

Visual Fidelity Maximized Sampling for Large Trajectory Data Visualization

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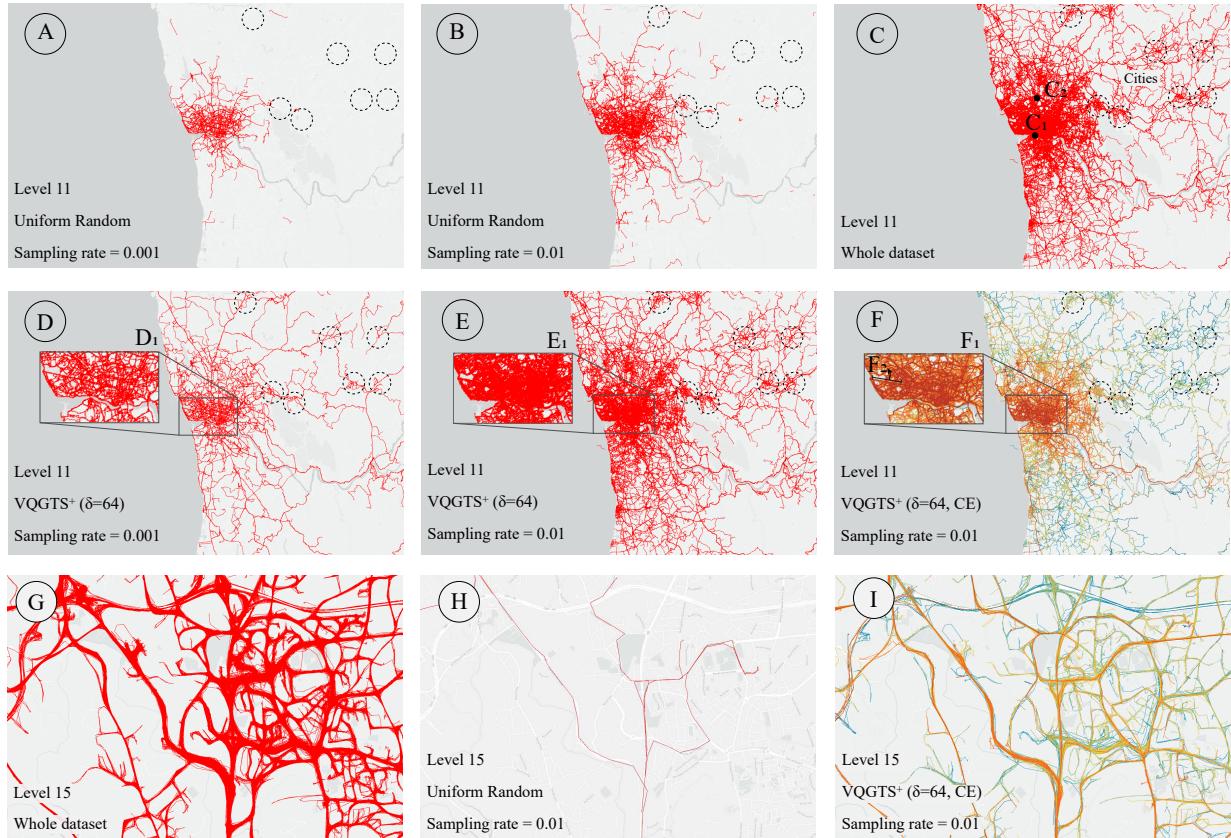


Fig. 1. Experiment results: A and G:the ground truth at level 11 and 15; B and H: uniform random sampling at level 11 and 15; C, D, E, F and I: VAGTS with different parameters

Abstract— In this work, we present a novel sampling approach for line-based visualization of large trajectory data, targeting at maximizing the visual fidelity of sampled trajectory visualization. We introduce a new measurement of fidelity loss using pixel-oriented proximity between two visualization images. From the metric we formulate the sampling as an NP-hard optimization problem, and develop an efficient algorithm – VFMS??, to approximate the optimal solution. VFMS encapsulates various control parameters including sampling rate and level of details (LODs), which complement with color coding to empower the effectiveness of trajectory visualization. We conduct a formal study to compare VFMS with state-of-the-art sampling methods on several large trajectory datasets. The experiments show that our approach improves visual fidelity by xxx% (numbers?) meanwhile keeps computational efficiency. Qualitative user studies further demonstrate the feasibility of our approach in XXX (concrete applications?).

Index Terms—Trajectory visualization, data sampling, visual quality

1 INTRODUCTION

Nowadays, the widely used location-acquisition devices lead to an explosive increase of the movement data which is recorded in the form of trajectories. For example, the taxis trajectory is one of the common studied movement data which is always considered as the representative of human movement trace in a city. Using the taxi dataset in Shenzhen as an example, more than 1 million trajectory data can be collected every day, which are recorded by the sampling locations. The analysis over these databases can be applied in many fields such as traffic management [27], urban planning, route recommendation [35] and

location-based services [15, 34].

Visualizing a large collection of trajectories are used frequently in map service or smart city applications. The most popular and conventional method is the line-based visualization [7]: connecting the passing points of movement objects by polylines. To handle the big dataset, many visualization products such as Spotfire¹ and Tableau² support advanced database management systems as a “backend” for

¹<https://www.tibco.com/products/tibco-spotfire>

²<https://www.tableau.com/>

the efficient data processing the query. The current visualization tools always don't scale well for the presentation of very large trajectory dataset due to the two challenges, visual clutter and limited rendering speed, which hinders the abilities of human-users for interactively exploring the dataset and identifying the movement patterns. In recent years, most of the visualization research works mainly try to address the visual clutter issue by proposing new techniques such as the spatial aggregation [26, 32], edge bundling [25, 33] and density map [14, 23]. Instead, in this paper, we focus on the challenge of inefficient rendering in the large trajectory dataset by involving data sampling techniques.

It is time consuming to generate very simple visualization when the data size become very large. Using Porto taxi data ³ as an example, Table 1 demonstrates the rendering time at each dataset size. It shows that normal method takes more than 14 minutes to generate the graphics for 1 million trajectories, which is far beyond the human-acceptable response time for the interactive exploration [24]. One work closely related to ours is ScalaR [2], which adds a reduction layer between visualization layer and data management layer. The reduction layer uses an uniform random sampling method to sample data once the query results are large enough, thus to reduce the amount of data to be visualized. Further more, Park et al. propose VAS [18] which implements new sampling techniques to guarantee the visual quality. However, these sampling techniques are designed for the simple dataset, and have been approved effective in scatter plot or map plot. However, the trajectory sampling is more challenge due to the complexity of data form(e.g. varying lengths, lack of compact representation, difficulty in measuring the similarity) that makes traditional density-biased sampling techniques inappropriate. A naive solution to employ sampling idea for large-scale trajectory visualization problem is randomly selecting several trajectories from the data set then visualize it by graphics device. However, the visualization result may be not acceptable by the user because of the visual information loss in the sparse distributed regions.

Table 1. The time used to generate the visualization with different trajectory amount.

Data size	Time (ms)
100	2
1,000	16
10,000	143
100,000	1,416
1,000,000	13,950

The major challenges to design visual quality guaranteed sampling method are: (I) how to define visual quality theoretically? (II) how to guarantee the quality of the sampling-based visualization result? **In this work, we study how to reduce the rendering time and preserve the visual quality for the large-scale trajectory visualization.** We extend the motivation of visualization-aware sampling to trajectory dataset and propose a novel sampling strategy, **visualization aware trajectory sampling(VATS)**, that produces high-visual-quality line-based trajectory visualization at different zooming resolutions. We first format visual quality by defining the loss function between the visualization results of the whole dataset and sampled dataset. With the loss function, we analyze the hardness of the problem, and devise a visual quality guaranteed sampling algorithm for it. Figure 2 depicts an comparison among the ground truth, uniform random sampling and our proposed method. With the same sampling set size(1%), the proposed method generates a higher-fidelity visualization and support the multi-resolution very well. At last, color encoding are applied to enhance the distribution of trajectories.

We summarize our contribution as follows:

- We formulate VATS as an optimization problem.
- We prove VAST problem is NP-hard and offer an efficient approximation algorithms.

³<http://www.geolink.pt/ecmlpkdd2015-challenge/dataset.html>

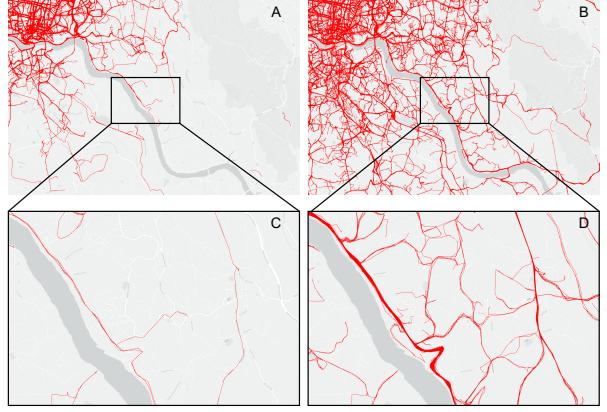


Fig. 2. Trajectory sampling generated by uniform random sampling(A,C) and VQGTS(B,D) at same sampling rate. In both high-level(A,B) and low level(C,D) view, our approach preserved more detail information about the trajectories especially for the sparse regions.

- We conduct several experiments using real-world data to demonstrate the effectiveness of the proposed method in comparison with random uniform sampling.

The remaining parts are constructed as follows: section 2 discusses the related work. In section 3, we identify the specific problem and provide an overview of our solution. We define the problem and propose the solution in the section 4 and 5. The implementation and experiment setting are introduced in section 6. In section 7, we conduct case studies and user studies to evaluate our approach. Finally, we conclude this paper and propose the possible future directions in section 8.

2 RELATED WORK

The most related techniques to our work include the visual analysis of trajectory dataset, the methodology of large data visualization and data sampling.

2.1 Trajectory analysis

Trajectory, consisting of a sequence of spatial locations, is the most common form of the object movement. To support the understanding and analysis of the trajectory dataset, many visualization and visual analytics system are developed. The detailed summary of these work is presented in [7]. These techniques can be classified into three categories according to visualization form: point-based visualization, line-based visualization and region-based visualization.

The point-based visualization capture the basic spatial distribution of the passing points of the moving object. Furthermore, many density-based methods such as the kernel density estimation(KDE) are applied based on the point-based visualization [4, 16, 31], by the sacrifice of the detail the information of trajectories, these methods alleviate the visual clutter caused by large amount of data. Furthermore, to be better applied in the city environment, advanced KDE techniques are developed to capture the moving patterns along the road networks [3, 30]. In the study of urban traffic, the point-based visualization can capture the hot regions, but unable to identify the movement of the individual case and reveal the moving information such as the direction and origin-destination [7]. Line-based techniques are the most commonly used visualization methods which present the trace of the movement as polylines, thus to preserve the continuous moving information [11, 12]. However, due the large amount of the trajectories, the line-based methods always cause serious visual clutter due to the cross of the polylines. To alleviate this problem, the clustering techniques are applied in the visual analytics for various dataset such as flight [8], taxi trips [22] and hurricane trajectories [1]. Moreover, advanced interaction techniques [9, 13], sampling techniques [] and edge bundling techniques [33] are also developed to better present the movement patterns. The region based techniques divide the whole region into sub-regions in advance and then visualize the traffic situation before the sub-regions. These methods visualize the macro-pattern very well by

leveraging different aggregation techniques such as the administrative regions [10], uniform grid [28] and spatial clustering results [26].

2.2 Interactive visualization for large dataset

The movement dataset, such as the urban traffic, always contains millions of trajectories. Limited by the rendering capability of graphic devices, generating visualizations for such scale of dataset always need to take considerable amount of time.

Advanced computing techniques have proposed in the visualization of large dataset. Chan et al. present ATLAS [5] which leverages the powerful multi-core server and advanced caching techniques for the efficient data communication between server and client. Piringer et al. [21] propose a multi-threading architecture for the interactive visual exploration. This method takes advantage of multi-core devices and avoids the pitfalls related to the multi-threading thus to provides quick visual feedback.

Aggregation approaches leverage the aggregation operation implemented before visualization to reduce the items will be rendered. Specifically for the spatial temporal data, these method can be further categories according to how to generate the spatial partitions. For example, OD Map [28] divides the whole map into nested uniform grid, and uses the color of a grid to present the flow magnitude. Some work directly use the hierarchical administrative regions [10] as basic units and use visualization the flow by linkage between these units. All the uniform grid- and administrative region-based method are static because they are predefined. On the other hand, the region can be divided dynamically according the movement patterns. For example, MobilityGraph [26] leverages a spatial graph clustering algorithm to aggregate the tweet posts.

2.3 Data sampling techniques

Another widely applied technique to support the large data analysis is sampling technique which has been studied in both database and visualization communities. A good sampling method will reduce the data size as much as possible and still preserve the specific important feature.

Current advancing sampling techniques in the visualization domain are mostly designed for the scatter plot and aim to not only solve the overrawing of the points but also try to preserve the information distribution of the original dataset. Some works design advanced sampling algorithms to preserve the meaningful data items according to the analyzing requirement such as the multi-class data analysis and hierarchical exploration [6]. Furthermore, to the usage of more visual channels of the points other than location such as color [6], size [29] and opacity are discussed. Closely related to our work, Park et al. [18] proposed the visualization-aware techniques for the scatter plot. They proposed visualization-inspired loss which effectively evaluates the visual loss of the sampling result and validates the proposed method based on three common visualization goals: regression, density estimation and clustering.

In comparison with the sampling techniques for scatter plot, the trajectory sampling is more challenging because of the complexity of the trajectories [20]. Most of the existing trajectory sampling techniques cluster the trajectories first and then select the most representative trajectories from each cluster, which highly depend on the distance calculation and clustering algorithms [19]. Some techniques further focus on the clustering and sampling of trajectory segments instead of the whole trajectories [17].

3 PROBLEM FORMULATION

When exploring a large collection of trajectories, efficient and effective large-scale trajectory visualization is challenging in both academia and industry. The reasons are (i) the size of trajectory data is very large (e.g., several GB in an hour), and (ii) the limited rendering ability of existing commercial graphics device (e.g., XXX).

Many exiting visual analytics systems leverage powerful database manage system as the backend to facilitate the fast data processing. Based on the solution proposed in ScalaR [2], a common visualization framework involving sampling technique is illustrated as Figure 3,

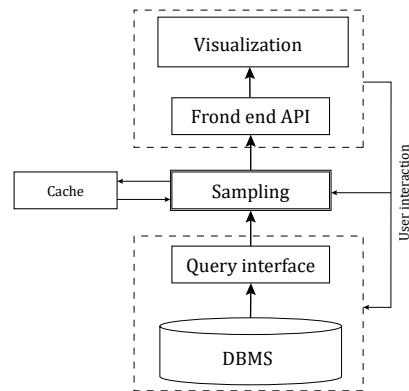


Fig. 3. A visualization framework involving sampling layer between the front-end and database management system.

where a sampling layer is set between the backend and frontend. Since the sampling methods are always designed for complicated task, the algorithms may not be efficient enough to support the interactive data exploration. Thus the cache model is always implemented to save the sampling results. In our scenario, the users query large amount of data(e.g. all Shenzhen trajectories in one week) once and then conduct interactive multi-resolution exploration based on the sampled data, thus the method need to guarantee the visual quality well across different resolutions.

Sampling is a delta-facto solution for the problems with big data. Target at the sampling requirement, the naive solutions such as uniform random sampling cannot generate acceptable because the serious visual information loss. In this section, we first define a loss function to evaluate the visual quality between the visualization results between whole dataset and sampled subset. Then we analyze the hardness of the problem and design algorithms for it.

3.1 Problem description

Problem 1 (Sampling-based trajectory visualization problem). *Given a large-scale trajectory dataset T and an integer k , the trajectory visualization problem is selecting a subset of trajectories $R \subseteq T$, such that loss function $loss(R, T)$ is minimized.*

From the user's perspective, there are many ways to define the loss function $loss$ between the visualization result qualities of the sampled subset R and the whole dataset T . For example, [18] defined point-based loss function for very large scatter points visualization. However, it is not applicable for trajectory data visualization. In order to address that, we propose a novel loss function for trajectory visualization problem.

Intuitively, the visual quality difference between the visualization results of two trajectory datasets depends on the user specified visualization level of details (a.k.a., LOD). Given an empty canvas (e.g., displaying device) with a user specified level of details, the visualization process is rendering the trajectories into canvas with the given level of details (e.g., the number of pixels in each row and each column). Considering a trajectory data set T and a subset of trajectories $R \subseteq T$, The visual quality loss between R and T is defining as the different pixels of the visualization results about R and T in the canvas with specified LOD. We then define the loss function of sampling-based trajectory visualization problem as $loss(T, R) = \frac{V(T) - V(R)}{V(T)}$, where $V()$ measures the number of rendered pixels in the canvas of a given trajectory dataset.

Given a trajectory data set T and an integer k , our research objective is finding subset R , such that the visualization quality loss function $loss(T, R)$ is minimized, i.e.,

$$\min_{R \subseteq T, |R|=k} loss(T, R) = \frac{V(T) - V(R)}{V(T)}.$$

3.2 Hardness analysis

In real-world applications, the pixels in canvas will be rendered by different colors according to the specified visualization scheme. For the

sake of presentation, we analyze the hardness of our research objective with a simple render manner of visualization result. In particular, for each pixel in the canvas, it will be rendered if there is a trajectory pass through it, otherwise it will not be rendered. Suppose each pixel in the canvas has an unique id, let \mathcal{U} be the universal set of all pixels in the canvas. For each trajectory $T_i \in T$, it consists of a set of pixels in the canvas, e.g., it is a subset of \mathcal{U} . Thus, the subset R also is a subset of \mathcal{U} as $R = \bigcup_{R_i \in R} R_i$.

Our research objective is minimizing loss function $loss(T, R) = \frac{V(T) - V(R)}{V(T)}$. Obviously, the visualization result of T is a constant value, denotes as C . Our research objective of Problem 1 can be transformed as follows:

$$\begin{aligned} \text{Objective : } & \min_{R \subseteq T, |R|=k} \frac{V(T) - V(R)}{V(T)} \\ & \Leftrightarrow \min_{R \subseteq T, |R|=k} \frac{C - V(R)}{C} \\ & \Leftrightarrow \max_{R \subseteq T, |R|=k} \bigcup_{R_i \in R} R_i \end{aligned}$$

It is equivalent to select sized- k trajectory set R from T which $\bigcup_{R_i \in R} R_i$ is maximized.

It is a typical set cover maximization problem⁴, which is a well-known NP-hard problem in literature.

4 VISUAL QUALITY GUARANTEED SAMPLING APPROACH

Due to the hardness of the Problem 1, we first introduce a straightforward solution for it in Section 4.1. Then, we propose a visual quality guaranteed sampling approach in Section 4.2. Last, we devise several optimizations to improve the efficiency and effectiveness of our proposal in Section 4.3.

4.1 Uniform Random Sampling Algorithm

The straight forward solution for Problem 1 is uniform random sampling. As the pseudocode in Algorithm 1 shown, it randomly selecting k trajectories from T , then render these selected k trajectories into the canvas.

Algorithm 1 RandSampling(T, k)

```

1: Initialize result set  $R \leftarrow \emptyset$ 
2: while  $|R| < k$  do
3:    $R_{tmp} \leftarrow \text{RAND}(T - R)$ 
4:    $R \leftarrow R \cup \{R_{tmp}\}$ 
5: Return  $R$ 
```

Obviously, the uniform random sampling algorithm has good performance. However, it does not provide any guarantee on the visual quality of the visualization result.

4.2 Visual Quality Guaranteed Sampling Algorithm

In this section, we present our visual quality guaranteed sampling algorithm for Problem 1. We start our presentation by elaborating the relationship between visual quality of sampled set R and user zoom level. Obviously, for a given sampled set $R \subseteq T$, it has different loss values at different user zoom level. The reason is the map are of the same canvas region will be updated at different zoom level. For example, Google map⁵ provides zoom levels range from 0 to 20, where level 0 is the lowest level (e.g., the whole world), level 20 is the highest level (e.g., individual building, if available). In order to devise a zoom level oblivious visualization for sampled dataset R , we use the highest zoom level to define the size of each pixel in the canvas in our problem. For each trajectory $T_i \in T$ is a set of pixels at highest zoom level in the canvas.

⁴https://en.wikipedia.org/wiki/Maximum_coverage_problem

⁵<https://www.google.com/maps/preview>

The visual quality guaranteed sampling algorithm employs greedy paradigm. In particular, it finds the trajectory T_i in T which maximize the union set of $R \cup T_i$ at each iteration, as Line 3 shown in Algorithm 2. It terminates after k iterations and returns R as result set for rendering.

Algorithm 2 VQGTS(T, k)

```

1: Initialize result set  $R \leftarrow \emptyset$ 
2: while  $|R| < k$  do
3:    $R_{tmp} \leftarrow \text{argmax}_{T_i \in T} R \cup T_i$ 
4:    $R \leftarrow R \cup \{R_{tmp}\}$ 
5: Return  $R$ 
```

Interestingly, Algorithm 2 has a nice theoretical property, i.e., it guarantees the visual quality of the returning set R , as proved in Theorem 1.

Theorem 1. *Algorithm 2 provides $1 - (1 - 1/k)^k \geq (1 - 1/e) \approx 0.632$ approximation result for large trajectory visualization problem (i.e., Problem 1).*

Proof. The optimal solution of Problem 1 covers OPT elements in k iterations. Let a_i be the number of newly covered elements at the i -th iteration, b_i is the total number of covered elements up to the i -th iteration (i.e., $b_i = \sum_{j=1}^i a_j$), and c_i be the uncovered elements after i -th iteration (i.e., $c_i = OPT - b_i$). According to greedy paradigm, we can conclude the number of newly covered elements at the $(i+1)$ -th iteration is always greater than or equal to $\frac{1}{k}$ of the number of uncovered elements after the i -th iteration, i.e., $a_{i+1} \geq \frac{c_i}{k}$. We prove Theorem 1 by proving $c_{i+1} \leq (1 - 1/k)^{i+1} \cdot OPT$. It holds $c_1 \leq (1 - 1/k) \cdot OPT$ as follows.

$$\begin{aligned} a_1 &\geq c_0 \cdot 1/k = 1/k \cdot OPT \quad \text{as we concluded} \quad a_{i+1} \geq \frac{c_i}{k} \\ \Leftrightarrow b_1 &\geq 1/k \cdot OPT \Leftrightarrow -b_1 \leq -1/k \cdot OPT \quad \text{as} \quad a_1 = b_1 \\ \Leftrightarrow OPT - b_1 &\leq OPT - 1/k \cdot OPT \Leftrightarrow c_1 \leq (1 - 1/k) \cdot OPT \end{aligned}$$

For inductive hypothesis assume $c_i \leq (1 - 1/k)^i \cdot OPT$. Thus,

$$c_{i+1} = c_i - a_{i+1} \leq c_i - c_i/k = (1 - 1/k) \cdot c_i = (1 - 1/k)^{i+1} \cdot OPT$$

Hence, it holds $c_k \leq (1 - 1/k)^k \cdot OPT$. It is equivalent to $b_k \geq (1 - (1 - 1/k)^k) \cdot OPT \geq (1 - 1/e) \cdot OPT \approx 0.632 \cdot OPT$. \square

4.3 Optimization Techniques

With the above analysis, Algorithm 2 provides a visual quality guaranteed sampling algorithm for large trajectory data visualization problem. However, it is impractical for (very) large trajectory dataset (i.e., billions of trajectories) as the time complexity analyzed in the following Lemma 1.

Lemma 1 (Time Complexity). *Given trajectory dataset T and an integer k , the time complexity of Algorithm 2 is $O(k \cdot m \cdot |T|)$, where m is the maximum length of the trajectory in dataset T .*

Proof. The complexity analysis is straight forward as all trajectories (i.e., $|T|$) will be updated (i.e., $O(m)$ for each one) and the trajectory with maximum number of uncovered pixels will be selected at each iteration (k iterations in total). Thus, it is $O(k \cdot m \cdot |T|)$. \square

Motivated by this, we devise an lazy updating manner to accelerate the running time performance of our proposed visual quality guaranteed sampling algorithm. The core idea is the submodularity of the covered pixels of result set R as shown in Lemma 2.

Lemma 2 (Submodularity). *Given a trajectory T_i and two result sets S, S' , where $S \subset S'$ and $T_i \notin S'$, it holds $|S \cup T_i| - |S| \geq |S'| \cup T_i| - |S'|$.*

Proof. Let the contribution value of trajectory T_i to a given result set S as $|S \cup T_i| - |S|$. It is the new covered pixels of $|T_i|$, i.e., $|T_i| - |T_i \cap S|$. It holds $T_i \cap S \subseteq T_i \cap S'$ as S' is a superset of S . Thus, we have $|T_i| - |T_i \cap S| \geq |T_i| - |T_i \cap S'|$, it is equivalent to $|S \cup T_i| - |S| \geq |S' \cup T_i| - |S'|$. \square

With the help of submodularity property, it reduces a lot of unnecessary trajectory updating computations. In particular, we maintains a max-heap for the number of uncovered pixels of each trajectory w.r.t., result set R . Figure 5(a) shows a tiny max-heap example about the numbers of uncovered pixels of each trajectory from T_1 to T_7 with result set $R = \emptyset$. At the 1st iteration, the root node of the max-heap will be selected, i.e., T_3 in Figure 5(a). At the 2nd iteration, the number of uncovered pixels of the root node T_1 is updated to 7 w.r.t. result set $R = \{T_3\}$ (see gray node at Figure 5(b)). T_1 will be selected at the 2nd iteration without updating the number of uncovered pixels in other trajectories, i.e., all white nodes at Figure 5(b) as the submodularity property holds.

In summary, in the lazy updating manner, the number of uncovered pixels in each trajectory will only be computed with the latest result set R when it is necessary, e.g., only T_1 will be updated at the 2nd iteration in Figure 5. It reduces many unnecessary computations through the lazy updating manner, e.g., all white nodes did not update at the 2nd iteration in the above example. We analyze the time complexity of Algorithm 2 with lazy updating manner in Theorem 3.

Lemma 3 (Optimized Time Complexity). *Given trajectory dataset T and an integer k , the time complexity of Algorithm 2 with lazy updating manner is $O(|T| + k \cdot m \cdot t \log |T|)$, where t is the maximum number of updating among all k iterations and $t \ll |T|$.*

Proof. It first takes $O(|T|)$ time to construct the max-heap. Then, it incurs $O(m \cdot t \log |T|)$ cost to select the trajectory with maximum uncovered pixels at each iteration (k iterations in total). Hence, the overall cost is $O(|T| + k \cdot m \cdot t \log |T|)$. \square

Bo: To exemplify, Algorithm 2 costs 2.3 hours to return the results on Lisbon taxi trajectory dataset. However it only takes 3.2 seconds with lazy updating manner.

5 ADVANCE APPROACH: VQGTS⁺

Even though our proposed visual quality guaranteed sampling VQGTS produces good quality visualization result for large trajectory dataset when comparing with random sampling method. In this section, we devise an advanced VQGTS (i.e., VQGTS⁺) to further enhance the visual quality of VQGTS by exploiting (i) the inherent characteristic in the large trajectory dataset, and (ii) the interpretation ability of human beings.

We then elaborate (i) and (ii) by the examples in Figure 4. Considering Lisbon trajectory dataset, Figure 4(a) shows its visualization result of VQGTS with sampling ratio 1%. The distribution of real-world trajectory dataset is non-uniform inherently. For example, the dense region (Lisbon downtown) has much more trajectories than the sparse region in Figure 4(a). Obviously, it is much easier for us to distinguish the difference between sparse regions rather than dense regions in Figure 4(a) and (b). The major reason is that end users will treat the two dense regions in Figure 4(a) and (b) as identical since the interpretation ability of human beings is limited at such level of details. However, the visual difference between the two sparse regions in Figure 4(a) and (b) at that level of details is in the range of ours interpretation ability.

Hence, the returning result of visual quality guaranteed sampling method VQGTS could be further improved by delivering richer information at sparse regions, i.e., enhancing the visual details in the region where is in the range of end user's interpretation ability. Motivated by this, we devise an advance approach VQGTS⁺ (see Algorithm 3) by incorporating a parameter δ during trajectory selection process in VQGTS to achieve the above goal. In particular, we employ the parameter δ to model the end user's interpretation ability at the most high level of details. Surprisingly, our advance approach VQGTS⁺ not only

provides better visualization result when comparing with VQGTS with the same sampling rate (e.g., Figure 4(a) and (b) are the returning result of VQGTS and VQGTS⁺ respectively), but also embeds the popularity of selected trajectories by encoding the rest trajectories in the dataset in them, e.g., Figure 4(c) is the visual result of VQGTS⁺ with color encoded popularity.

Instead of measuring the contribution of each trajectory w.r.t the selected trajectories in R directly, we introduce interpretation tolerance parameter δ to capture end user's interpretation ability at the highest zoom level. Specifically, suppose the pixel with location (x, y) in canvas is covered by result set R at the highest level, the pixels around (x, y) are not necessary to cover as they are beyond the interpretation ability of end users. It means the end user cannot distinguish the visual quality difference between rendering (x, y) and rendering all pixels in from $(x - \delta, y - \delta)$ to $(x + \delta, y + \delta)$ even at the highest zoom resolution. Fortunately, we can incorporating the interpretation tolerance parameter δ into our proposed visual quality guaranteed trajectory sampling algorithm in Algorithm 2 by slightly revising it. As illustrated in Algorithm 3, it measures the contribution of each trajectory w.r.t the selected trajectory set R 's augmented set R^+ (in Line 4). The augmented set R^+ will be updated by the selected trajectory R_{tmp} and its tolerance pixels set (in Line 6).

Algorithm 3 VQGTS⁺(T, k, δ)

```

1: Initialize result set  $R \leftarrow \emptyset$ 
2: Initialize augmented result set  $R^+ \leftarrow \emptyset$ 
3: while  $|R| < k$  do
4:    $R_{tmp} \leftarrow \text{argmax}_{T_i \in T} \delta R \cup T_i$ 
5:    $R \leftarrow R \cup \{R_{tmp}\}$ 
6:    $R^+ \leftarrow R^+ \cup \text{augment}(R_{tmp}, \delta)$ 
7: for each  $T_i$  in  $T - R$  do            $\triangleright$  Popularity encoding
8:    $R_j \leftarrow \text{argmin}_{R_i \in R} \text{augment}(R_i, \delta) - T_i$ 
9:    $R_j.cnt += 1$ 
10: Return  $R$ 

```

Moreover, we further exploit the result set of interpretation tolerance considered VQGTS to address the visual clutter problem in large trajectory visualization application. In particular, it selects the trajectory which has largest uncovered pixels by taking end user's interpretation tolerance on visual quality into account at each iteration, instead of only choose the trajectory with largest uncovered pixels in VQGTS. During the above selection process, some trajectories will not be included into the result set R even they have larger number of uncovered pixels. The reason is their uncovered pixels are too close to the pixels in the selected trajectory, i.e., within the tolerance area of selected pixels. Taken Figure 6(a) as example with $\delta = 1$, suppose trajectory a was selected at the first iteration, the trajectory selected in the second iteration is c , instead of b as almost all pixels in b is in the tolerance area of a 's. It means it embeds the popularity of each selected trajectory during the result set R selection process naturally. We define the popularity of each selected trajectory as the number of close trajectories in the rest dataset, i.e., $T - R$. Thus, we compute the popularity of trajectories in R from Line 7 to Line 9 in Algorithm 3. We then visualize the popularity of each selected trajectory by encoding its popularity by different colors. Figure 4(c) shows the returning result of advance approach VQGTS⁺ by encoding the popularities by colors. Obviously, the trajectories in dense region are more popular than these in sparse regions.

Last but not least, it is worth to point out that our advance approach VQGTS⁺ provides more better visual quality over VQGTS at arbitrary zooming resolutions. The key technique to achieve that is it considers the zooming resolutions inherently when introducing the interpretation tolerance δ . Take Figure 6 as an example, Figure 6(a) and (b) show two different zoom-levels. The zoom level in Figure 6(a) is higher than it in Figure 6(b). As our above elaboration, our advance approach VQGTS⁺ selects trajectory a and c at Figure 6(a). When it zoomed-out, as shown in Figure 6(b), it still capture the main sketch of the underlying dataset.

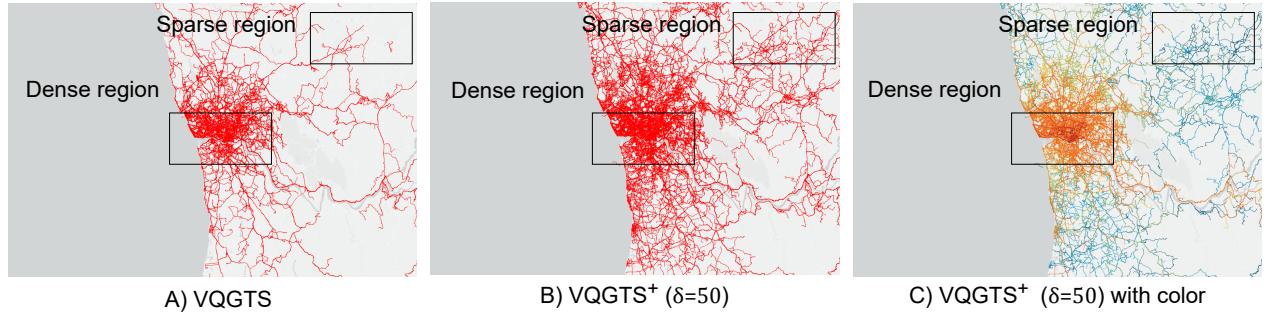


Fig. 4. Detail-aware visual quality guaranteed trajectory sampling, A: VQGTS, B: advanced VQGTS ($VQGTS^+$), C: $VQGTS^+$ and popularity encoded by color.

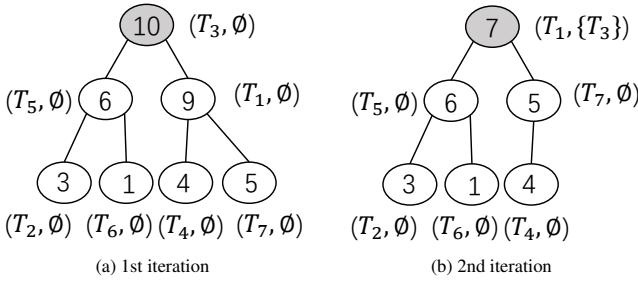


Fig. 5. Lazy updating manner illustration

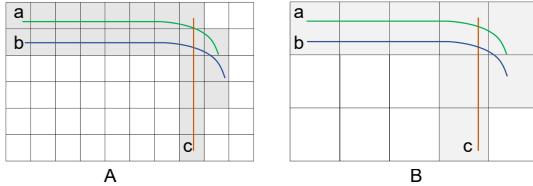


Fig. 6. Zoom resolution2

6 VISUALIZATION AND IMPLEMENTATION

Platform/language/space-time consume

7 EVALUATION

We first applied our approaches to several real-world dataset and compare our method with the uniform random sampling. Then we conduct several user studies on specific analysis tasks.

7.1 Experimental results

In this section, we evaluate our method by presenting the applications on three taxi trajectory datasets: Porto, Shenzhen and Chengdu. We compare the visualization among the full dataset, random sampling and the proposed method from different levels of details.

7.1.1 Case of Porto Distinct

Our first example uses taxi trajectories collected from 442 active taxis in the city of Porto distinct, Portugal⁶. The trajectories cover several cities in and around the Porto distinct. Figure 1 (A - F) show the top level trajectory visualization of different approaches and the parameter settings. Figure 1 C present the visualization generated by the whole dataset, from which we can get an overview of the movement patterns in Porto district. For example, many trajectories are concentrated in the center of the figure(shown around point Figure 1C₁) indicating that the most taxi activities are around the **Porto City**. In addition,

⁶<http://www.geolink.pt/ecmlpkdd2015-challenge/dataset.html>

the many other regions with dense trajectory cluster also indicate the location of the cities in the Porto district(shown as the dash circle in Figure 1 C). Figure 1 B and E depict the visualization generated by uniform random sampling and $VQGTS^+$ respectively. Both of these two sampling methods take 0.01 as the sampling rate. The uniform random sampling almost only preserves the visual elements around the Porto City. Figure 1 depicts visualization generated by $VQGTS^+$, which looks the same as the whole dataset. Not only the Porto City but also the margin city patterns are preserved, which are shown as the dash circles in 1 E. Another important factor affecting the visual fidelity of sampling results is the sampling rate. Figure 1 B and C show the sampling results of random method with sampling rate set as 0.01 and 0.001. With the decreasing of the sampling rate, the shape of the trajectory visualizations clearly shrink to the Porto City. Figure 1 E and D demonstrate the visualization of $VQGTS^+$ with the sampling rate of 0.01 and 0.001, from which we observe that when the sampling rate is decreased, the framework of the trajectories is preserved while the trajectories around Porto City are significantly removed since more **blank space/gap** can be found in the center of figure as shown in Figure 1 D₁. Figure 1 F shows the visualization generated by $VQGTS^+$ with color encoding where the **representativeness** of a trajectory is encoded by color. As shown by Figure 1 E₁, no clear pattern can be found due to the dense concentration of massive trajectories. While in Figure 1 F₁, some trajectories with high representative score are highlighted by dark orange color such as F₂ in Figure 1 F, which indicates **road name**, a main street in Porto City. From the overview, $VQGTS^+$ can preserve the general structure very well in the comparison with uniform random sampling, and more information of the movement can be visualized with color encoding.

$VQGTS^+$ outperforms the uniform random sampling in the visualization of overview. Then we evaluate the performance of $VQGTS^+$ at different level of details. We first select several regions of interest as shown in the Figure 7 A. Region R3 is far away from Porto City and contains two other cities: Paredes and Penafiel. Region R3 has very few trajectories as shown in Figure 7 D₁. Figure 7 D₁ to D₄ show the visualization in region 3 at level 11. Compare with the visualization of full dataset, the random sampling almost misses all trajectories in this region(as shown in Figure 7 D₂). While $VQGTS$ samples much more trajectories than random sampling as shown in Figure 7 D₃. However, some meaningful trajectories are still missing such as the trajectory bundle shown in Figure 7 h, which is laid in on the road **road name** connecting the two cities of Paredes and Penafiel. Further more, the trajectory structure of city Penafiel is not precisely preserved(shown as region g in Figure 7 D₃ i) because some trajectory branches are missed. By setting the representative parameter as 64, $VQGTS^+$ generate a more confidential visualization than $VQGTS$.

There are three cities located in the region R2 including Ermesinde, Rio Tinto and Valongo. Region 2 is near to the center of Porto and there are more taxi trajectories. Figure 7 C₂ and C₃ present the visualization generated by $VQGTS^+$ with the representative parameters are set as 4 and 64. We observe that the visualization shown in Figure 7 C₃ have more details trajectory branches than Figure 7 C₂(as shown in region d

of Figure 7 C₂ and C₃). In this case, a larger representative parameter is more beneficial in preserving the details at this level. Furthermore, Figure 7 C₄ shows the visualization of VQGTS⁺(δ = 64) with color encoding. In the comparison with Figure 7 C₃, the visualization in Figure 7 further highlights the movement distribution, for instance, city Rio Tinto has more taxi activities than other two cities because region f in Figure 7 has more dark colored trajectories than region e and g.

The region R1 is the center of Porto city, which has the highest concentration of the trajectories and cause serious visual clutter if all trajectories are visualized(as shown in Figure 7 B₁). VQGTS⁺(δ = 4) greatly alleviates the visual clutter and preserves the framework which basically follows the road network as shown in Figure 7 B₂. Furthermore, when setting the representative parameter δ as 64, the structure is further clarified as shown in region b of Figure 7 B₃ and B₄, and have more trajectory details than VQGTS⁺(δ = 4) as shown in region a of Figure 7 B₂ and B₃.

7.1.2 Shenzhen Trajectories

We further evaluate the proposed approach using the taxi trajectories of Shenzhen, which includes 428K trajectories collected from ** taxis in one day. All the cases generated by sampling methods set the sampling rates as 0.01. Figure 9 A, B, C, D show the overview generated by whole dataset, random sampling, VQGTS⁺ and VQGTS⁺ with color encoding.

7.2 Expert overview

8 DISCUSSION

The experiment results and the user studies demonstrate that VQGTS⁺ outperforms the uniform random sampling in guaranteeing the visual quality and enriching the flow information. According to the user feedback and our own experience, the parameters δ will affect the visualization result across different map resolutions. Furthermore, we also notice that the proposed method also performs differently by various dataset. In this section, we will discuss these issues to clarify the characteristics of the algorithm and explain how these parameters make our method more effective.

8.1 Representative parameter

Generally speaking, the data sampling inevitably results in the information loss because only partial data are leveraged to generate the visualization. A well designed sampling algorithm for specific exploration tasks aims to preserve as much important information as possible with a limited size of sub-dataset. We have discussed the limitation of uniform random sampling technique in section(***)). A clear drawback of random sampling is that the region with low data distribution tend to have fewer preserved data, which may significantly influence of perception of human beings and reduce the visual quality. Our proposed solution VQGTS⁺ reduce the selection of the dense region by proposing idea of trajectory rejection that is a chosen trajectory may reject other nearby trajectories. An intuitive understanding for this parameters is that it indicates how close a candidate trajectories should be rejected. If the parameters is large, more trajectories in the dense region will be rejected and more trajectories in the sparse region will be preserved. While if the parameters is small, more trajectories at the dense region will be preserved. According to our user study, user explore the trajectory data mostly at the [dense regions](#), thus the recommended parameter setting is around [64](#). The users can also adjust the parameters according their own requirement, a general principle is that the larger δ and smaller δ will be helpful for the exploration in sparse region and dense regions, respectively. Moreover, if the users focus on the discovering the general patterns from the overview, a larger parameters is recommended.

8.2 Approach usability

The sampling method only designed for visualization purpose

9 CONCLUSION AND FUTURE WORK

Visualizing large trajectory dataset is challenge due to two reasons: visual clutter and long rendering time. Data sampling technique, an effective method in reducing the rendering time by shrinking the data size, has been applied in a variety of data. However, very few work target at the trajectory sampling especially from the perspective of visualization. The most commonly used sampling method, uniform random sampling technique, always generate results with very poor visual quality because very few trajectories located at margin regions can be preserved. We fill the gap by proposing a novel sampling techniques VQGTS⁺ which guarantees the visual quality at overview and reduce the visual clutter at the detail view. The technique characteristics and a series of parameters setting are discussed. We compare VQGTS⁺ with uniform random sampling in regarding to visual quality preservation and time-usage. We evaluate the effectiveness of proposed method by applying our method to different dataset and conducting users studies on specific interactive trajectory exploration tasks.

Even though it is recommended to use our method with caching techniques, our experience in the experiment shows that a faster algorithm will be more user friendly for the real world ad-hoc exploration tasks. For future work, we first plan to reduce the time usage by leveraging the advanced database techniques such as the indexing technique or use GPU acceleration. In addition, there are several directions can be further explored to enrich the information presented by the visualization. First we will develop different color encoding schema to present the spatial distribution of trajectory more precisely. In current schema, the color of one trajectory is the same, thus the color of the long trajectories may mislead the users because they pass through many regions with different level of the traffic crowdedness. One solution is to use gradient color schema to encode the trajectories. Another interesting direction is to extend the approach to support the multi-class characteristics which is a commonly existed in variety of trajectory dataset.

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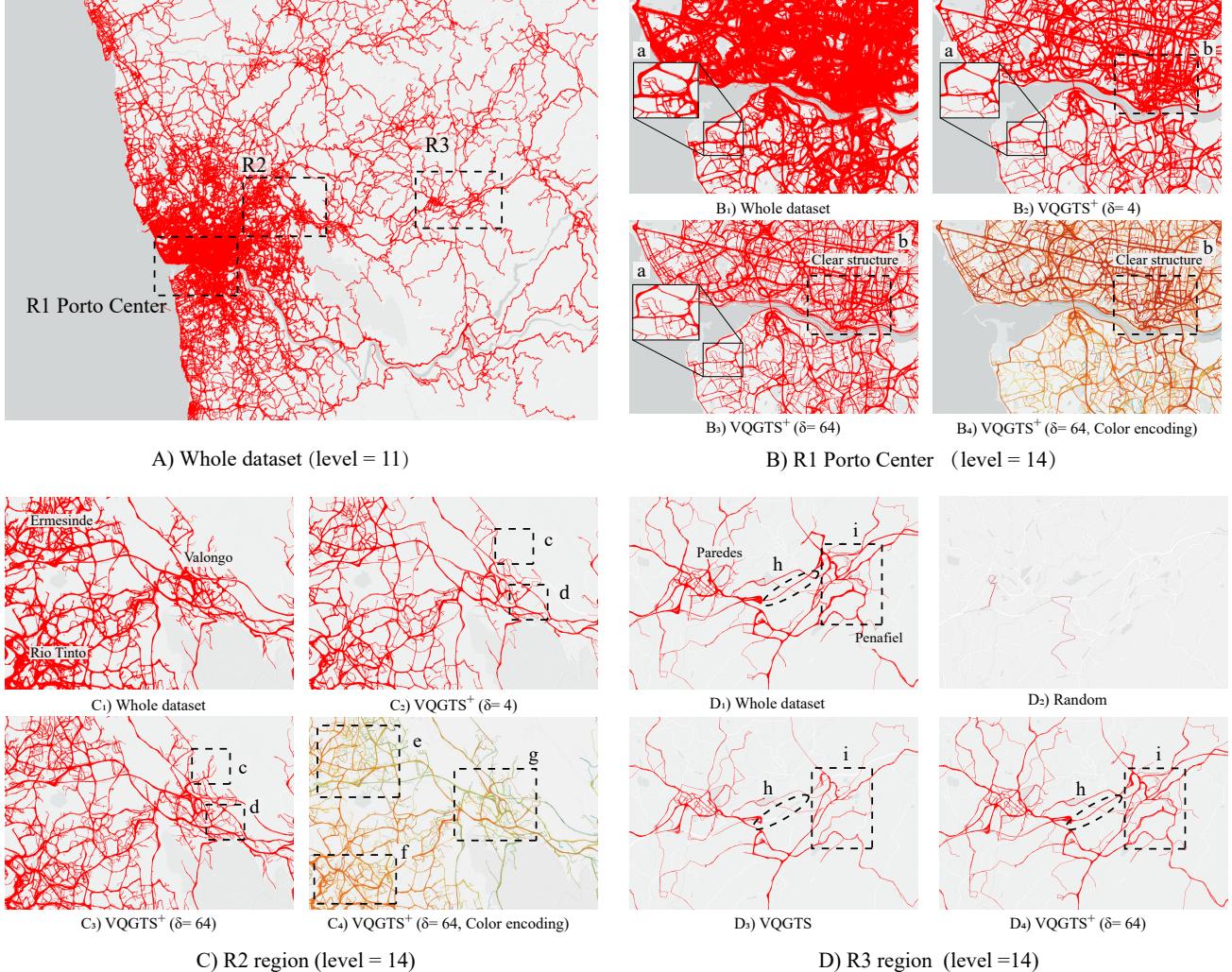


Fig. 7. Visualization at dense and sparse region respectively.

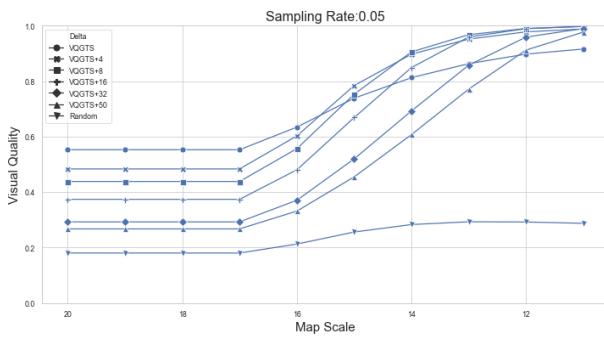


Fig. 8. Visual quality chart. X axis indicates map scale from detail view to overview; y axis indicate the visual quality.

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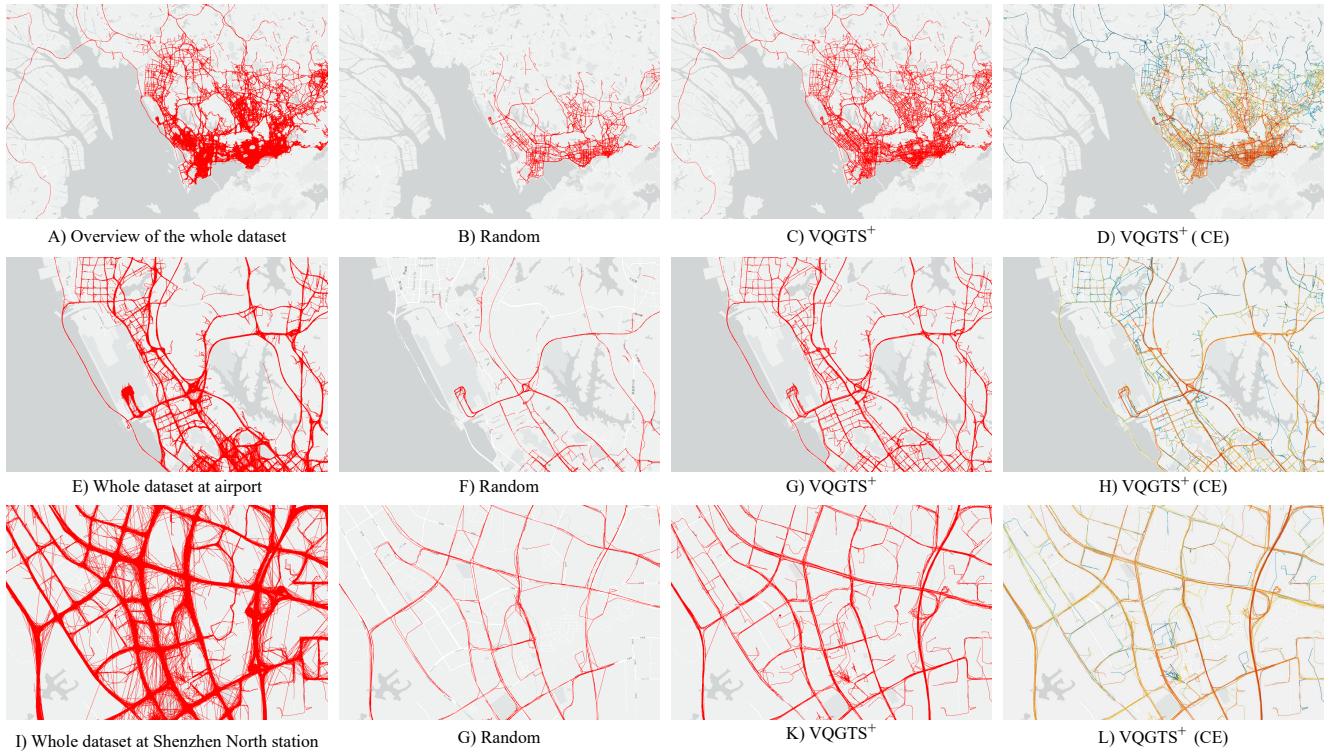


Fig. 9. Case study of Shenzhen.

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