric Fence Circumstances.* Journal of Advanced Transportation, 2022. **2022**.

49. Wu, Y., et al., *Analysis of the Relationship between Dockless Bicycle-Sharing and the Metro: Connection, Competition, and Complementation.* Journal of Advanced Transportation, 2022. **2022**.
50. Li, Y., et al., *Taxi Global Positioning System Data in Urban Road Network: A Methodology to Identify Key Road Clusters Based on Travel Speed–Traffic Volume Correlation.* Transportation Research Record, 2022. **2676**(1): p. 487-498.
51. Yu, Q., et al., *Mobile Phone Data in Urban Customized Bus: A Network-based Hierarchical Location Selection Method with an Application to System Layout Design in the Urban Agglomeration.* Sustainability, 2020. **12**(15): p. 6203.
52. Jin, Y., H. Zhang, and S. Bharule, *Modular Metacognitive Digital Twin Technologies for Greener Cities & Cleaner Mobility.* Advances in Applied Energy, 2022. **5**: p. 100081.
53. Hanson, B. and C. Seeger, *Mapping API's: Turf. js in the Browser Console.* 2018.
54. Lo, R.Y.-H., N. Rao, and A. Sayara, *Visualizing Linguistic Diversity in Vancouver.*
55. Chen, D., et al., *A New City Map.*
56. DINKAR, S. and A. SAINI, *COVID-19 Tracker & Vaccination Monitoring.* 2022.