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Route-Aware Edge Bundling for Visualizing Origin-Destination Trails in Urban Traffic

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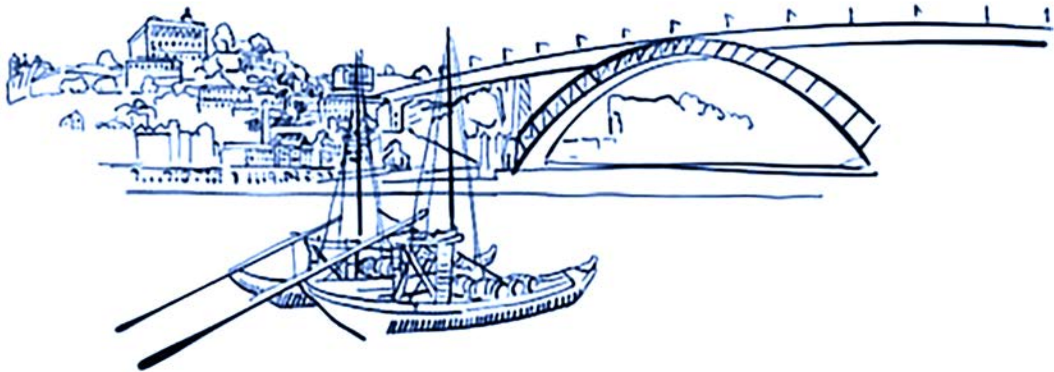

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- **Introduction**
  - OD Trails in Urban Traffic
  - Prior Edge Bundling Methods
  - Limitations of KDEEB

- **Route-Aware Edge Bundling**
  - Preprocessing:
    - map matching → hierarchical route structure construction → trail abstraction
  - Bundling
    - optimal kernel size setting → density map generation
  - Evaluation
    - Bundle termination
    - Bundle deviation

- **Conclusion and Future Work**

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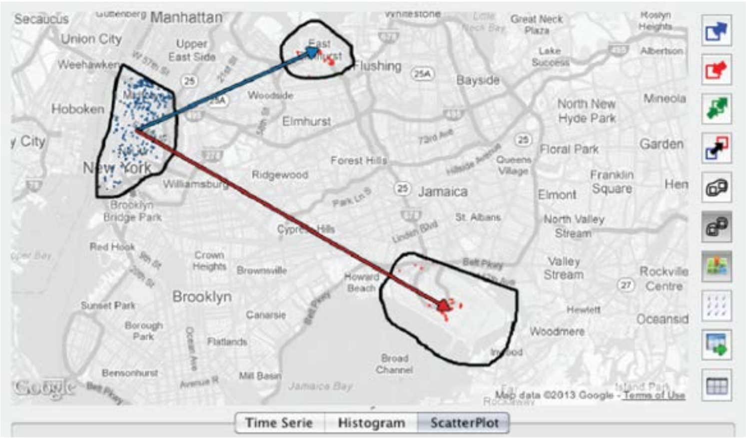
OD Trails in Urban Traffic

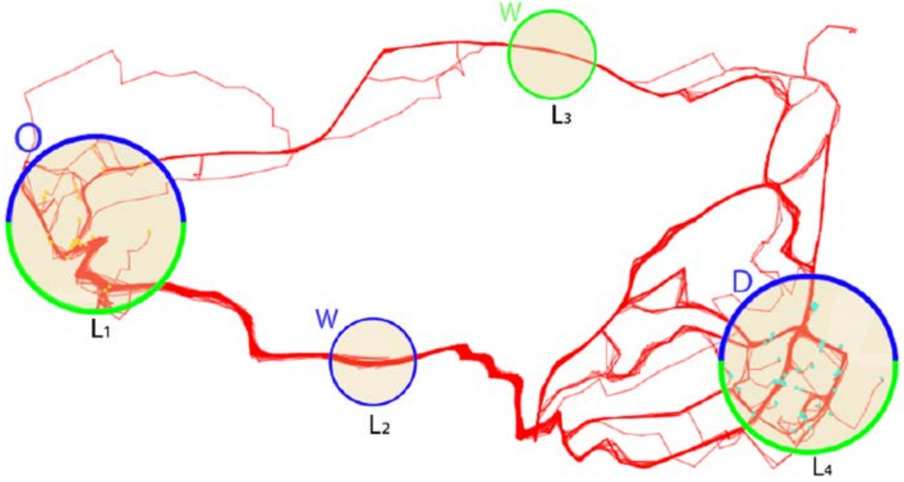


[Ferreira et al. 2013]

- Urban traffic data, e.g.,
  - Taxi trips in New York, Beijing, Shenzhen
  - Public transportation data in Singapore
  - Electric scooter tracks in Stuttgart

- Origin-destination (OD) is a fundamental concept in transportation, summarizing (people/vehicle/good) movements across geographic locations.

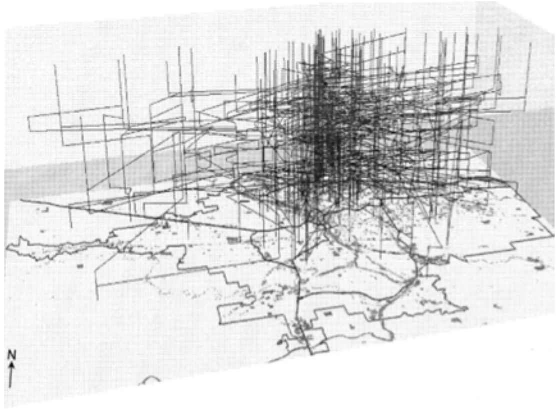
- Properties of OD trails in urban traffic
  - Locations
  - Times
  - Road network
  - Multi-modes



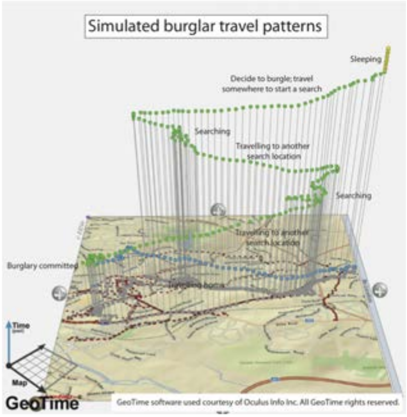
[Krüger et al., 2013]

OD Trail Visualization

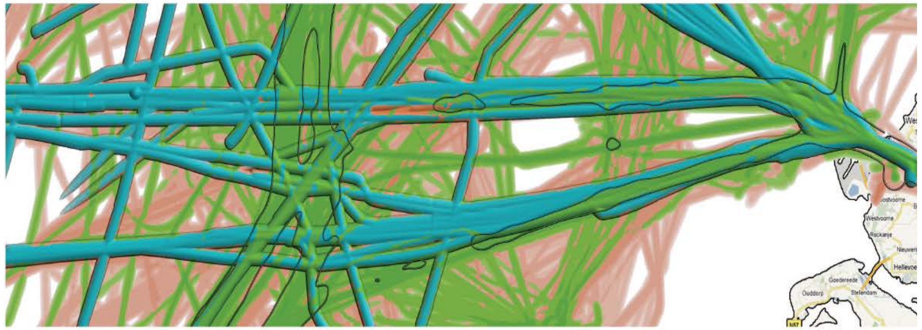
- Density Map
  - Summarize trajectories and overview distribution.
- Spatial Aggregation
  - Partition underlying territory into appropriate areas.
- Map Matching
  - Align position records with road network data.
- Direct depiction
  - Directly plot trajectories into 2D/3D displays.



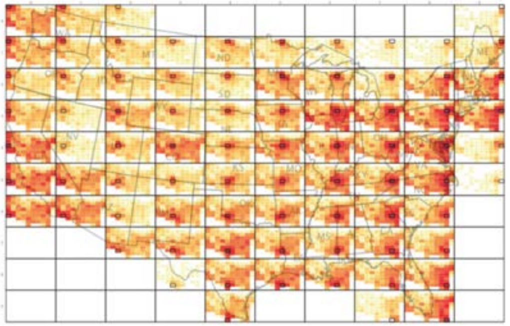
[Kwan, 2000]



[Kapler and Wright, 2004]



[Scheepens et al., 2011]



[Wood et al., 2010]

[Andrienko and Andrienko, 2011]

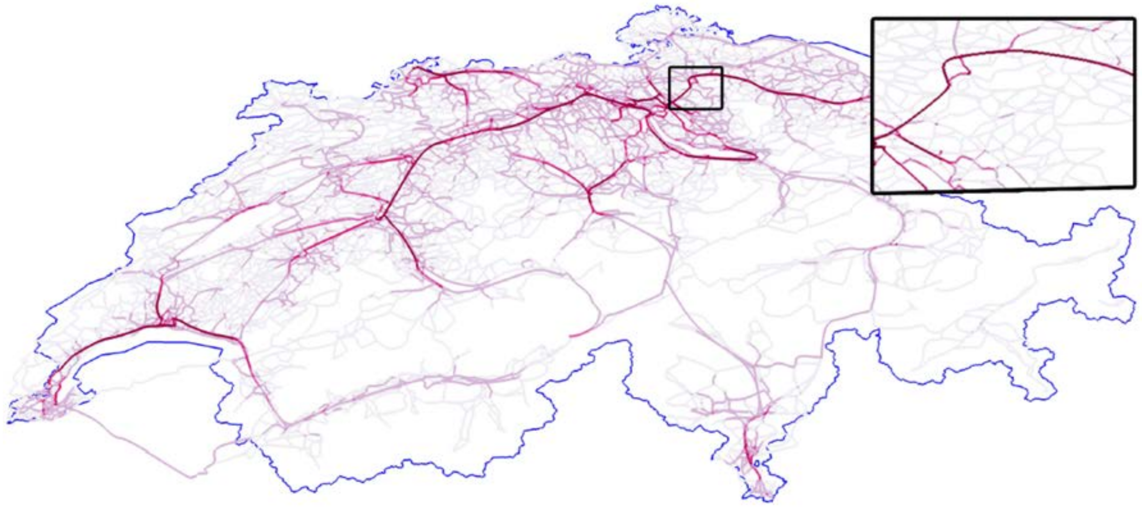
[Krüger et al. 2018]

Prior Edge Bundling Methods

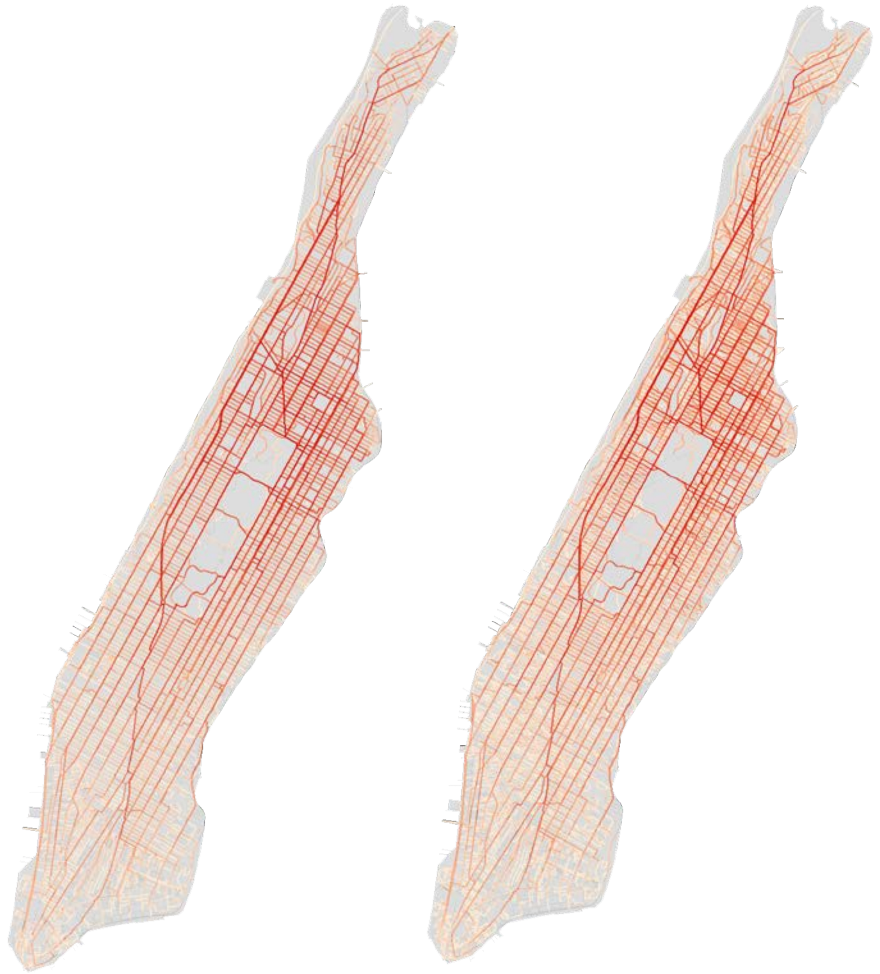
- *Geometry-based* methods: Use control mesh to specify how similar edges are routed.
  - Pros: Flexible to make control mesh
  - Cons: Constructing control mesh can be (very) slow
- *Force-based* methods: Model interaction between spatially close trails as a force field.
  - Pros: No need to make external control mesh
  - Cons: Slow – cannot handle a few thousands trails at interactive rates
- *Image-based* methods: Employ image-processing methods to accelerate the bundling process.
  - Pros: Feasible for GPU implementation – can process millions of trials at interactive rates.
  - Cons: No consideration of spatial constraints when applied to OD trails.

Prior Edge Bundling Methods

- *Constrained Bundling*: Specific constraints are considered.
  - Ambiguity
  - 3D curved surfaces
  - Directions
  - Obstacles avoidance
  - **Vector map**



Vector map for Swiss commuter data
[Thöny & Pajarola, 2015]



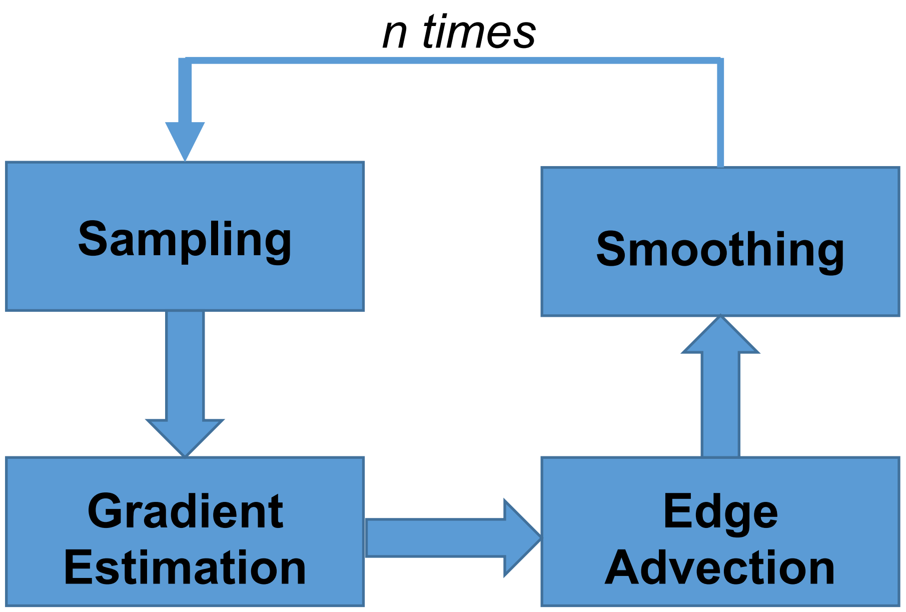
Map matching Vector map

Kernel Density Estimation Edge Bundling (KDEEB)

- We chose KDEEB for the basis of our method:
  - Fast in speed, meanwhile simple enough to implement
  - Be able to incorporate specific constraints
- KDEEB pipeline
  - Sampling
  - Gradient estimation

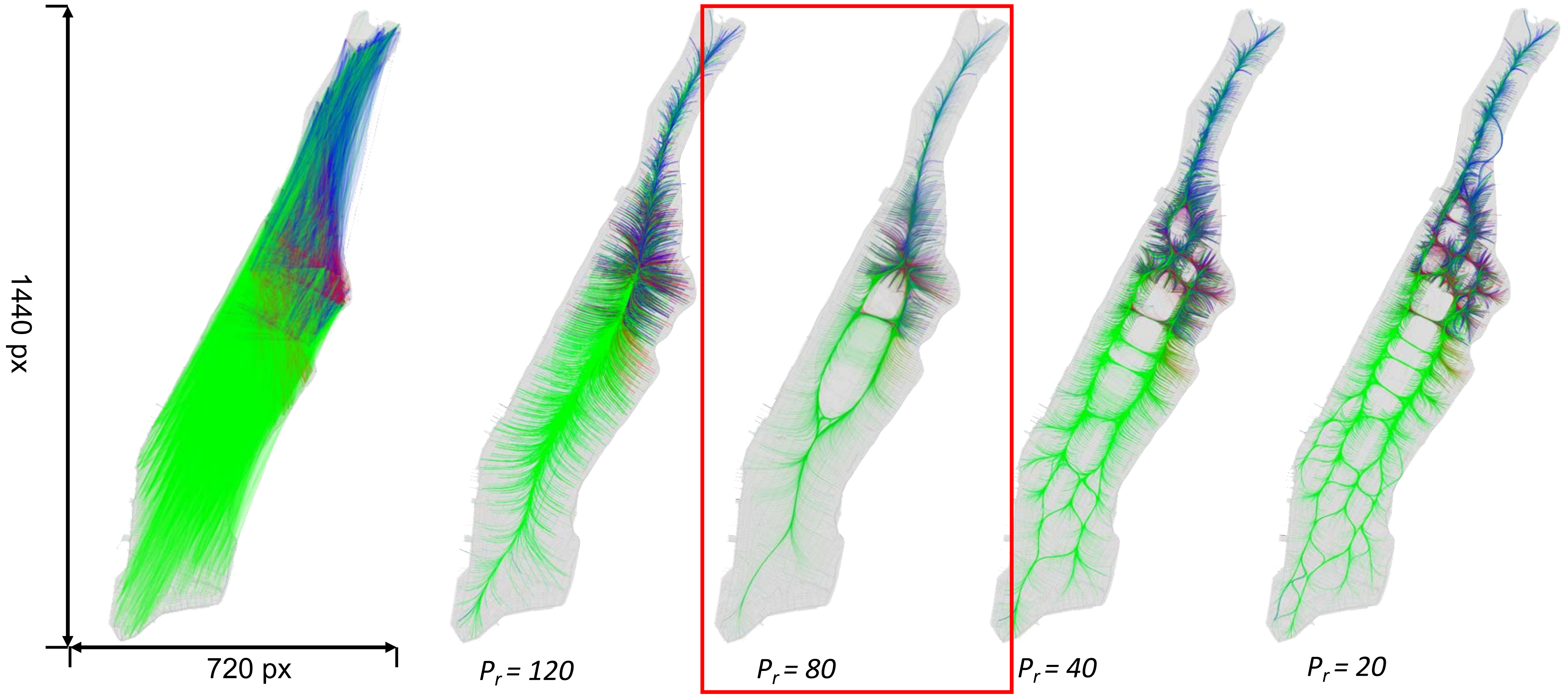
$$\rho(\mathbf{x} \in \mathbb{R}^2) = \sum_{\mathbf{y} \in D} K\left(\frac{\|\mathbf{x}-\mathbf{y}\|}{p_r}\right)$$

  - Advection
  - Smoothing
- Iterate *n* times until stable layout
  - Predefined 10 or 15 times
  - Automatically determined at runtime?

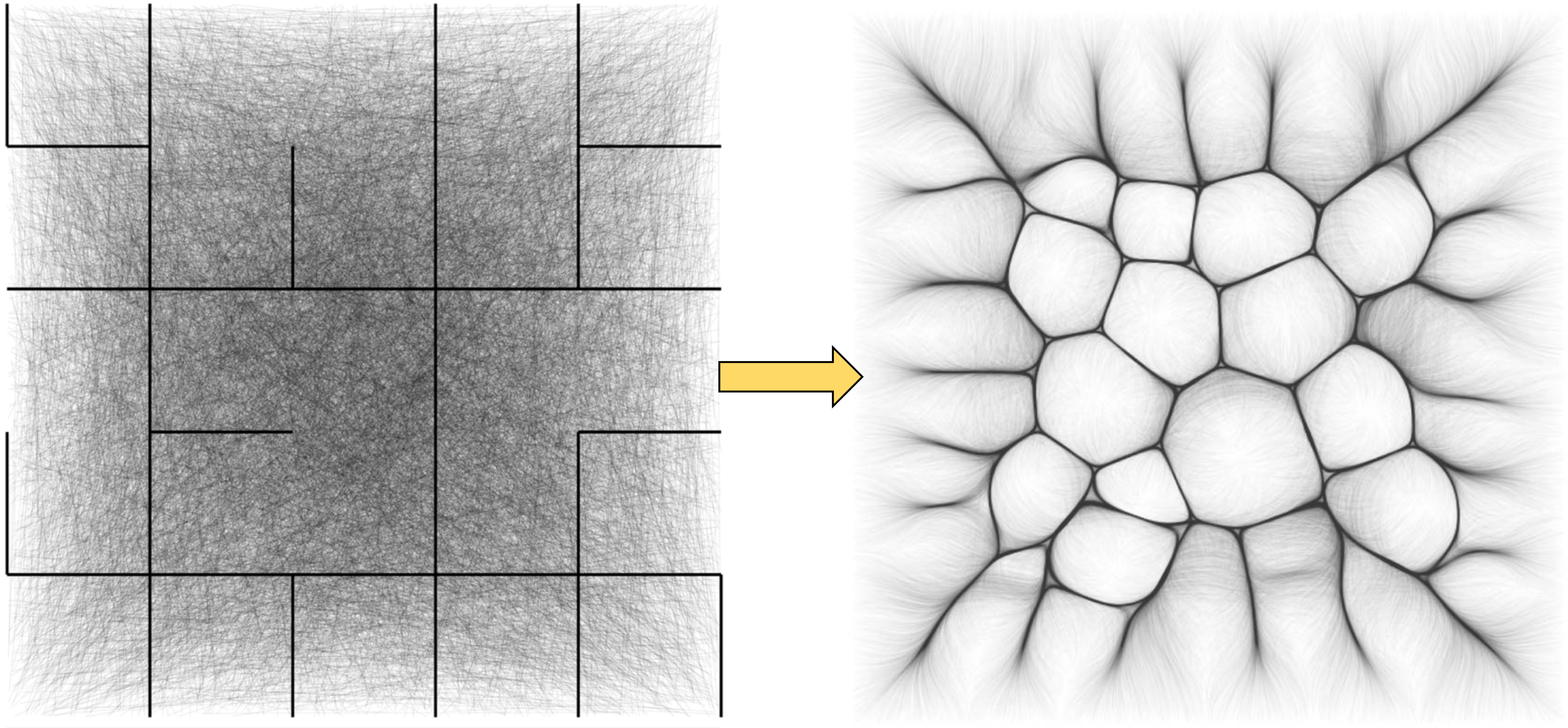


Limitations of KDEEB: What is a suitable pr?

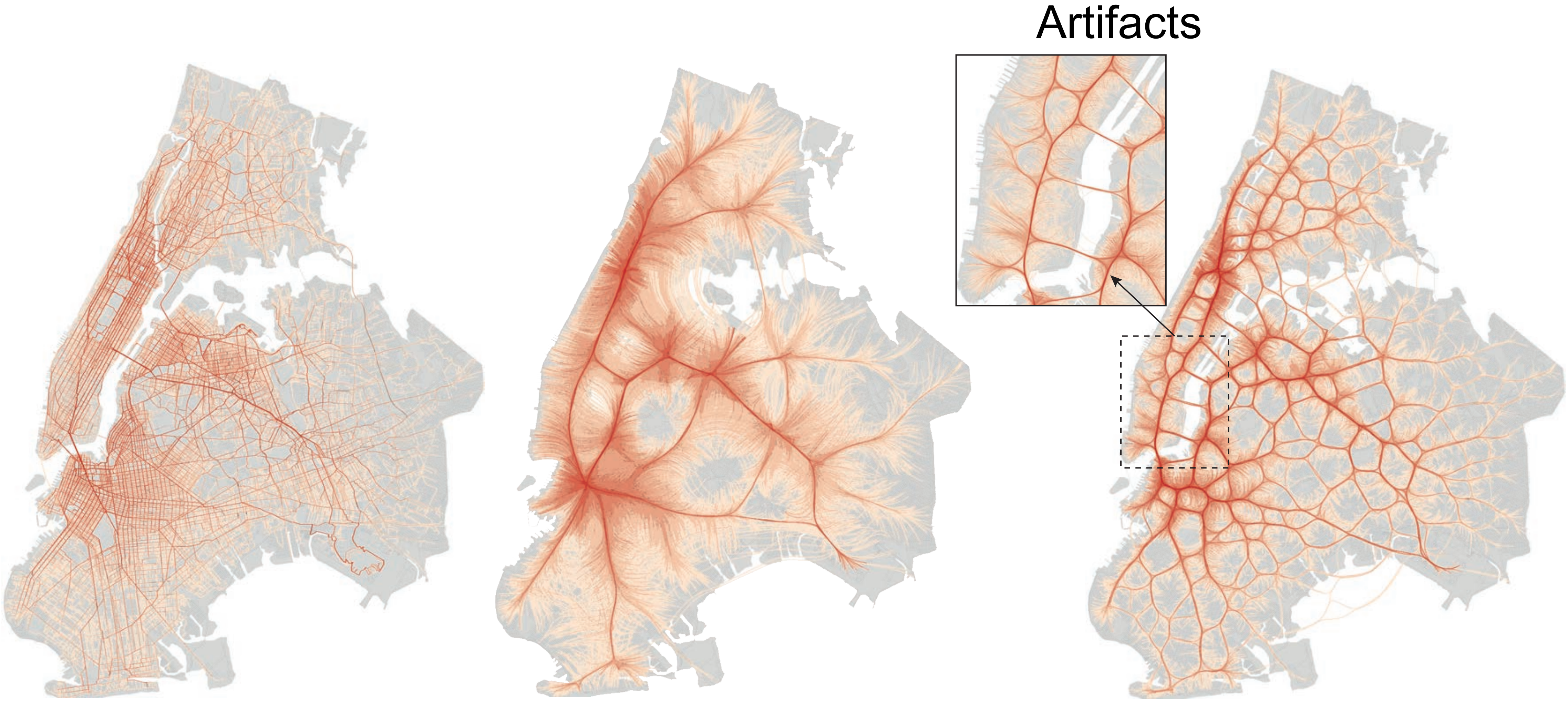
- KDEEB: 5% of graph drawing size
  - $5\% \times \sqrt{1440^2 + 720^2} = 80.5$



Limitations of KDEEB: Road neglect



Limitations of KDEEB



Map Matching

KDEEB ($p_r = 60$)

KDEEB ($p_r = 21$)

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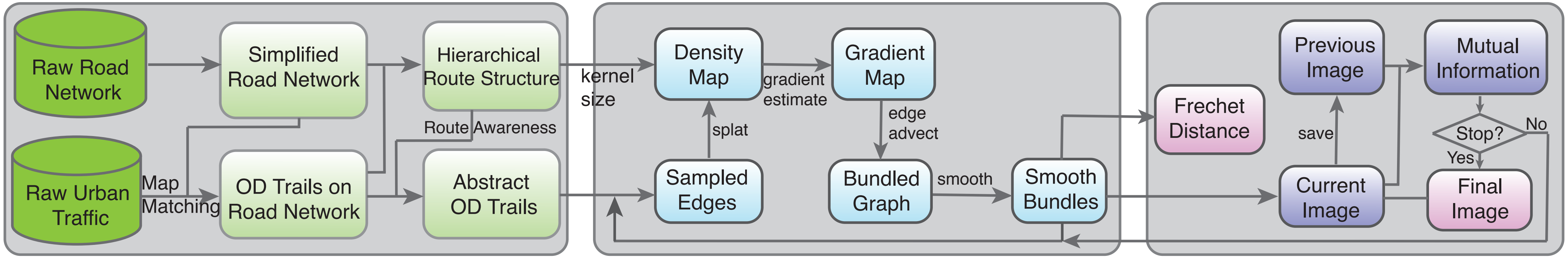
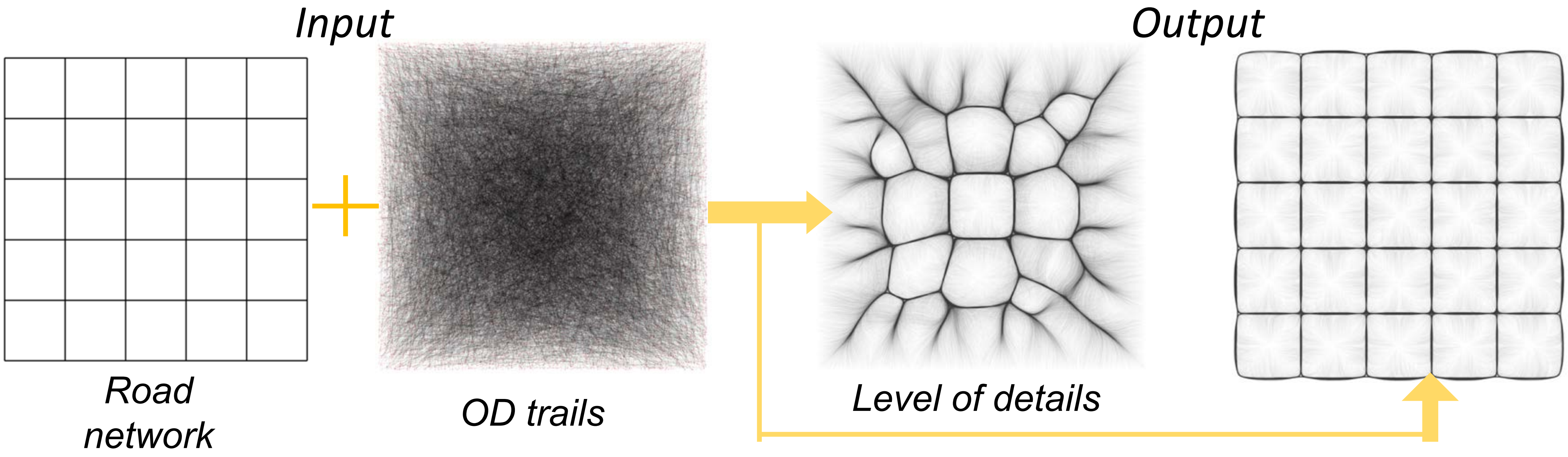
Route-Aware Edge Bundling

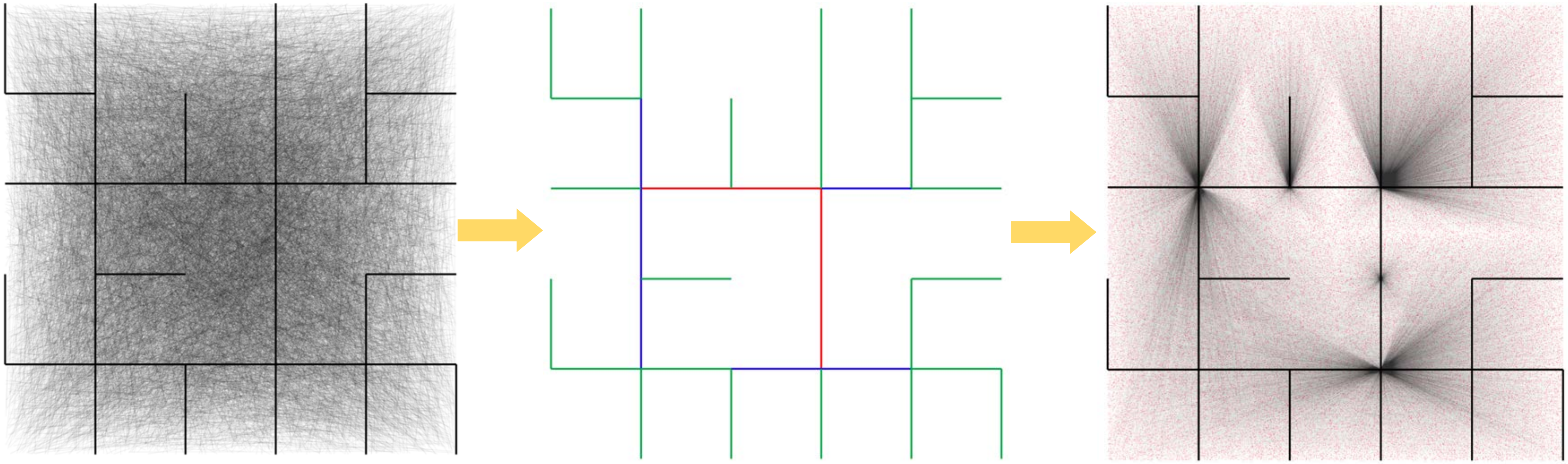
- RAEB pipeline: 1) Preprocessing, 2) Bundling, and 3) Evaluation





Preprocessing

- Build a simplified hierarchical road and traffic network representation.
  - Map matching: shortest path for OD only, ST-matching for GPS traces
  - Hierarchical structure construction: route length, road hierarchy, flow magnitude
  - Trail abstraction: route awareness (p_{ra})



OD Trails & Road network

Hierarchical route structure

Trail Abstraction

Bundling

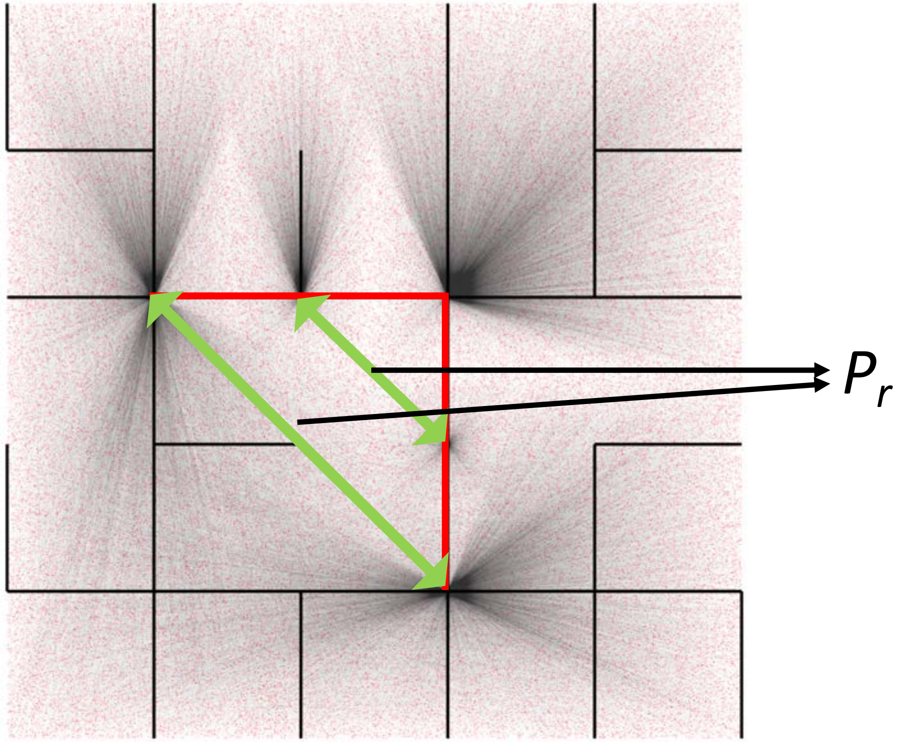
- KDEEB applied to the hierarchical structure.
  - Optimal kernel size setting
  - Density map generation

$$\rho_{raeb}(\mathbf{x} \in \mathbb{R}^2) = \sum_{\mathbf{y} \in D} K\left(\frac{\|\mathbf{x}-\mathbf{y}\|}{p_r}\right) + \theta \sum_{\mathbf{r} \in R_{aware}} \Theta(\|\mathbf{x}-\mathbf{r}\|);$$

Algorithm 1 KernelSizeSetting

Input: Top N routes $P = \{P_1, ..., P_N\}$
Output: Initial kernel size p_r

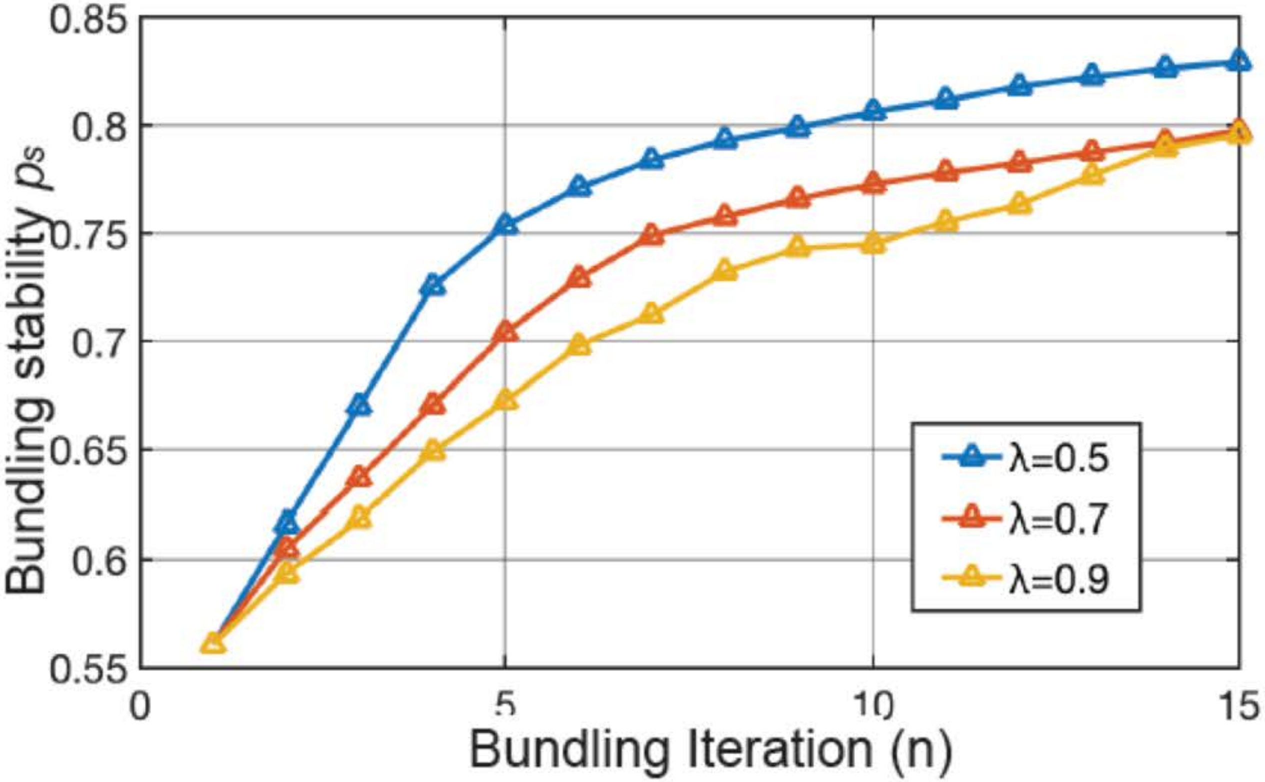
for i = 1 to N **do**
  for j = i + 1 to N **do**
    $d[i][j] = d[j][i] = \text{DiscreteFrechetDistance}(P_i, P_j)$
$C = DBSCAN(P, \varepsilon, minNum)$;
$C_{max} = \text{argmax}_{C_i \in C} |C_i|$;
$d_{geo} = 0$;
for each $P_i \in C_{max}$ **do**
  for each $P_j \in C_{max}$ && $i \neq j$ **do**
    $d_{geo} = d_{geo} + d[i][j]$;
$p_r = d_{geo} / |C_{max}| / (|C_{max}| - 1) / 2$;
return p_r

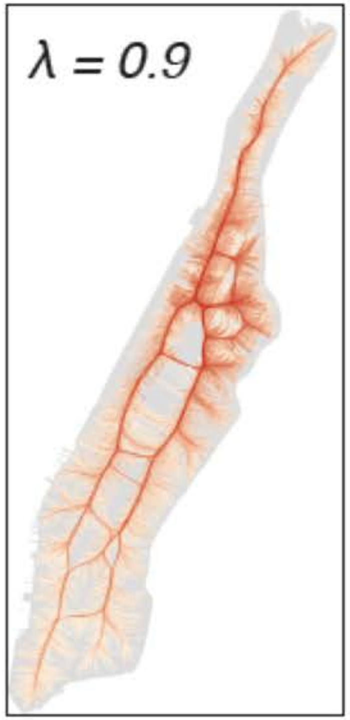


Evaluation

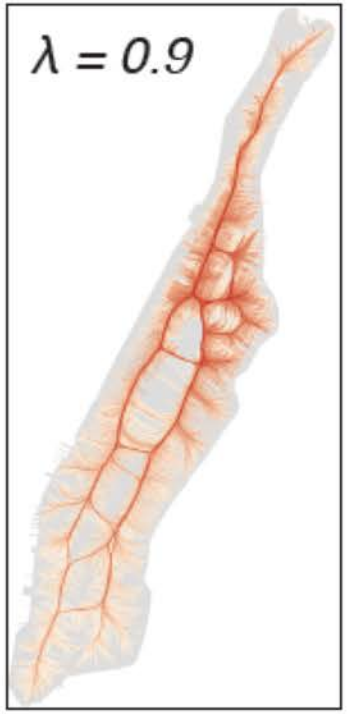
- Termination: Bundle stability (p_s) to determine when to stop iteration
- Bunc … t

$$NMI(X,Y) = \frac{2MI(X,Y)}{H(X)+H(Y)} \qquad MI(X,Y) = \sum_{x \in X} \sum_{y \in Y} p(x,y) log\left(\frac{p(x,y)}{p(x)p(y)}\right)$$





$n = 10$



$n = 11$

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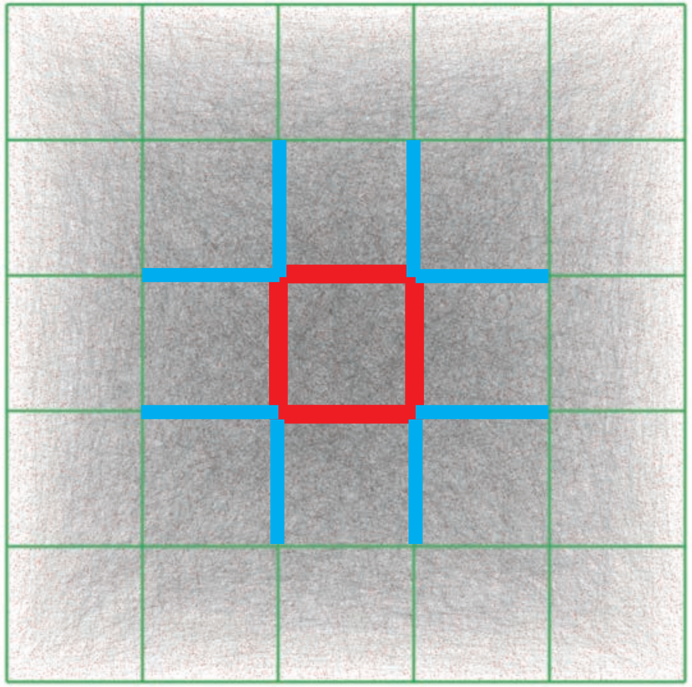

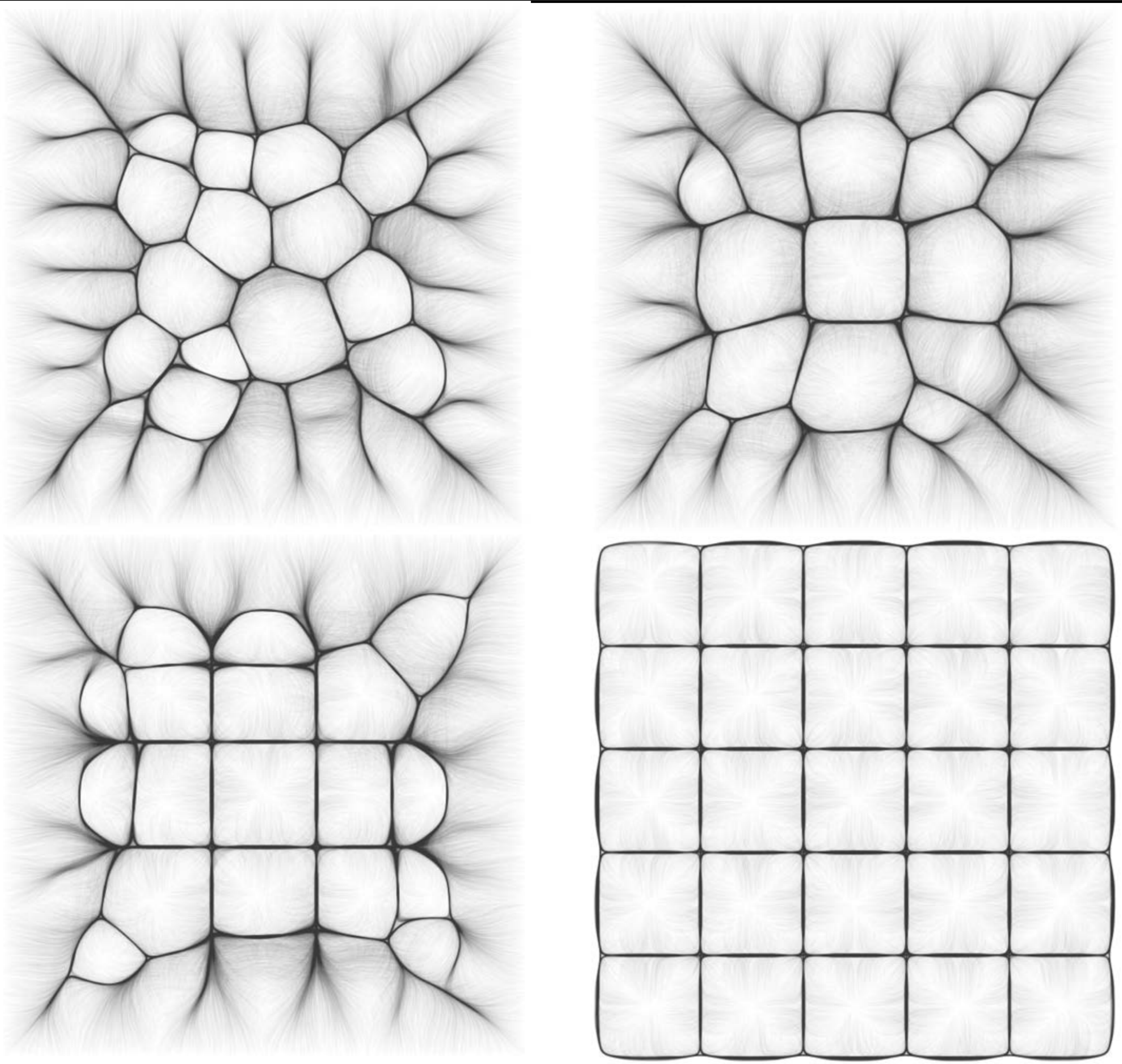

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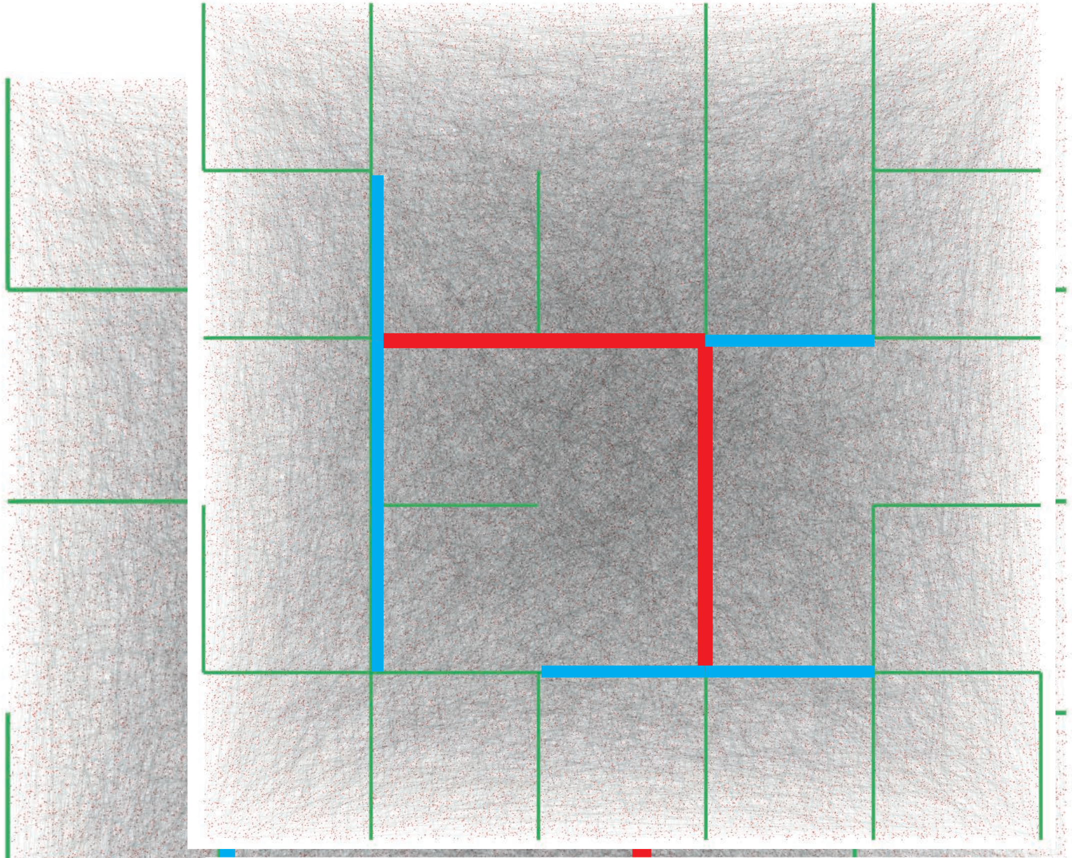
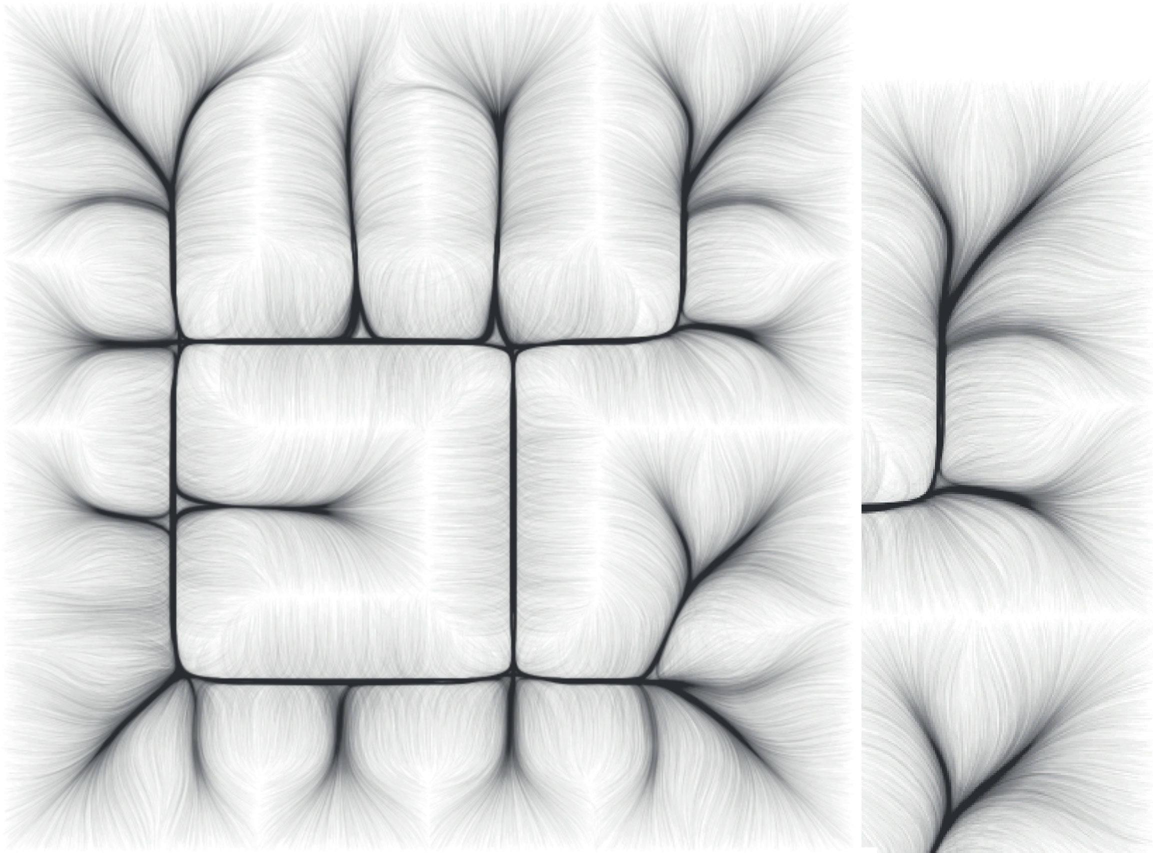
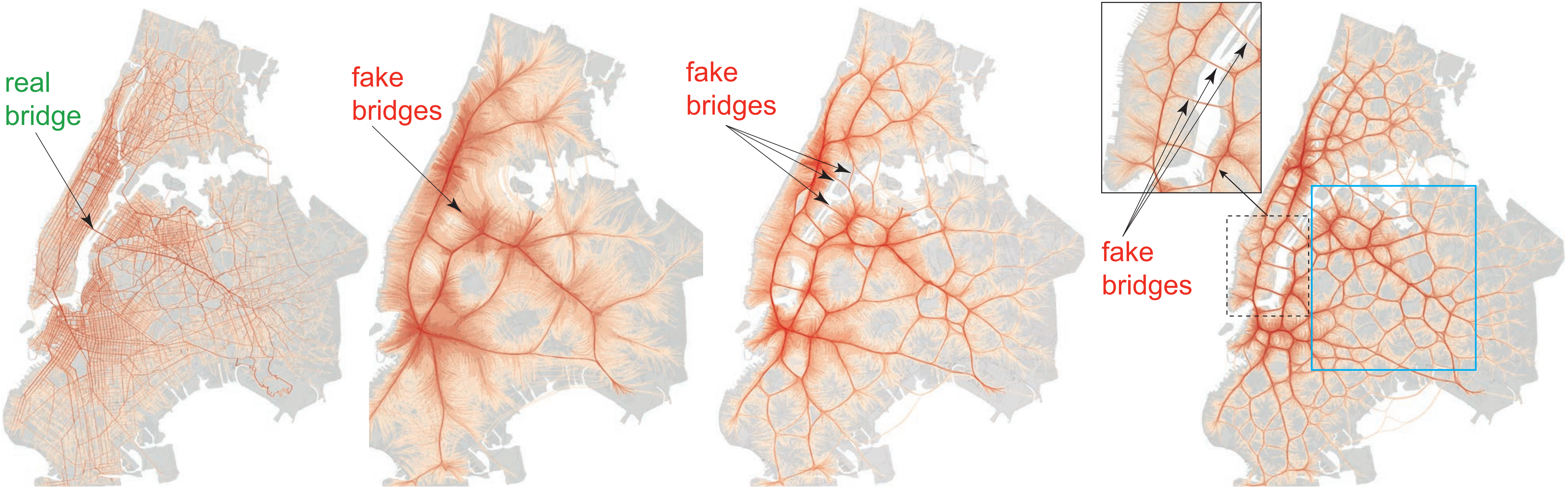




Dataset	Edge samples	p_n	Time (sec.)		Deviation (pixels)	
			KDEEB	RAEB	KDEEB	RAEB
Synthetic	4.6M	13	40.3	50.7	18.37	12.58
New York	3.1M	11	34.3	42.9	15.40	9.88
Shenzhen	1.3M	8	13.8	22.8	13.71	10.53

Application 2: NYC Taxi



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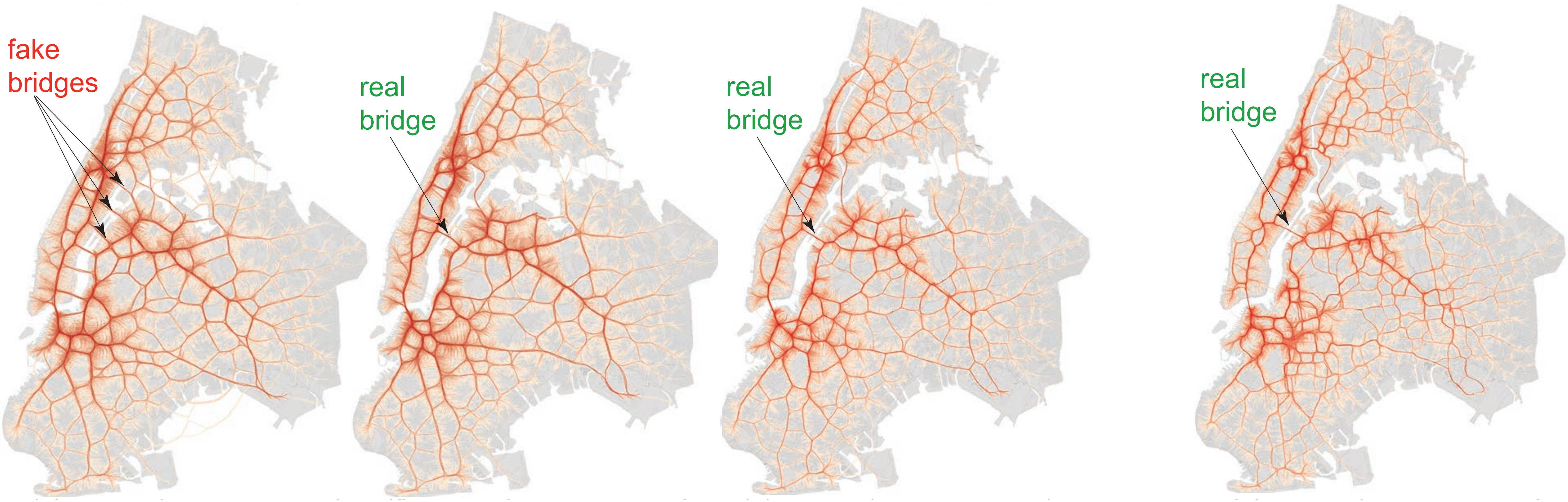

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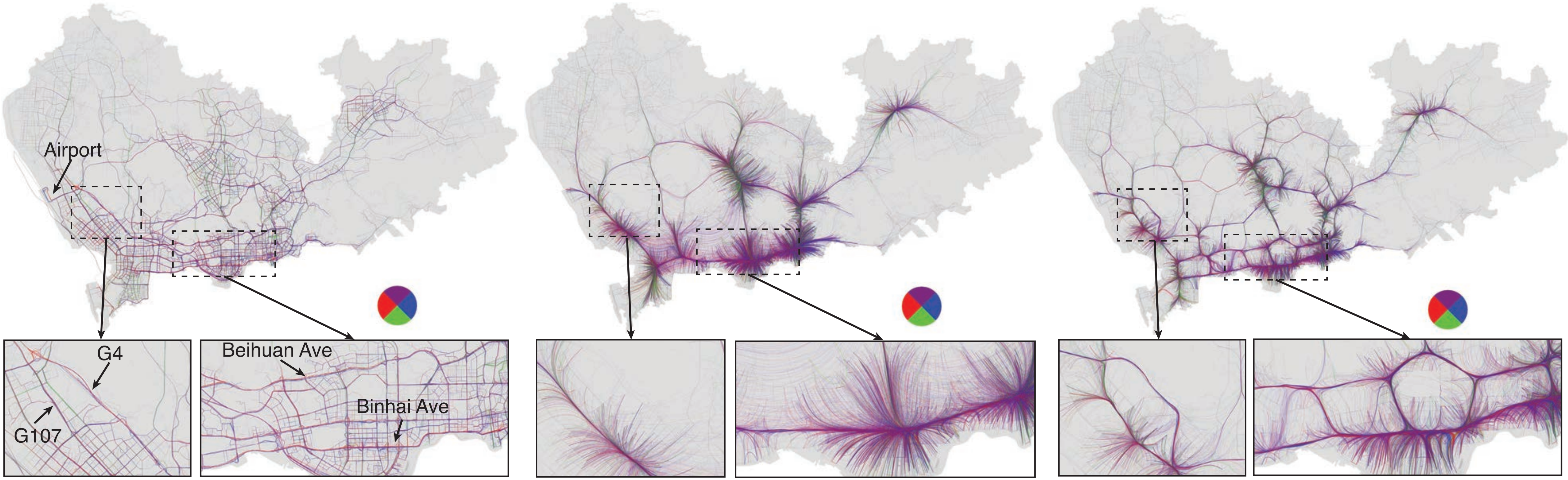
Application 3: Shenzhen Taxi



(a) Map Matching (b) KDEEB (c) RAEB

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Discussions

- RAEB constrains trails to a given road network
  - **Route awareness (p_{ra}):** controls how bundles follow roads at a user-selected hierarchy level.
  - **Kernel size (p_r):** determined by both the road network geometry and its resolution in image space.
  - **Bundling stability (p_s):** automatically stops bundling when this similarity exceeds a given threshold.
- RAEB outperforms KDEEB on both synthetic and real OD trails
  - Visually more realistic
  - Quantitively closer to ground-truth results
  - Comparable running time
- Limitations and future work
  - Visual hints on bundle deformation
  - Incorporate directional bundling techniques
  - Local and adaptive parameter settings: p_{ra} and p_r

Q & A

谢谢！

Thank You!

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