A Proposal of Road Network Hierarchization Method Based on Betweenness Centrality for Application to Vehicle Routing Problems

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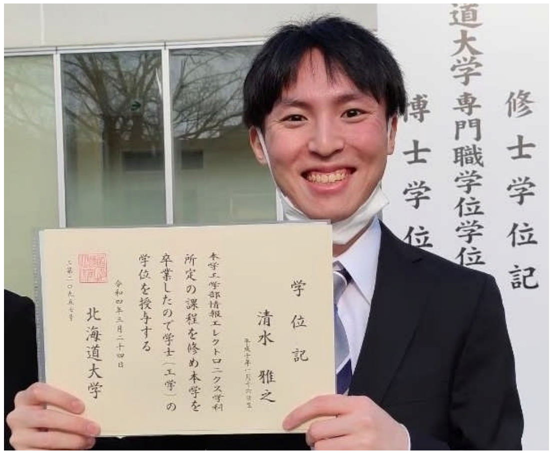
Self-introduction



- Name
  - Masayuki Shimizu
- Affiliation
  - Graduate School of Information Science and Technology, Hokkaido University, Japan
- His research area
  - Intelligent Traffic System, Route Search

Background

- The proliferation of online shopping necessitate efficient delivery methods in the industry
  - vehicle routing problems focus on efficient delivery routes

- Characteristics of routes used in real-world vehicle routing problems
  - **Large number of routes between customers**
  - **Consideration of driver preferences**

What is required for route search in vehicle routing problems
- computation of necessary routes between customers within a set time
- computation of routes that consider the diverse driver preferences

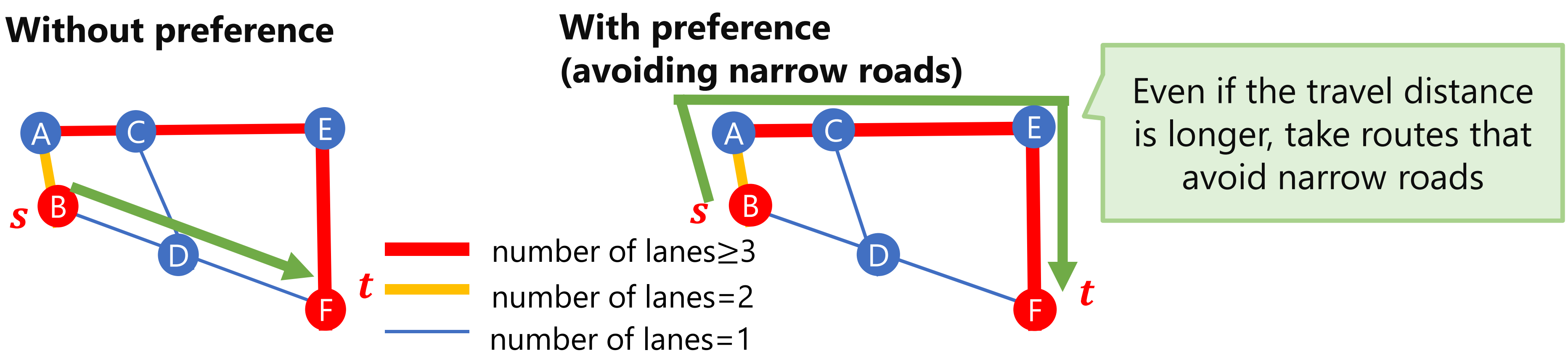
Route Search Considering Driver Preferences

- Driver Preferences
  - Elements that affect the route choices of drivers

Table 1 Examples of Driver Preferences

Static preference	Dynamic preference
Straight (Angle・Turn times)	Congestion (Length, waiting time)
Width (Road width・lanes・Road type)	Under Construction(Time zone・Roadblock)
Signal (Exist or No Exist)	Accident
Accident Site (Frequency of traffic accidents)	Weather (Snow condition)
Distance (Length of link)	

  - **In this study, we adopt avoidance of narrow roads**



Incorporating driver preferences into route search
Expressed as a weight for link cost

Research Objective

- To reduce the total computation time for route search
- To realize route search based on diverse driver preferences

Characteristics of the Assumed Situation

1. Processing many route searches within a fixed area in set time
2. Computing routes considering diverse driver preferences

Specific Situation

Example：Kerosene Delivery[1]

- Scale of the area, number of customers
  - Inside Sapporo city, 4 tank trucks, 2000 customers (approximately 40 deliveries per day), around 200 days
- computation of the necessary customer routes before the next delivery
- Driver preferences change depending on road and traffic condition

[1] Hirotaka Ooe, Soichiro Yokoyama, Tomohisa Yamashita, Hidenori Kawamura and Mitsuo Tada : Optimization of Kerosene Delivery Planning Using Tabu Search, IPSJ SIG Technical Report, No. 15, pp. 1-8.(2022)

- **Approaches to perform route searching quickly**
  1. Efficiency improvement of existing route search algorithms[2][3][4]
  2. Pre-computation

Route caching[5]

Example：pre-calculating and storing routes for key locations

Advantages
- Significantly reduce route search time
- Provide exact solutions

Disadvantages
- Difficult to consider diverse driver preferences

Hierarchization[6][7]

Example： Categorizing roads by type

Advantages
- Significantly reduce route search time
- Allow for considering diverse driver preferences

Disadvantages
- Cannot provide exact solutions

- **Reasons for adopting hierarchization**
  - Significant reduction of route search time is possible
  - Route search that consider diverse driver preferences is possible
  - Routes can tolerate a certain range of error in vehicle routing problems

[2] Pohl, Ira, "Bi-directional Search", in Meltzer, Bernard; Michie, Donald (eds.), Machine Intelligence, vol. 6, Edinburgh University Press, pp. 127–140. (1971),
[3] Hart, Peter E., Nilsson, Nils J., Raphael, Bertram : A formal basis for the heuristic determination of minimum cost routes, IEEE transactions on Systems Science and Cybernetics, Vol. 4, No. 2, pp. 100-107. (1968)
[4] Fredman, Michael L., Tarjan, Robert E. : Fibonacci heaps and their uses in improved network optimization algorithms, Journal of the ACM, Vol. 34, No. 3, pp. 596-615. (1987)
[5] Cohen, Edith, Halperin, Eran, Kaplan, Haim, Zwick, Uri : Reachability and distance queries via 2-hop labels, SIAM Journal on Computing, Vol. 32, No. 5, pp. 1338-1355. (2003)
[6] Geisberger, Robert, Sanders, Peter, Schultes, Dominik, Delling, Daniel : Contraction Hierarchies: Faster and Simpler Hierarchical Routing in Road Networks, Proceedings, pp. 319-333. (2008)
[7] Shota Fukuda, Kazuki Abe, Hideki Fuji, Tomonori Yamada, Shinobu Yoshimura : Layered route search method for large-scale multi-agent-based traffic simulation, IPSJ Journal, Vol. 59, No. 7, pp. 1435-1444. (2018)

Route Search Using a Hierarchical Network[7]

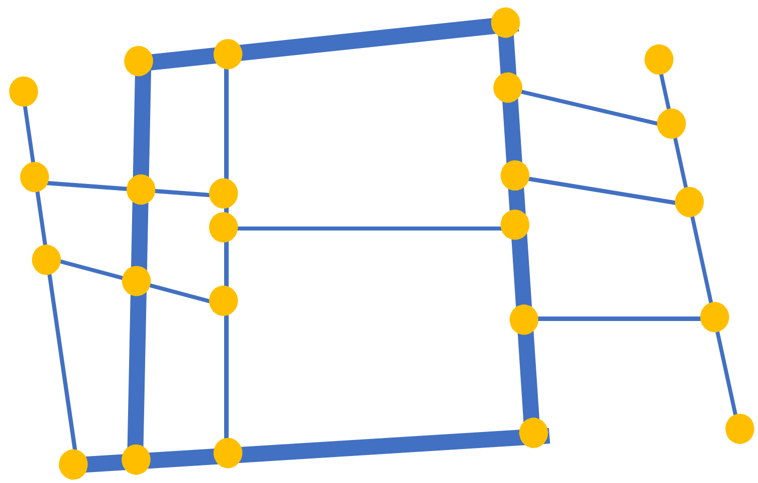
Input

- Hierarchical network : $\{G^1, G^2, \dots, G^N\}$
- A pair of origin and destination nodes (OD pair)

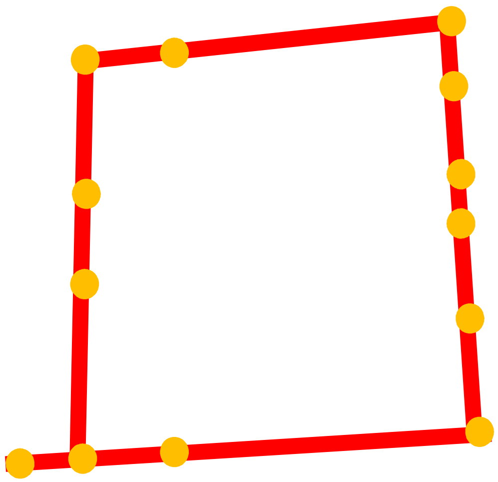
Output

- A route between OD pairs

In the case of a two-level hierarchical network

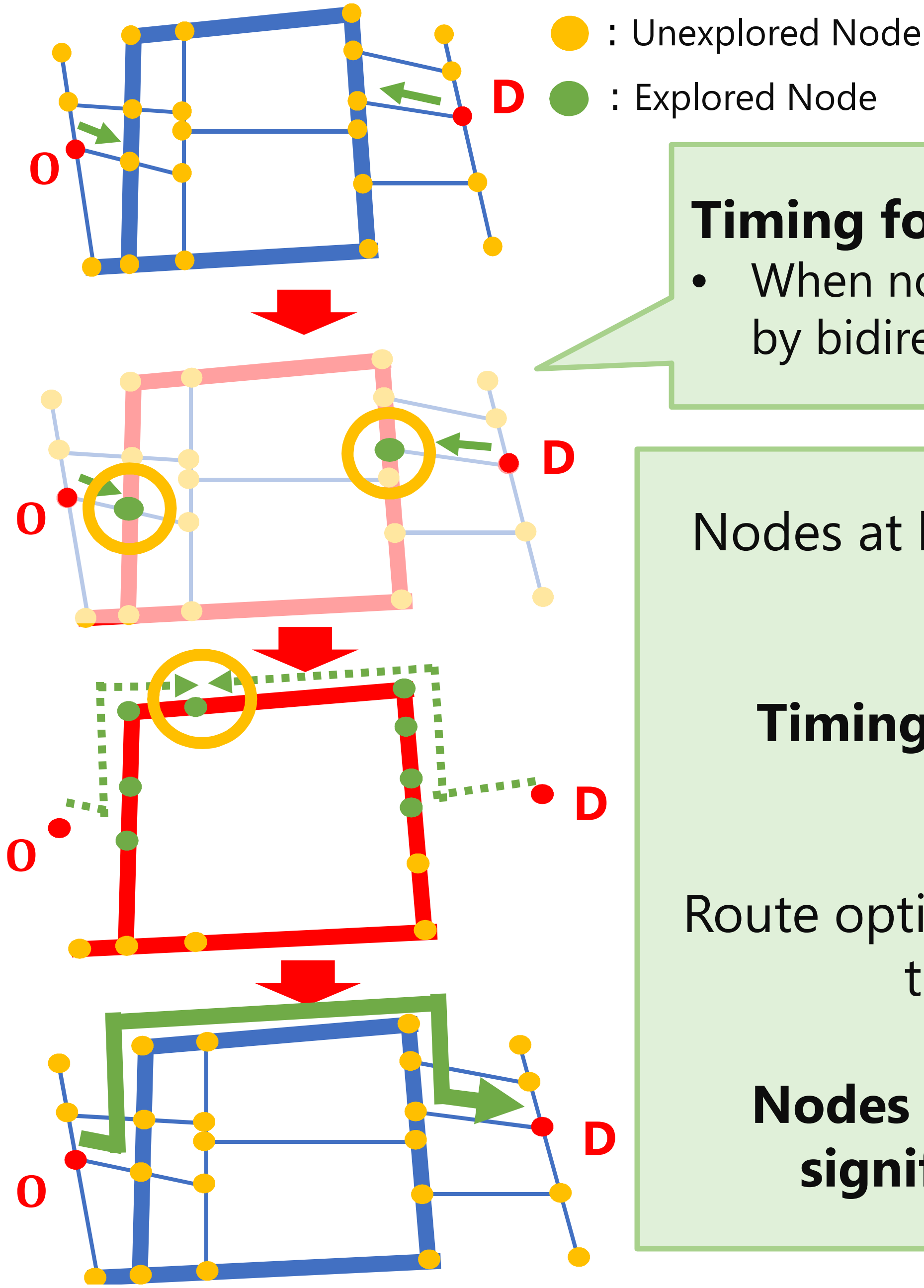


Hierarchical Level 1



Hierarchical Level 2

Route Search Using a Hierarchical Network[7]



The basic procedure is the same as bidirectional search

Timing for transition to upper-level networks

- When nodes in the upper-level network are reached by bidirectional search

Nodes at hierarchy transition are included in the output route

Timing of transition significantly affects solution accuracy

Route options become more limited as transition to upper-level networks occur

Nodes and links of upper-level networks significantly affect solution accuracy

Ideal Hierarchical Network

- **Mandatory conditions**
  - Inclusion relation
    - Nodes and links included in upper-level networks are also contained in the lower-level networks
  - Connectivity
    - Each level network is connected

- Upper-level networks are composed of nodes frequently traversed by minimum cost routes of each OD pair
  - Call as high importance nodes

Include high importance nodes in upper-level networks
→It is possible to reduce nodes to search while retaining less costly routes for the final selection

Indicators of Node Importance[8]

- Indicators to extract important nodes focusing on each node's properties and roles

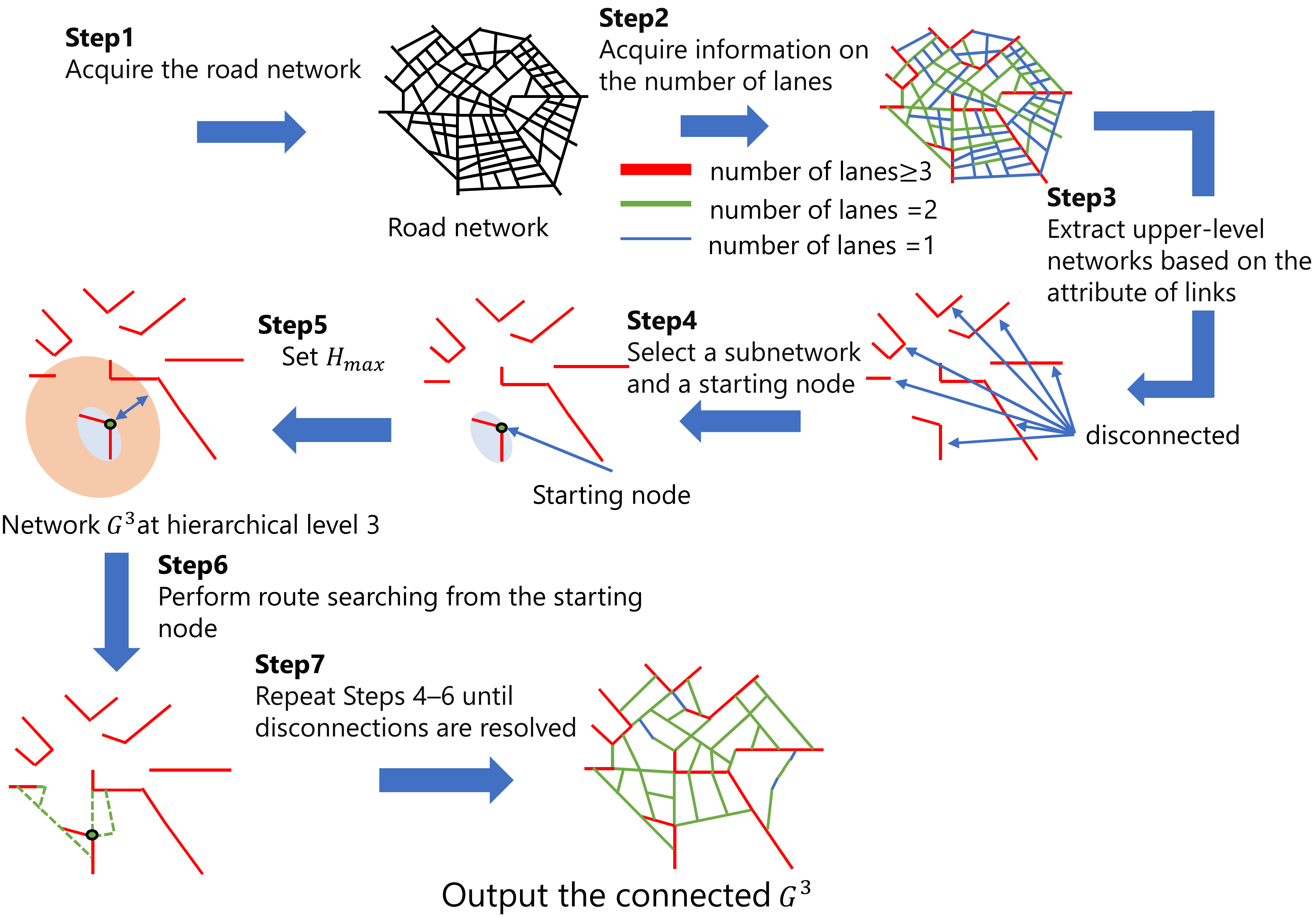
Degree centrality	Closeness centrality	Betweenness centrality
Evaluates how well-connected a node is	Evaluates proximity to all other nodes	Evaluate how often a node is used in the shortest route
Advantages	**Advantages**	**Advantages**
Identifies key hubs and connection points	Identifies nodes with high accessibility to others	Identifies nodes acting as bridges between many others
Disadvantages	**Disadvantages**	**Disadvantages**
Difficult to analyze structural network features	Difficult to identify nodes bridging many others	Does not directly evaluate overall node accessibility

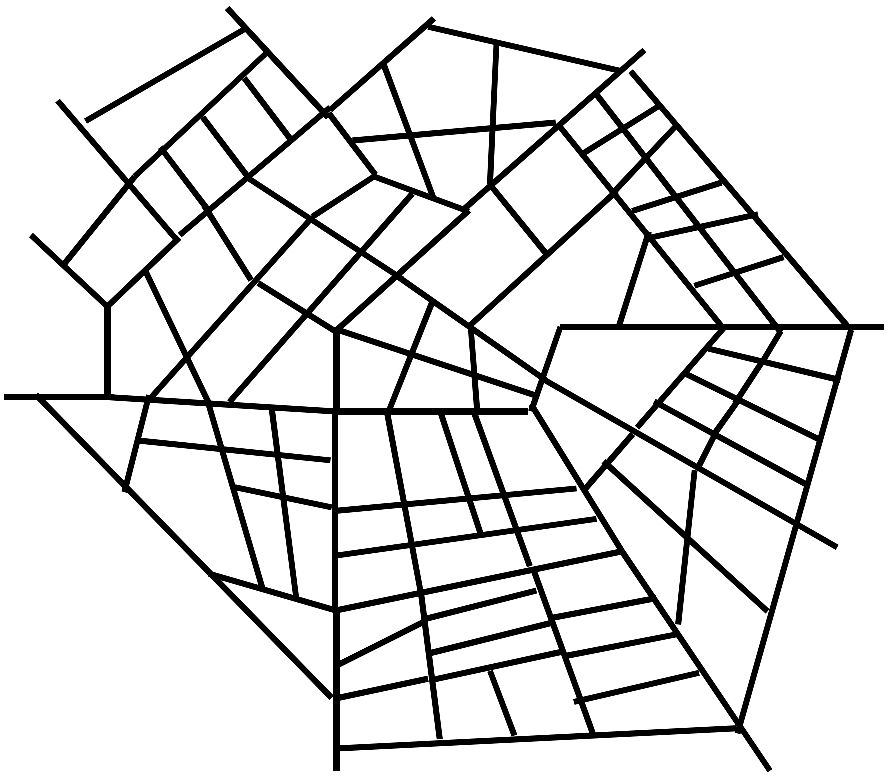
- **Set Centrality[9]**
  - Evaluate the importance as a set, considering the cooperation between nodes
    - Set closeness centrality: Facility location problems[10]
    - Set betweenness centrality: Billboard placement problems[11]

Adopt betweenness centrality and set betweenness centrality to extract nodes frequently traversed by minimum cost routes

[8] Linton C. Freeman: A Set of Measures of Centrality Based on Betweenness, Sociometry, Vol. 40, No. 1, pp. 35-41. (1977)
[9] Takayasu Fushimi, Kazumi Saito, Tetsuo Ikeda, Kazama Kazuhiro : Proposing Set Betweenness Centrality Measures Focusing on Nodes' Collaborative Behaviors and Its Application, The IEICE transactions on information and systems, Vol. J96-D, No. 5, pp. 1158-1165(2013)
[10] Kazumi Saito, Nobuaki Mutoh, Tetsuo Ikeda, Takuya Iriduki, Dai Nagata and Kanoko Ito： Speed-up of local improvement clustering method by incorporating lazy evaluation， Trans. of IPSJ TOM , Vol. 3, No. 1, pp. 62–72 (2010).
[11] Fushimi Takayasu, Saito Kazumi, Ikeda Tetsuo, Kazama Kazuhiro: Community Extraction Based on Betweenness Contribution of Group Centrality Nodes, IPSJ SIG Technical Report, Vol.2017-MPS-116, No.6, pp. 1-7 (2017)

Hierarchization Using the Prior Method[7]

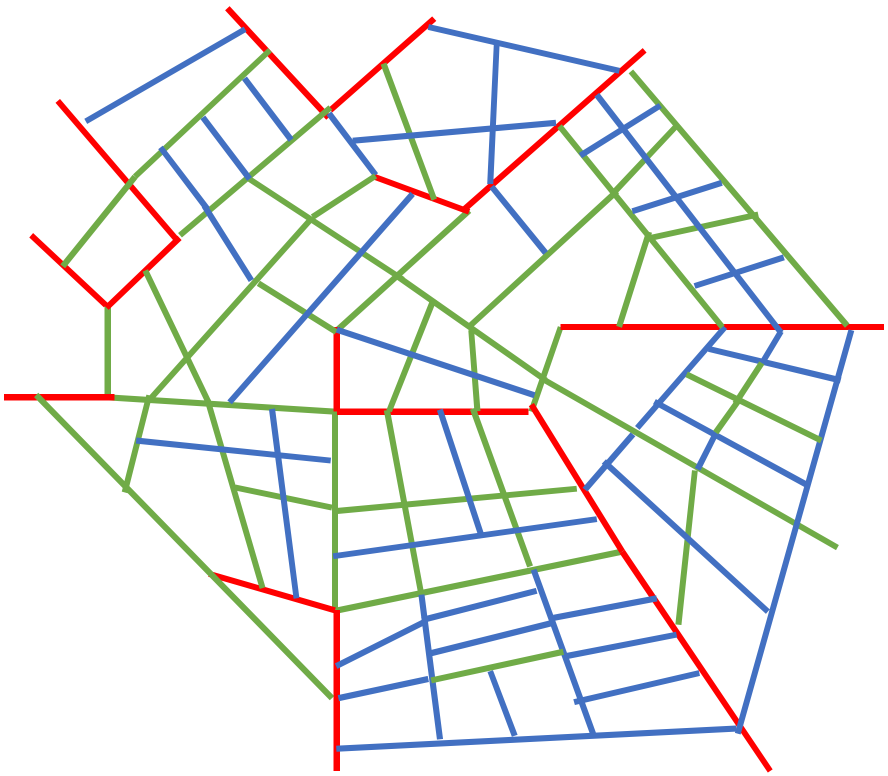




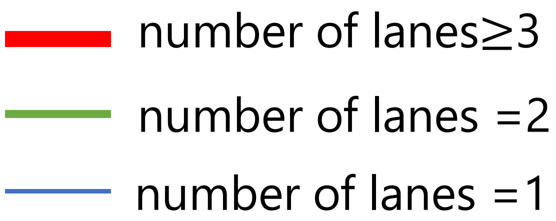
Road network

Step1
Acquire the road network

Hierarchization Using the Prior Method[7]

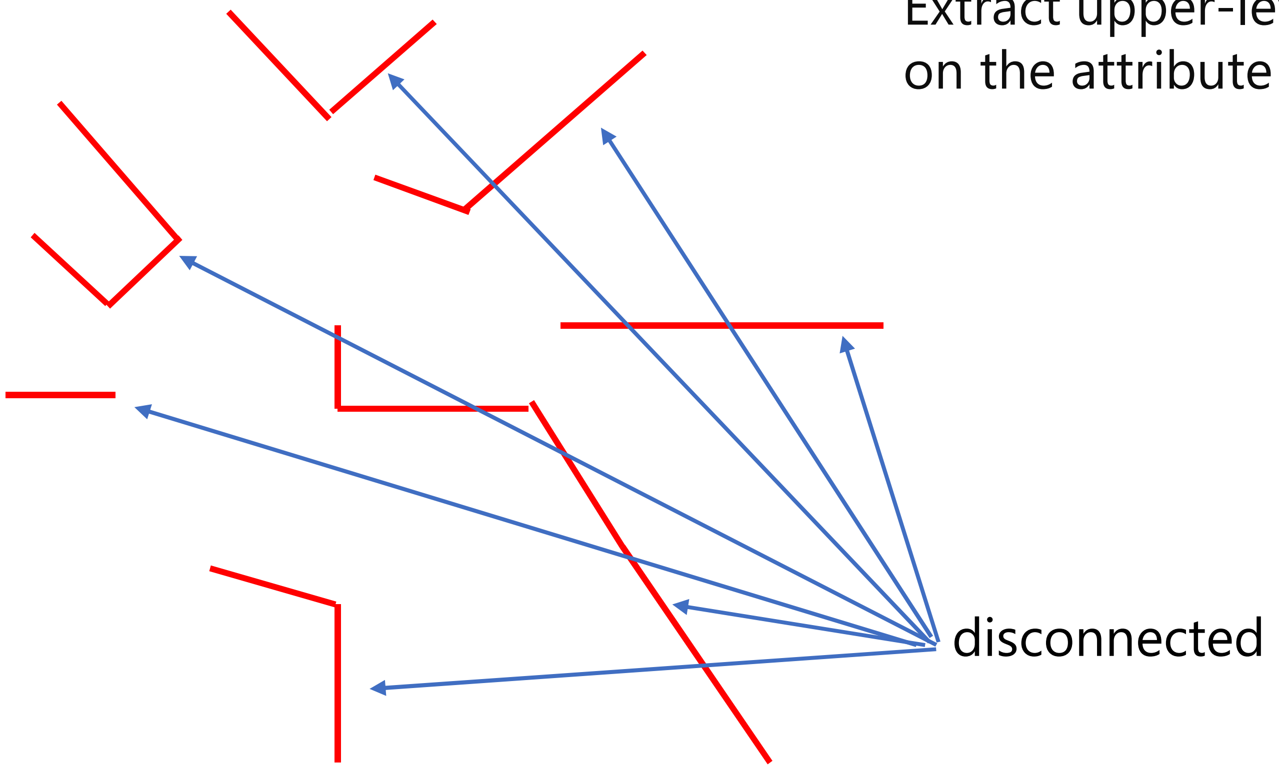


Step2
Acquire information on the number of lanes



Hierarchization Using the Prior Method[7]

Step3
Extract upper-level networks based on the attribute of links

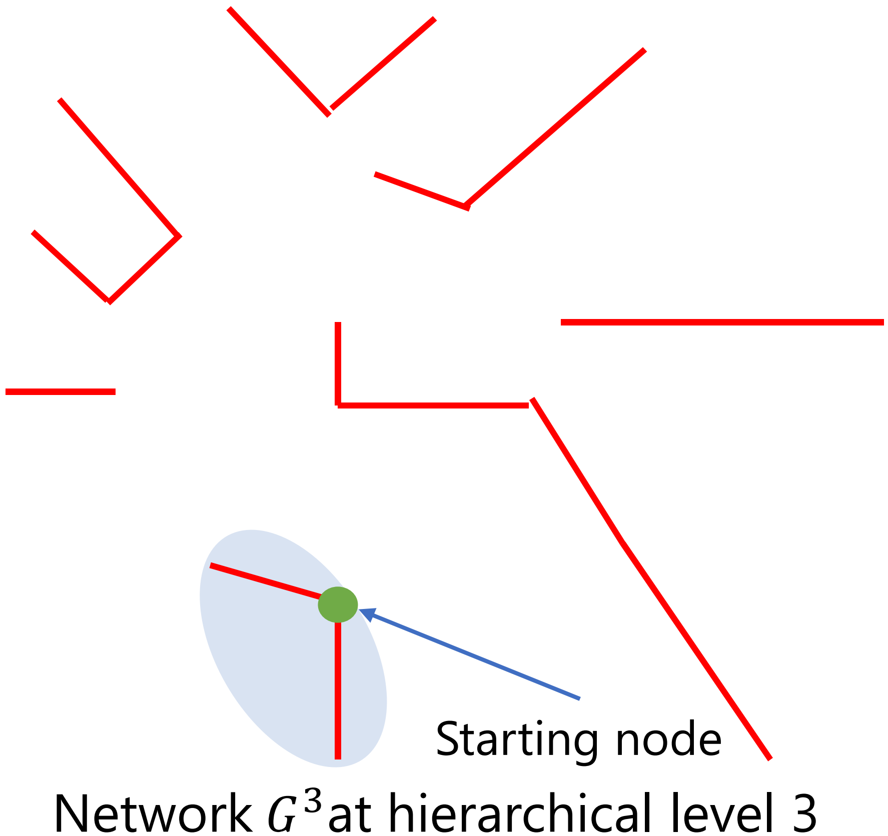


Network G^3 at hierarchical level 3

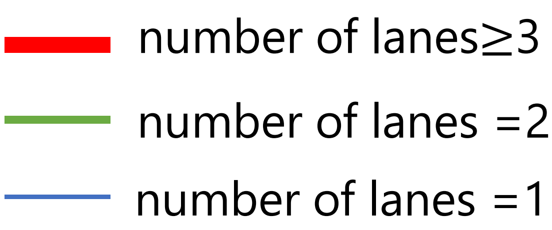
- number of lanes≥3
- number of lanes =2
- number of lanes =1

Hierarchization Using the Prior Method[7]

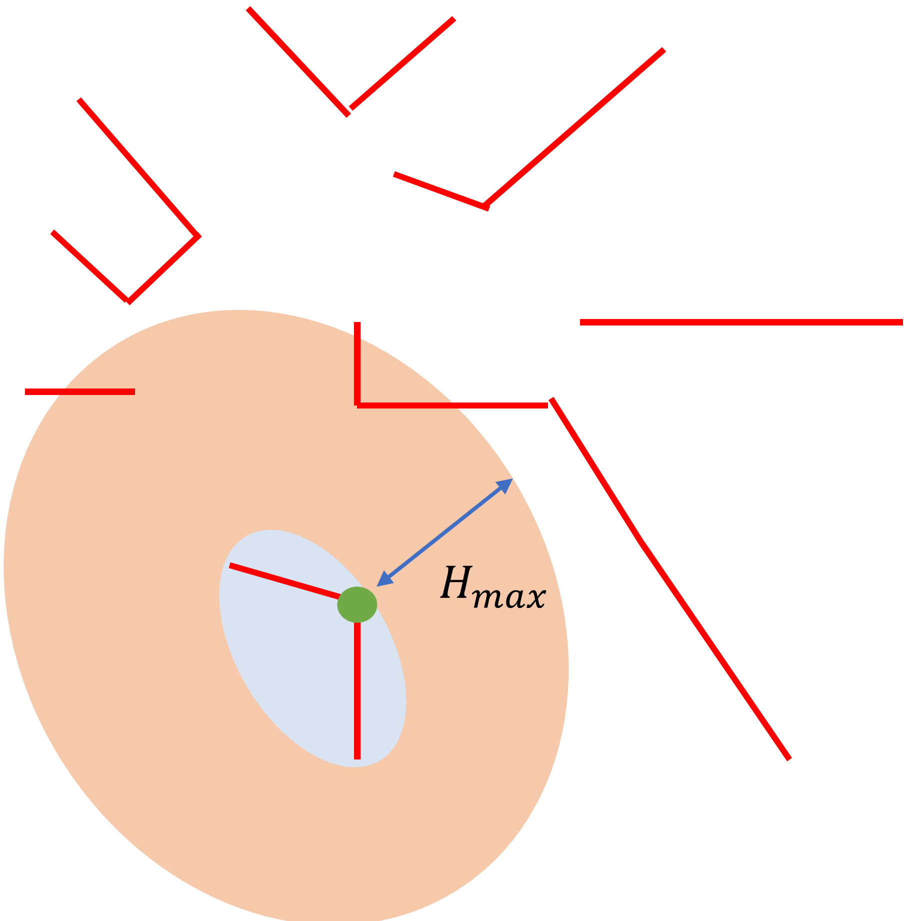
※ The following processes are executed in order from the lower-level networks
※ From now on, the explanation will use a network of hierarchical level 3



Step4
Select the subnetwork and a starting node



Hierarchization Using the Prior Method[7]

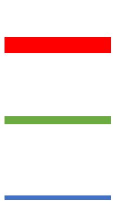


Network G^3 at hierarchical level 3

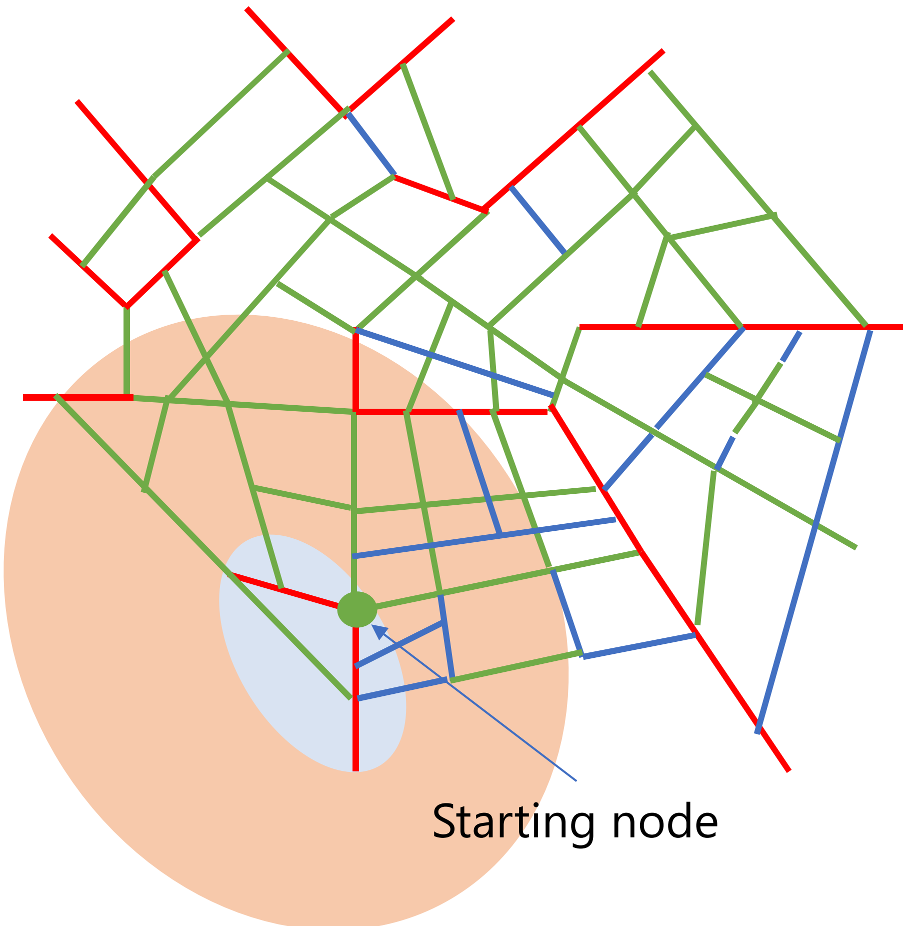
Step5

Set the threshold for how much to connect fragmented subnetworks

- Upper limit on the number of nodes to pass through from the starting node
- For example, we can set H_{max}=10, 20,…,100



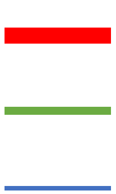
Hierarchization Using the Prior Method[7]

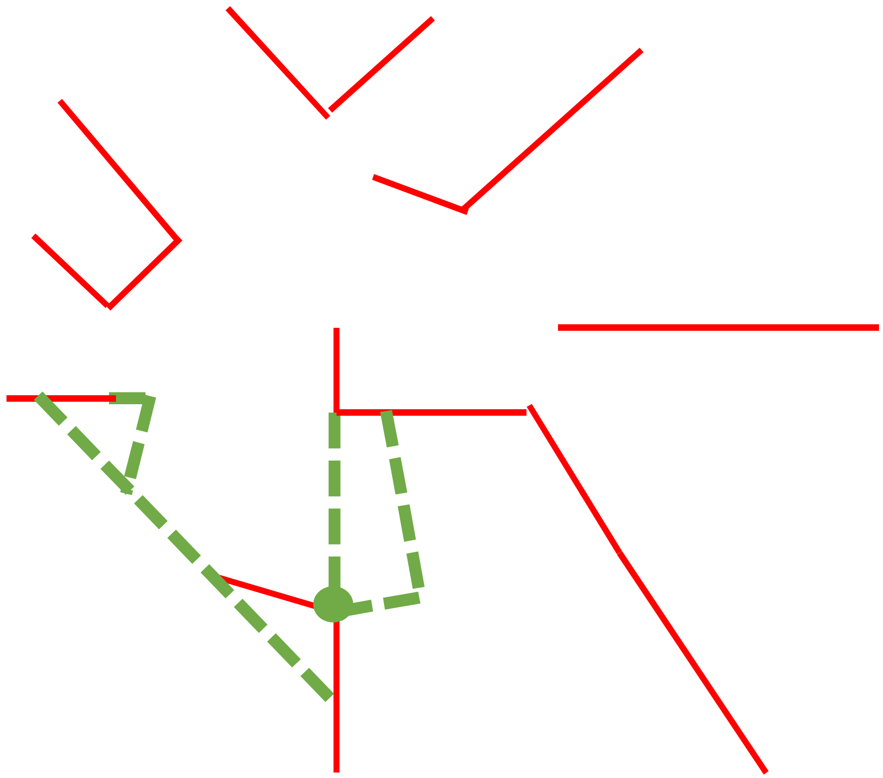


Network G^2 at hierarchical level 2

Step6
Perform route searching from the starting node

- **Search on G^2 from the starting node until reaching H_{max}**
- Save all routes leading to nodes within the different subnetworks from the starting node in G^3
- Add the nodes and links included in the routes





Network G^3 at hierarchical level 3

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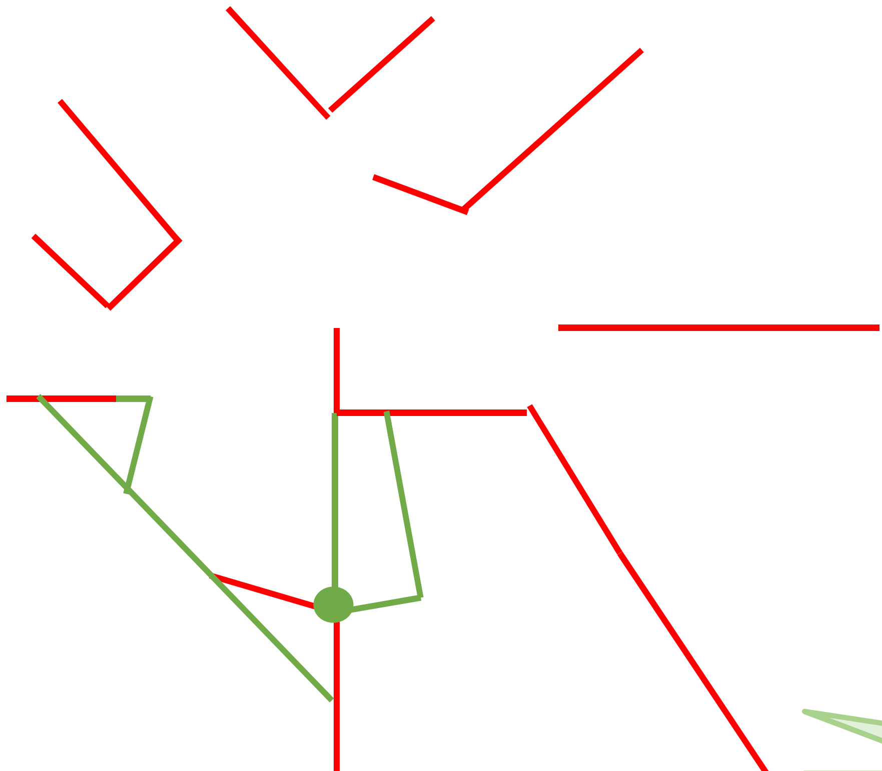

Network G^3 at hierarchical level 3

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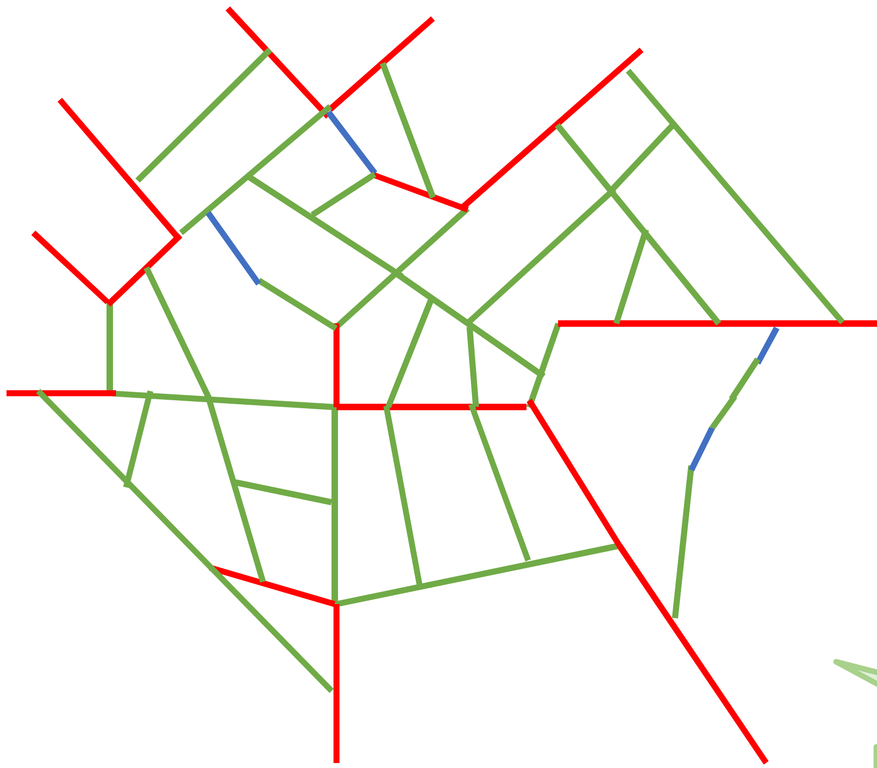
- Save all routes leading to nodes within the different subnetworks from the starting node in G^3
- **Add the nodes and links included in the routes**

Increase in the size of the hierarchical network
→ Increase in the computation time for route searching
Nodes with high importance nodes are not added to the upper-level networks
→ Increase of route costs

Hierarchization Using the Prior Method[7]



Network G^3 at hierarchical level 3

number of lanes≥3

number of lanes =2

number of lanes =1

Step7

Repeat Step 4–6 until disconnections are resolved

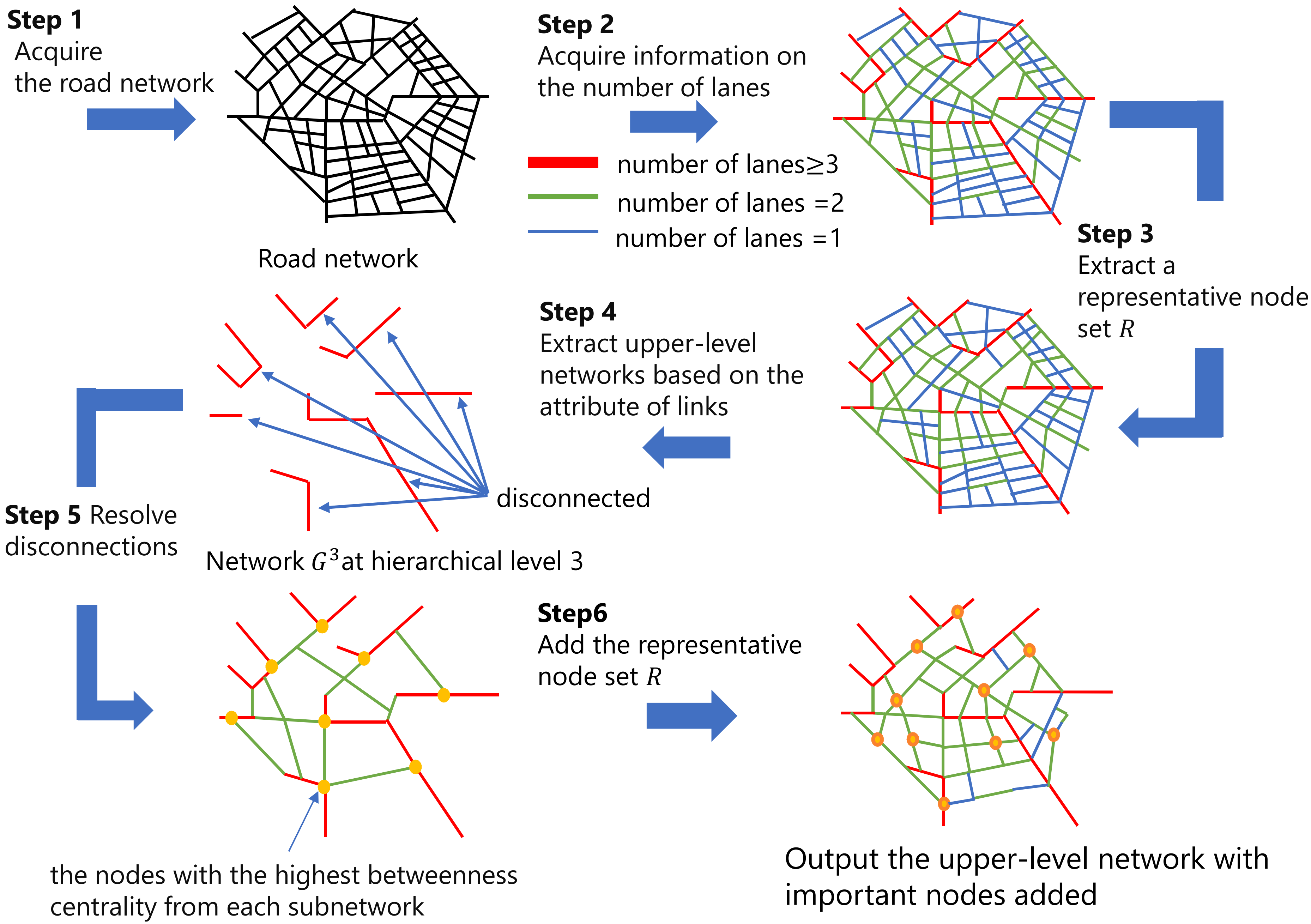
Step4
Select the subnetwork and the starting node

Step5
Set H_{max}

Step6
Perform route searching from the starting node

Output the connected G^n

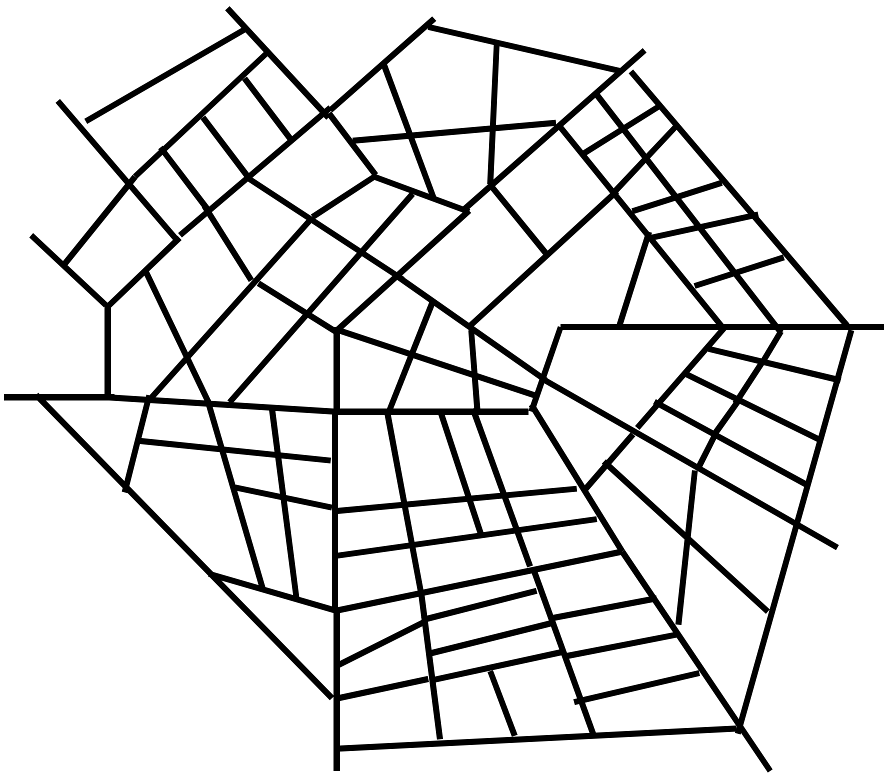
Hierarchization Using the Proposed Method



Hierarchization Using the Proposed Method

same as the prior method

Step1
Acquire the road network

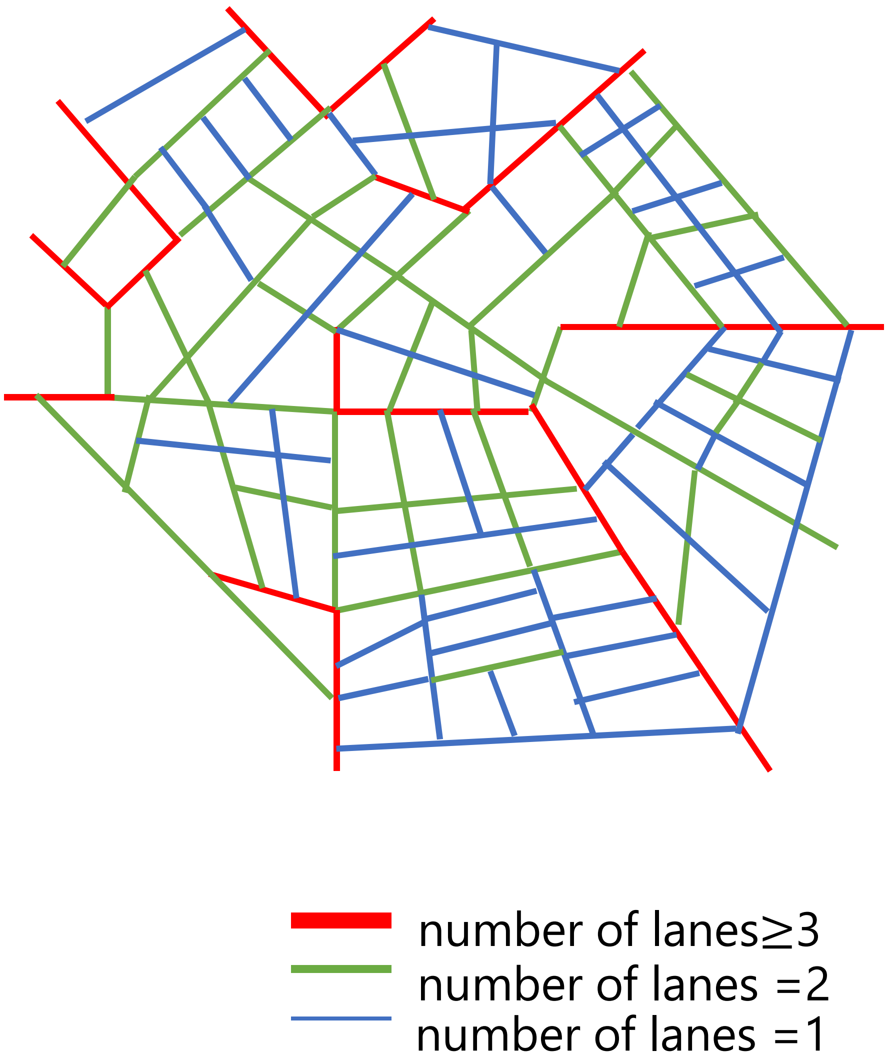


Road network

same as the prior method

Step2

Acquire information on the number of lanes



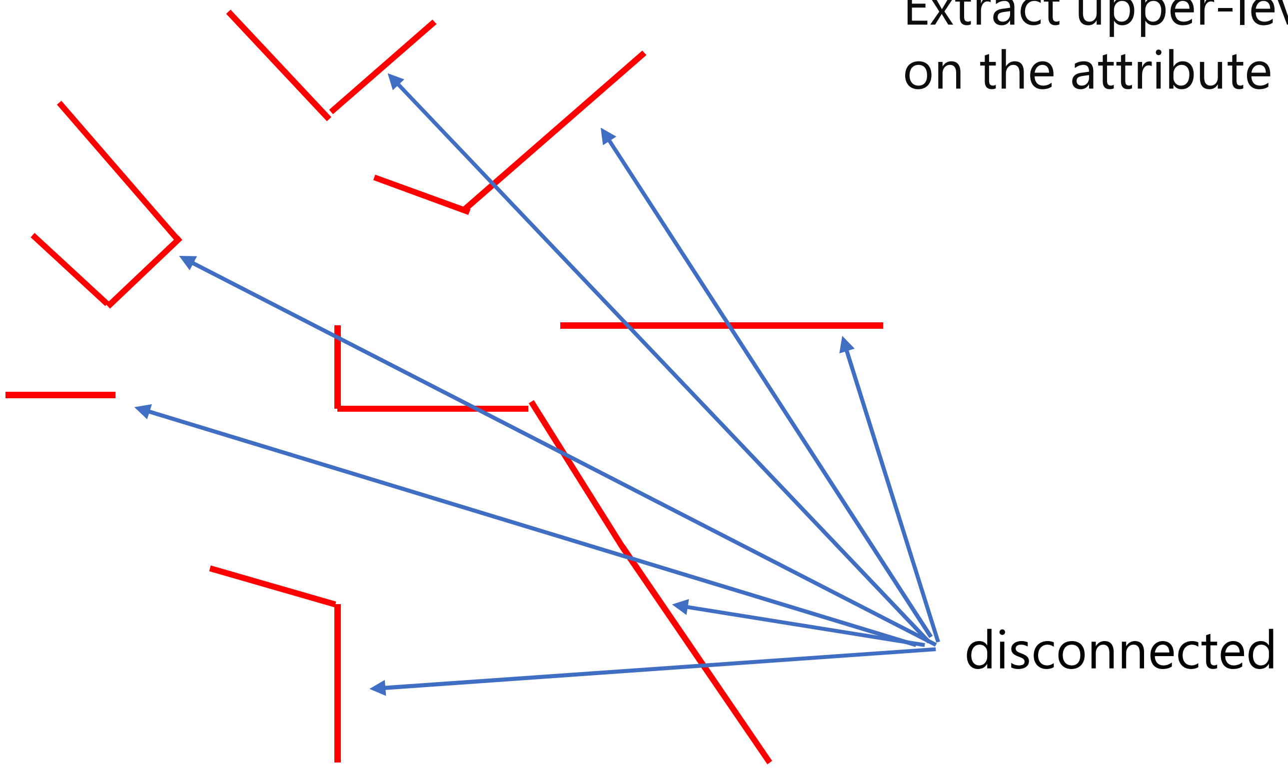
Step3 Extract a representative node set R

- Representative node set R ： A set of nodes with high set betweenness centrality
  - Difficult to precisely compute in large networks
    - Adopt the method of [12]
- **Procedure**
  - Set weights for link costs
  - Acquire route information
    - Randomly extract $M = O\left(\frac{\log V}{\epsilon^2}\right)$ OD pairs from the network
    - compute all minimum-cost routes of the M OD pairs
  - Extract the representative node set R
    - Approximate computation of set betweenness centrality from the obtained routes
    - Approximate compute the betweenness centrality of individual nodes
- Parameters
  - Weights for link costs
    - Affect the minimum cost routes between sampled OD pairs
  - ϵ
    - Control the number of OD pairs used in the approximation
  - K
    - Control the number of elements in the representative node set

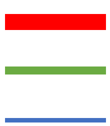
[12] Yoshida, Yuichi: Almost linear-time algorithms for adaptive betweenness centrality using hypergraph sketches, Proceedings of the 20th ACM SIGKDD international conference on Knowledge discovery and data mining. (2014)

same as the prior method

Step4
Extract upper-level networks based on the attribute of links



Network G^3 at hierarchical level 3



Hierarchization Using the Proposed Method

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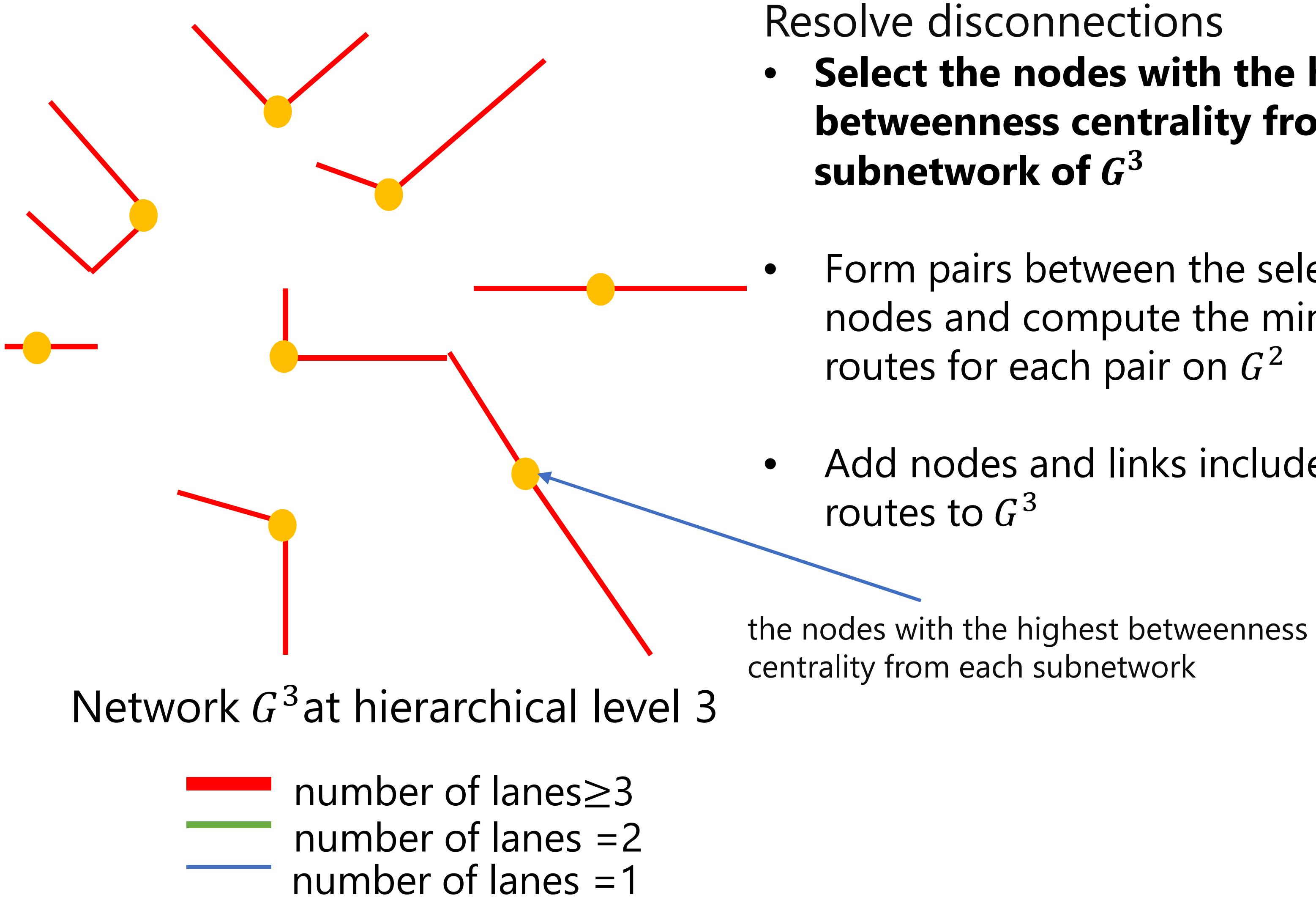


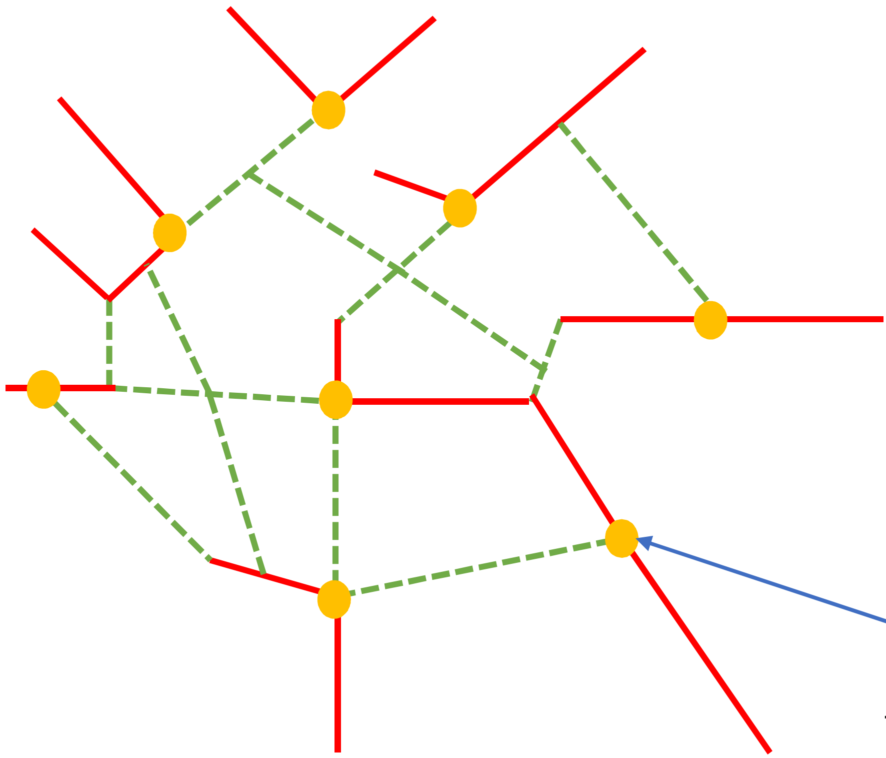
Network G^3 at hierarchical level 3

Step5

Resolve disconnections

- **Select the nodes with the highest betweenness centrality from each subnetwork of G^3**
- Form pairs between the selected nodes and compute the minimum cost routes for each pair on G^2
- Add nodes and links included in the routes to G^3

Hierarchization Using the Proposed Method



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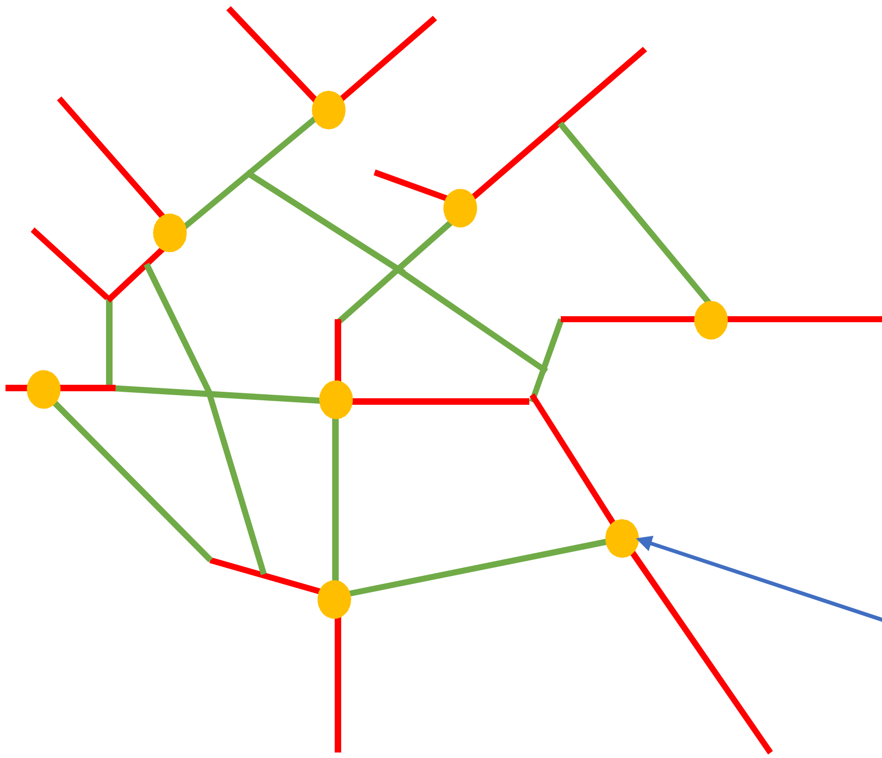
the nodes with the highest betweenness centrality from each subnetwork

Network G^3 at hierarchical level 3

number of lanes≥3
number of lanes =2
number of lanes =1

Hierarchization Using the Proposed Method



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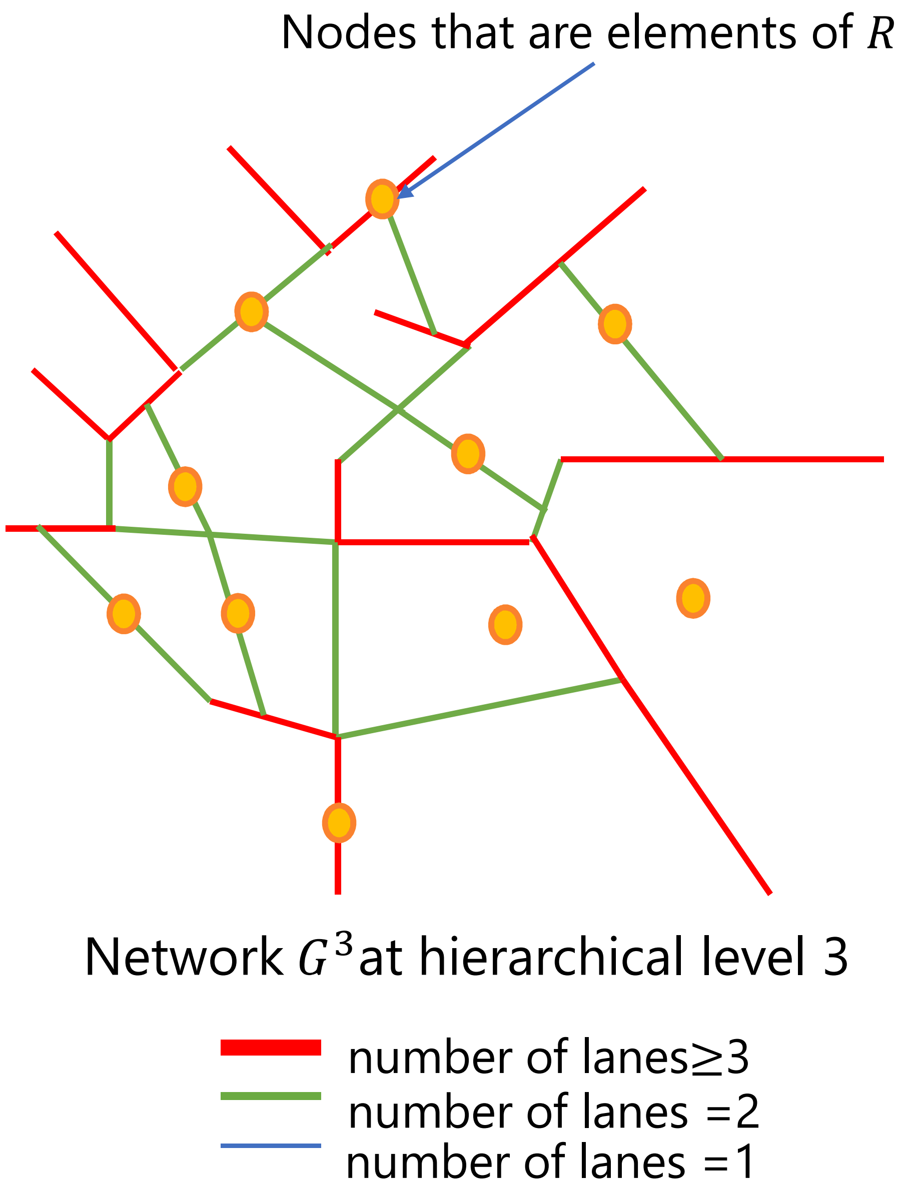
Nodes with the highest betweenness centrality from each subnetwork

Hierarchization Using the Proposed Method

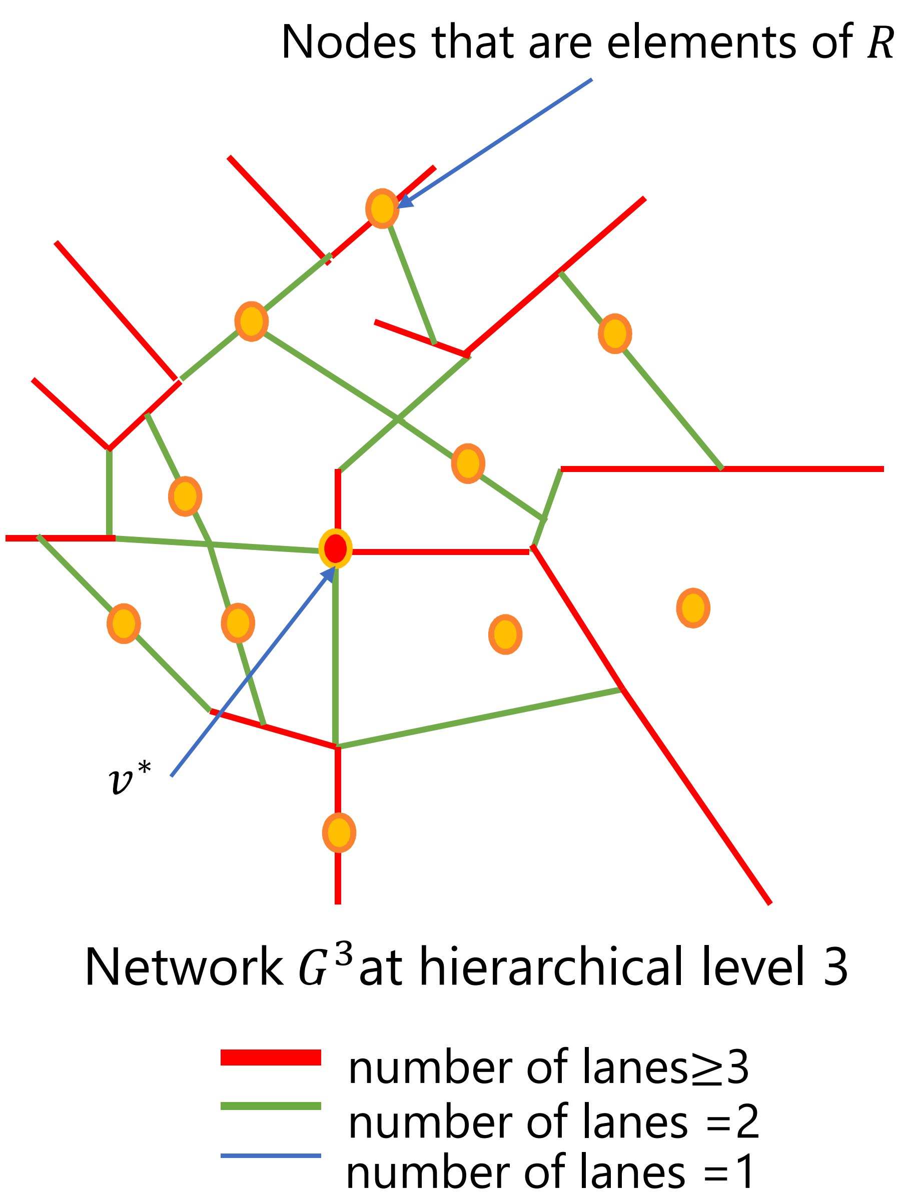


Network G^3 at hierarchical level 3

Step6

Add the representative node set R

- **Add nodes that are elements of R to G^3**
- Extract the node v^* with the highest betweenness centrality on G^3
- For each node in $v \in R \cup \{v^*\}$, form pairs and compute the minimum cost route for each pair on G^2
- Add nodes and links included in the routes to G^3



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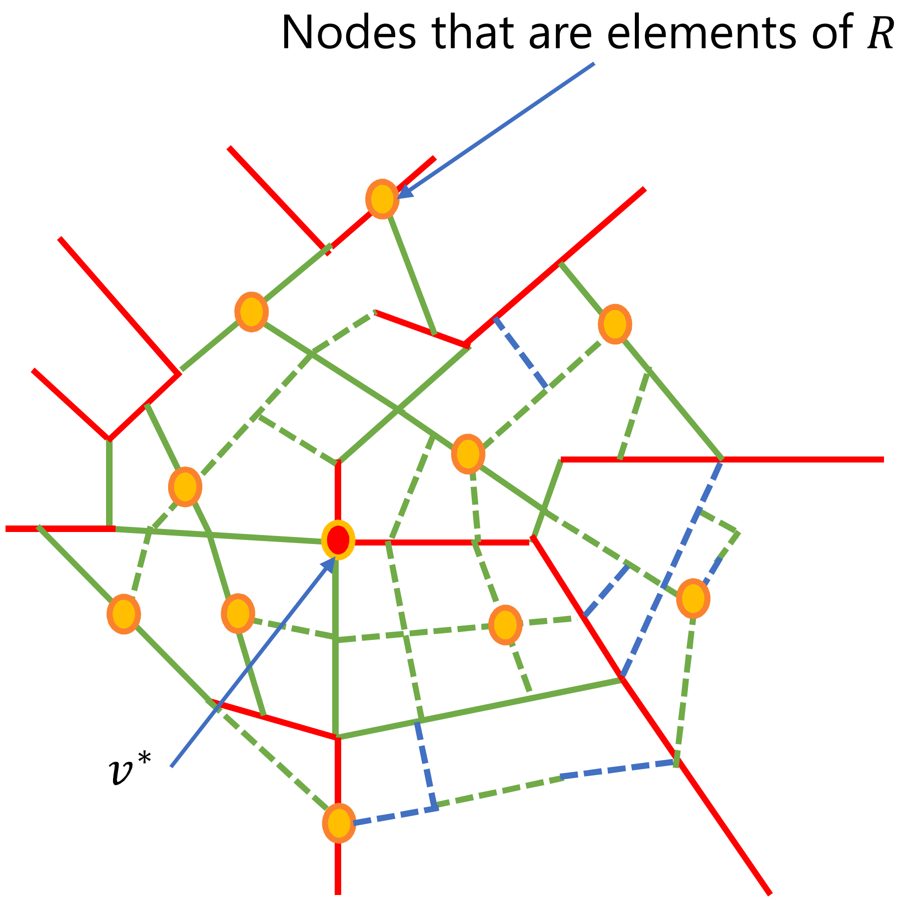
Hierarchization Using the Proposed Method



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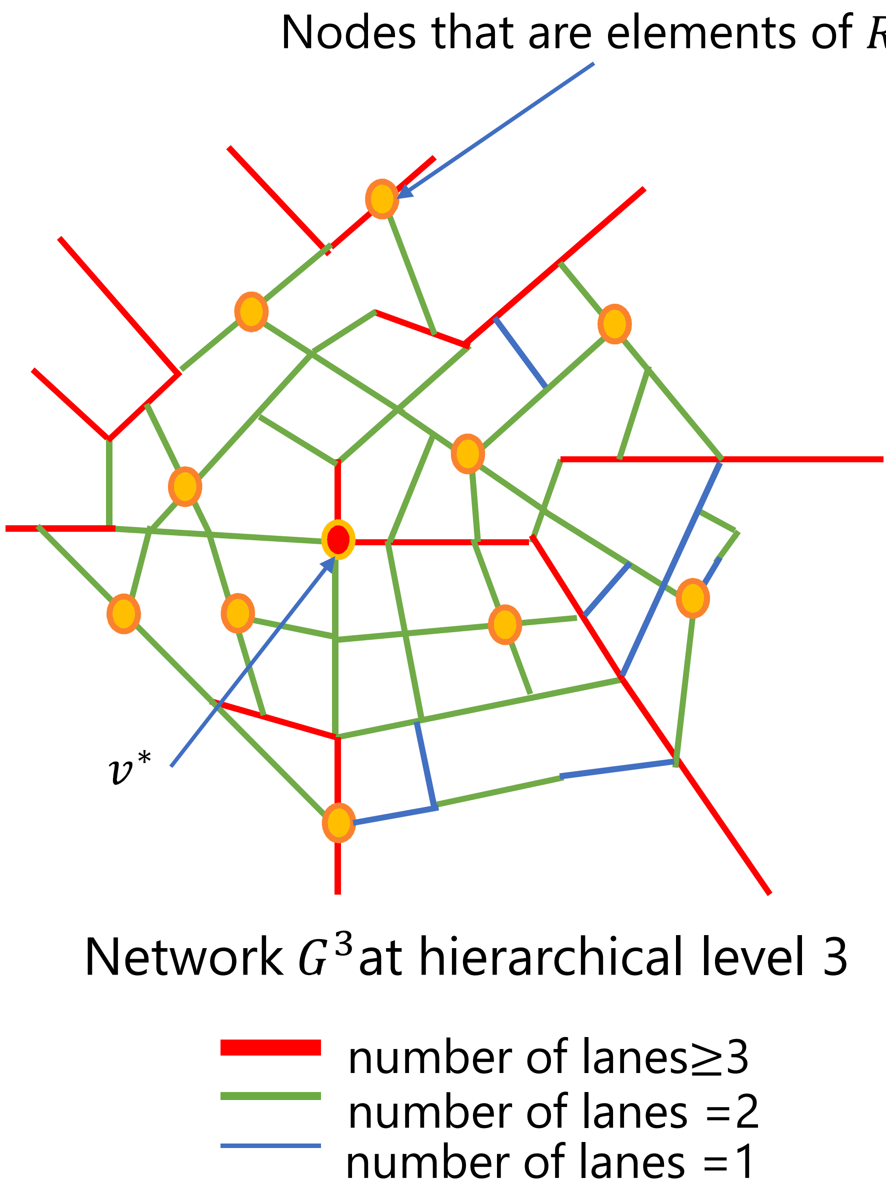

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- **Add nodes and links included in the routes to G^3**

Output the upper-level network with high important nodes added

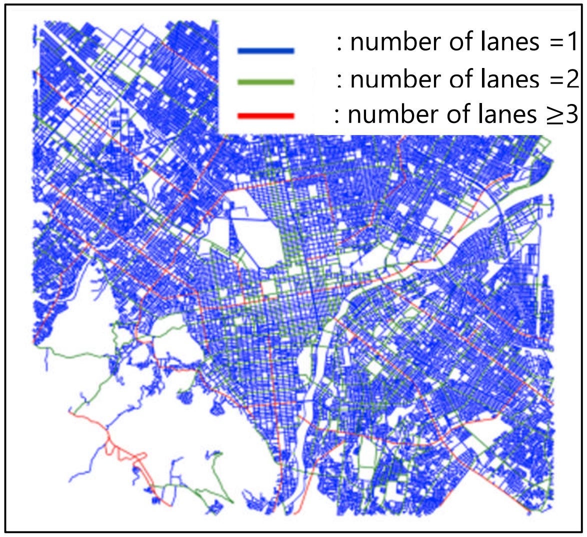
Experiment

- **Experiment Objective**
  - Validation of the proposed method's effectiveness toward:
    - Reducing the total computation time for route search
    - Realizing route search considering driver preferences

- **Experiment**：Route search using a road network
  - Experimental Setup
    - **Validation targets**
      - Without hierarchical networks
      - With hierarchical networks
        - » Prior method (disconnection resolution based on hop count)
        - » Proposed method (disconnection resolution based on betweenness centrality, addition of the representative node set)
  - **Evaluation**
    - Comparison between hierarchization methods
      - Size and construction time of each hierarchical network
    - Comparison with exact solutions (minimum-cost routes)
      - Total computation time and total cost of route search
      - Average route length

Experimental Setup

- Route search algorithm
  - A* algorithm
- Target area
  - A 14 km square area around Sapporo Station
    - Obtain lane information and link lengths with OpenStreetMap[13]



Target network

- Number of OD pairs
  - 5,000 pairs randomly extracted from each of the following ranges
    - Classified based on the Euclidean distance of each OD pair

Table2 Number of OD Pairs by Distance

	Euclidean distance of OD pairs [km]						
	0-2.5	2.5-5.0	5.0-7.5	7.5-10.0	10.0-12.5	12.5-15.0	15.0-17.5
number of OD pairs	5,000	5,000	5,000	5,000	5,000	5,000	5,000

[13] Foundation, O.: OpenStreetMap, OpenStreetMap Foundation (online), available from ⟨https://www.openstreetmap.org⟩ (accessed 2022- 09-07).

Types of Driver Preferences

- Four driver preference types A_1, A_2, A_3, A_4
  - Differing in their degree of avoidance to narrow roads

- The passage cost $\tilde{c}_{e,i}$ of link e for each driver's preference type A_i is set using the true cost c_e of e

$$\tilde{c}_{e,i} = w_{e,i} c_e \quad (1)$$

  - c_e is the Euclidean distance between link endpoints
  - The weight $w_{e,i}$ for the link based on road's lane count l_e
    - Values used for A_1, A_2, A_3 are from the prior method[14],[15]

Table3 Weights $w\_(e,n)$ for Link Cost by Type of Driver Preference

Type of Driver Preference	weight	number of Lanes		
		$l_e = 1$	$l_e = 2$	$l_e = 3$
A_1	$w_{e,1}$	10	5	1
A_2	$w_{e,2}$	4	2.5	1
A_3	$w_{e,3}$	2.768	1.607	1
A_4	$w_{e,4}$	1	1	1

Degree of avoidance to narrow roads: high (A_1) → low (A_4)

[14] Toshiyuki Nakamura, Toshio Yoshii, Ryuichi Kitamura：Development of a simplified network which represents all roadway links, Infrastructure planning review, Vol. 23, pp. 441–446 (2006).
[15] Toshiyuki Nakamura, Toshio Yoshii, Ryuichi Kitamura： Traffic Simulation Model with Simplified Network for Large-scale Networks, Japan Society of Civil Engineers, Vol. 60, pp. 71–72 (2005).

Selection of Parameters

- Max route computation time for the next delivery plan: **10 hours**
- Choose parameters that minimize total route cost within the limit time

Table 4 Parameter Settings for Each Road Network Hierarchization Method

Road network hierarchization method	Parameters			
	Weight for link cost	ϵ	H_{max}	K
Prior method	-	-	100	-
Proposed method	$w_{e,2}$	0.02	-	100

H_{max} : The threshold for how much to connect fragmented subnetworks, the search range from the starting node
ϵ : Error parameter
K : The number of elements in the representative node set

- Computing environment
  - AMD EPYC 7402 24-Core Processor, 24 cores 48 threads

Size and Construction Time of Hierarchical Network

Table 5 Size and Construction Time of Hierarchical Networks by Each Hierarchization Method

Road network hierarchization method	n	number of nodes	number of nodes	Construction Time
Original network	1	31,139	49,967	-
Prior method	2	12,774	15,798	0h01m44s
	3	4,765	5,155	
Proposed method	2	7,527	7,975	2h03m29s
	3	4,372	4,523	

Comparison with the prior method

1. Construction Time
   - Increased from 1 minute to 2 hours with the proposed method
     - **Acceptable** for scenarios in situations with the following characteristics:
       - Necessary for hundreds of thousands to millions of route searches
       - Reusable unless road network information changes

2. Number of Nodes and Links at Each Level Network
   - **Reduced by about 40%** at level 2

Result of Route Search for Entire Section

Table 6 Results of route search by type of driver preference for each method

Road network hierarchization method	A_1		A_2		A_3		A_4	
	T_{total} [s]	C_{total} $[10^3\mathrm{km}]$	T_{total} [s]	C_{total} $[10^3\mathrm{km}]$	T_{total} [s]	C_{total} $[10^3\mathrm{km}]$	T_{total} [s]	C_{total} $[10^3\mathrm{km}]$
Exact solution	145,665	936.62	107,100	609.67	95,096	507.15	48,987	357.59
Prior method	7,276	1,005.16	6,475	638.95	5,929	528.47	3,818	**383.86**
Proposed method	**5,791**	**982.98**	**5,175**	**632.41**	**4,953**	**521.51**	**3,641**	394.41

T_{total} : Total computation time for route search
C_{total} : Total cost of the route

- **Total computation time for route search**
  - Comparison with the exact solution
    - **Reduced to 4–7%**
  - Comparison with the prior method
    - **Reduced by about 20%**

- **Total cost of the routes**
  - Comparison with the exact solution
    - Increased by about 5–10%
  - Comparison with the prior method
    - **Reduced by about 2–3%**(increase about 3% for A_4)

Average Route Length for Each Section

※ The result for driver preference type A_1 is excerpted
(The same trends are observed for other types of driver preferences)
※ The sections are partial excerpts

Table 7 Average Route Length per Section for Type A_1 Driver Preference

Road network hierarchization method	Average Route Length [km]		
	0-2.5	7.5-10.0	15.0-17.5
Exact solution	2.87	13.33	21.95
Euclidean distance	1.56(-45%)	8.71(-35%)	15.87(-28%)
Prior method	3.09(+7%)	13.33(0%)	21.80(-1%)
Proposed method	3.06(+7%)	13.23(-0.7%)	21.68(-1%)

- **Error in average route length compared to the exact solution**
  - Euclidean distance
    - **-45 to -30%**
  - Prior method
    - **-1 to 7%**
  - Proposed method
    - **-1 to 7%**

Summary of Experiment

- **computation time**
  - Comparison with the prior method
    - Time to construct hierarchical network **increased from 1 minute to 2 hours**
    - Total computation time for route search **reduced by about 20%**
  - Comparison with the exact solution
    - Total computation time for route search **reduced to 4–7%**
- **Total cost of the routes**
  - Comparison with the prior method
    - **Reduced by about 2–3%**
  - Comparison with the exact solution
    - **Increased by about 5–10%**
- **Error in average route length compared to the exact solution**
  - Euclidean distance is -45 to -30%
  - Prior method is -1 to 7%
  - Proposed method is -1 to 7%

The proposed method builds a hierarchical network improving total route cost within computation time limits, outperforming the prior method

Discussion

- The proposed method reduces the size of the hierarchical network while improving total route cost compared to the prior method
  - Transition between hierarchies upon reaching high importance nodes
    - Keeping lower cost routes as candidates
    - Reducing the search area

- The proposed method computes necessary routes within time constraints for diverse driver preferences, improving average route length compared to Euclidean distance
  - Demonstrate effectiveness for kerosene delivery planning

Conclusion

- We propose a road network hierarchization method to decrease total route search time and consider diverse driver preferences
  - using betweenness centrality for network constructing

- A computational experiment was conducted targeting Sapporo City
  - Construction time increased to about 2 hours compared to the prior method
  - Possible to build a hierarchical network that reduces total route cost and computation time

- The applicability to real-world vehicle routing problems was demonstrated