Final Event

Sustainable mobility on existing infrastructure
Is that possible?

Vienna, 24. June 2026

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A Seamless Communications Architecture

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Needs for the Pod-System

Challenges

- Enabling coordinated and flexible mobility services across the heterogeneous Pods4Rail infrastructure such as rail, road, and cableway networks.

Wireless communication problems:

- Existence of white zones in some areas of Pods4Rail architecture (e.g., rural areas)
- Radio coverage problem due to urban infrastructures, hills, mountains, etc.

Proposed solutions:

- Embed multi-technology connectivity for Pod elements (TU, CU, Pod).
- Integrate higher layer technologies (Software Defined Networking (SDN), Network Function Virtualization (NFV), Edge computing, etc.) for flexible network management.

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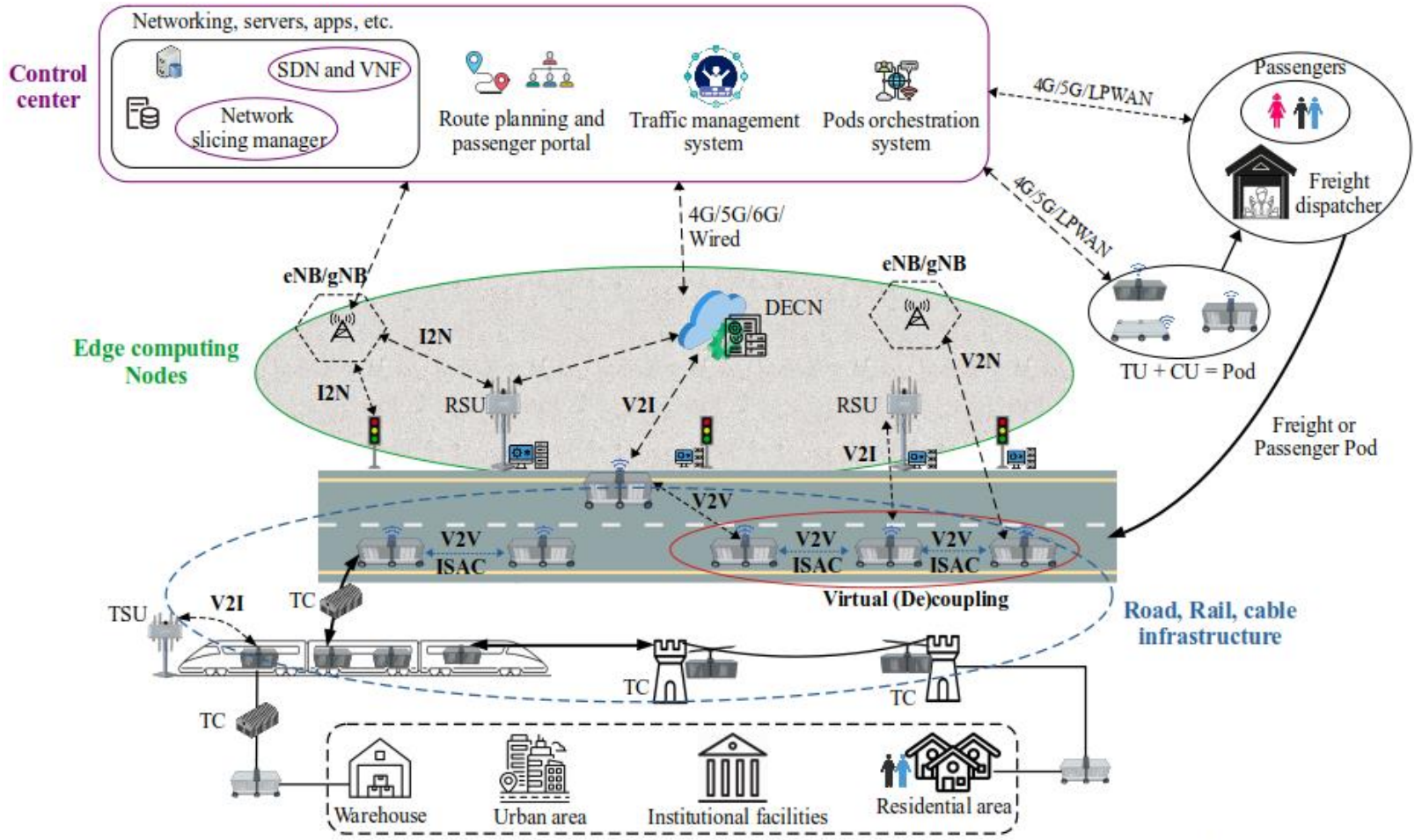
A Seamless Communications Architecture



Pod elements (units)	Infrastructure	Communication mode	Connectivity technology
Transport Unit (TU) Carrier Unit (CU) Pod (PodCar)	Transfer center (TC): transfer & dock TU to new CU RSU: Road Side Unit TSU: Track Side Unit eNB/gNB: 4G/5G Base station DECN: Dedicated Edge Computing Node	V2V: Vehicle (Pod) to Vehicle (Pod) V2I: Vehicle to Infrastructure V2N: Vehicle to Network I2N: Infrastructure to Network	ITS-G5 C-V2X; 5G NR V2X ISAC: Integrated Sensing and Comm. 4G/5G/6G LPWAN

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Requirements for the Communication System

Requirements will vary depending on

- the applications foreseen → safety or non-safety related
- the type of link → Intra Pod, Pod to Pod, or Pod to Infrastructure
- type of scenario → road, rail, cable-based systems, etc.

- Availability - continuity of service evaluated regarding a given level of received power for a given percentage of time and distance in different environments)
- Reliability - maximal admissible Packet error rate and the time to come back to nominal situation after a failure. It includes also the resistance to volunteer and non-volunteer interferences
- Throughput and bandwidth - ability to support required data volumes
- End-to-end delay and latency - particularly for mission critical applications (voice or video)

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Communication Requirements for Automotive

Service (example)	Latency	Data Rate	Reliability	Type of communications	Type of message
Autonomous Navigation (HD Map Local Acquisition)	30 ms	1 Mbps (UL)/ 2.88 Mbps (DL)	0.99	V2V, V2I	CAM, DENM, CPM
Remote Driving (Automated parking)	50 ms	14 Mbps (UL)/ 6 Mbps (DL)	0.99999	V2I	-
Cooperative Manoeuvre (Lane merge)	60 ms	128 kbps	0.99	V2V	MCM, PCM
Cooperative Perception (See Through)	50 ms	14 Mbps (UL)/ 14 Mbps (DL)	0.99	V2V	CAM, DENM, CPM
Cooperative Safety (Vulnerable Pedestrian Protection)	30 ms	128 kbps	0.9999	V2V, V2I, V2P	VAM, CPM
Infotainment (UDH Video)	500 ms	15 Mbps	-	V2V, V2I	-
Remote diagnostics	-	-	-	V2I	-

[Campolo et al., 2017], [Mei et al., 2019], [5GCAR Consortium, 2019]

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Possible Communication Standards

	TU - CU, Running	TU - CU, Docking	Pod - Pod Road	Pod - Pod Rail	MEC/Infra-structure - TU/CU/Pod	User - Dispatch Center
5G NR, FR1						
6G, FR1						
6G, FR3						
Wi-Fi 7/8						
LEO Satellite Comm.						
5G NR V2X, 5.9 GHz						
5G NR V2X, FR2						
6G V2X, 5.9 GHz						
6G V2X, FR2						
ITS-G5 rel 2, 5.9 GHz						
ITS-G5 rel 2, 65 GHz						
IEEE.15.4 UWB						

not applicable	
average applicable	
good applicable	

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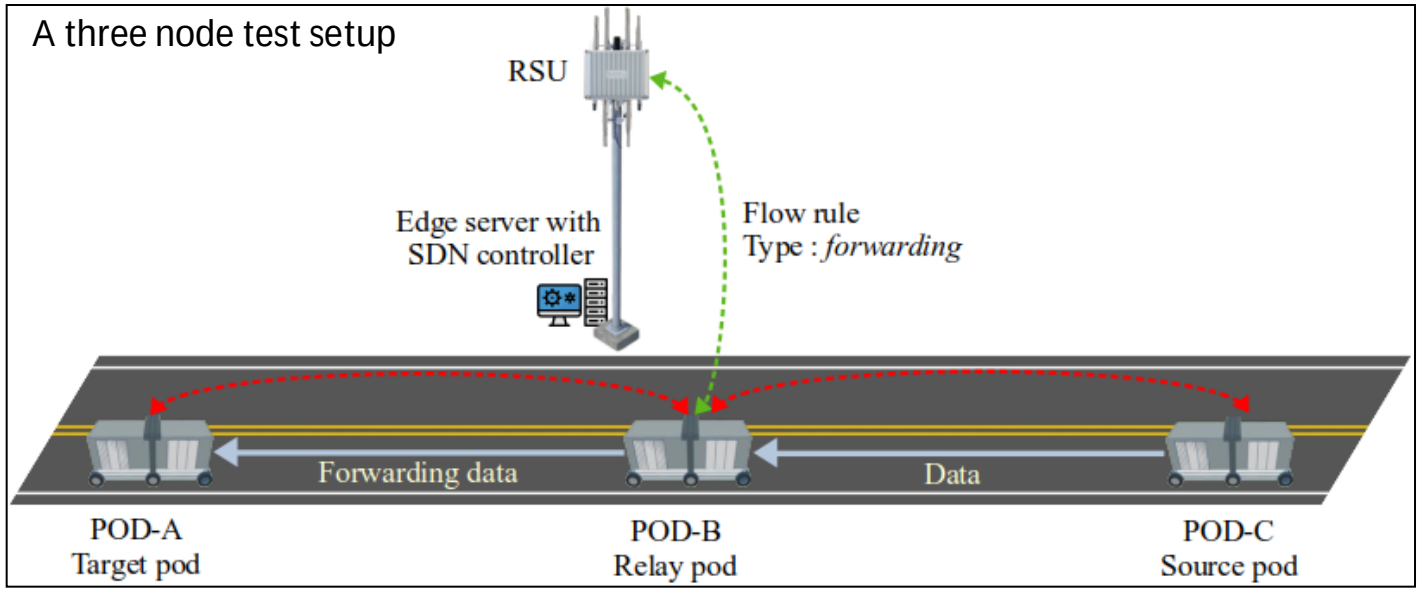
Testbed Setup and Performance Evaluation

A three node test setup



System configuration for performance evaluation.

Parameter	Value
Frequency	5.92 GHz
Bandwidth	10 MHz
Transmit Power	23 dBm
MCS	MCS0 (BPSK 1/2) and MCS2 (QPSK 1/2)
Vehicle Speed	70 km/h
Channel Condition	EVA model (EVA328 → 5900 MHz)
SDN Link	srsRAN (LTE mode), 1800 MHz, 5 MHz band-width
Transmission Interval	10 ms (100 Hz)
Packet Size	140 bytes (Standard CAM size)
Number of Packets	100,000
Evaluation Metrics	Latency, Packet Delivery Ratio (PDR)

The experiments were conducted using

- Cohda Wireless MK6 devices: MK6 OBU for the Pods and MK6 RSU for the RSU
- Edge server : Dell Workstation
- V2X technology : ITS-G5
- Link between RSU server and Pods : 4G based on srsRAN_4G and USRP B210
- Communication protocol : MQTT protocol

Laboratory Testbed

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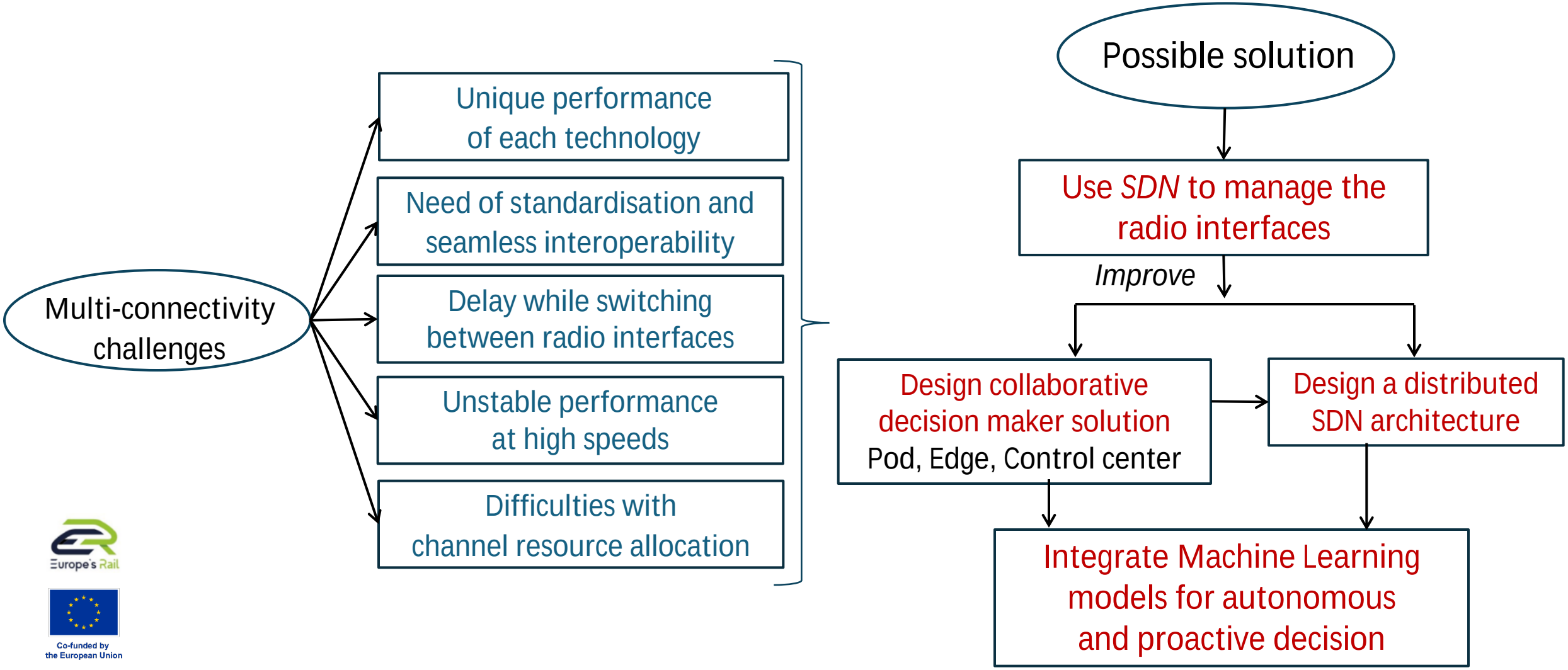
Multi-connectivity challenges and proposed solutions



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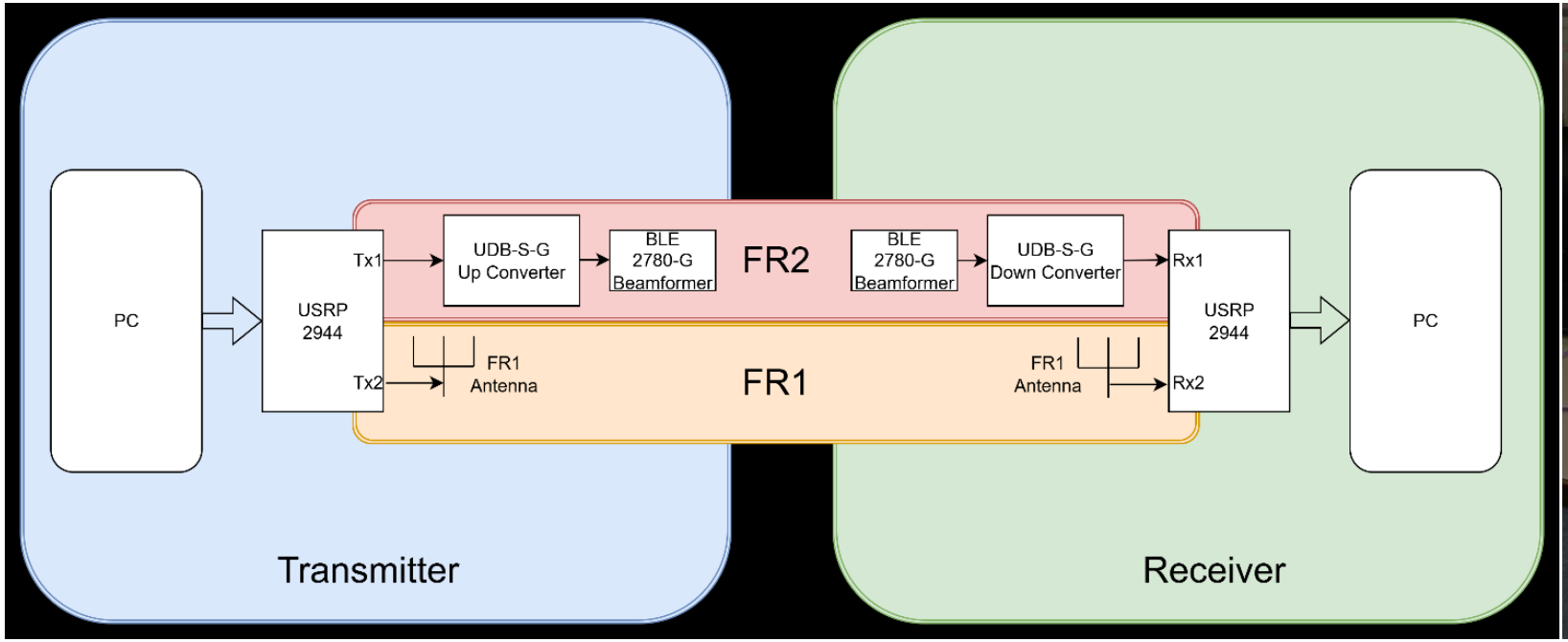
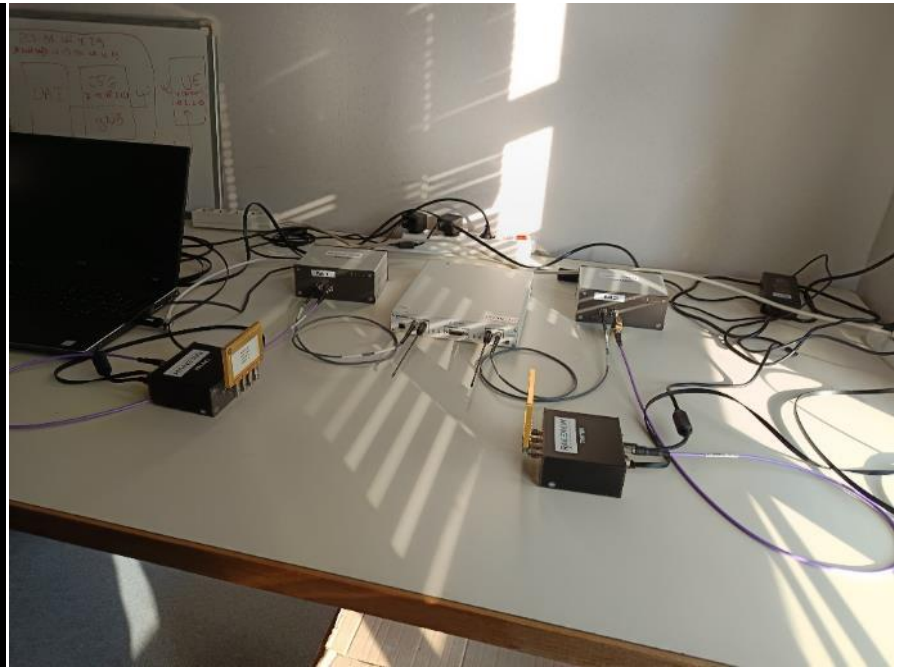
Example of mmW Bench Tests





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Conclusions

- To achieve seamless connectivity in Pods4Rail system, a highly dynamic and variable environment, a multi Radio Access Technologies solution is suggested
- The merits and de-merits of various RAT switching mechanisms across on-board, edge and control center layers, were discussed
- The experimental results demonstrate that link recovery can be performed collaboratively by the edge and on-board layers to preserve service continuity under dynamic mobility conditions
- It’s observed that the overall latency, including link recovery time and message forwarding, is within the required threshold for V2X safety messages

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Future Perspectives

- Design a distributed SDN architecture essential for Pods4Rail system
- Integrate machine learning models for autonomous and proactive decision
- Design an adaptive service orchestration strategies for urban rail pod systems to dynamically manage services under varying network and mobility conditions
- Take into account wireless communications evolutions with 3GPP 6G that will introduce mmW communications (very high data rate and ultra low latency), ISAC communications (this can help localization and surveillance) and RIS (Reflective Intelligent Surfaces)

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Localisation Aspects

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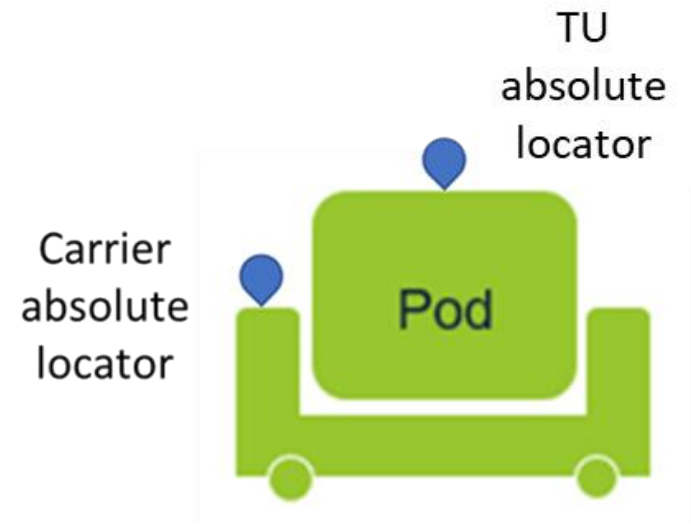
Localization

- Localization of the carriers and TUs important for
  - Traffic coordination
  - Passenger information



- Multimodal availability required for the Pods concept
- Two localization methods were considered in detail:
  adaptive GNSS-based localization (antenna on the top)
  Magnetic field-based localization (sensor anywhere on carrier / TU)

Communication links used to exchange localization information between different carriers and/or TUs

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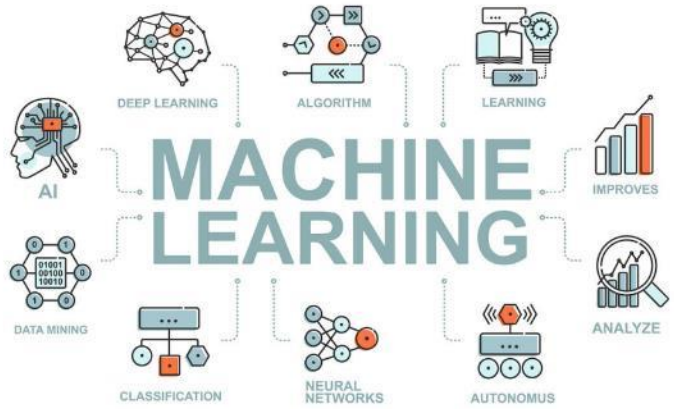
To answer all Pods requirements and offer optimal performances in every condition, the capacity of the system to adapt to the conditions is of main interest.

Context-aware localization has emerged as a promising solution for adjusting positioning systems to dynamic environmental conditions.

Machine learning (ML) has proven to be a powerful tool, providing accurate classification and real-time adaptability to improve context detection and the dynamic adjustment of positioning systems.



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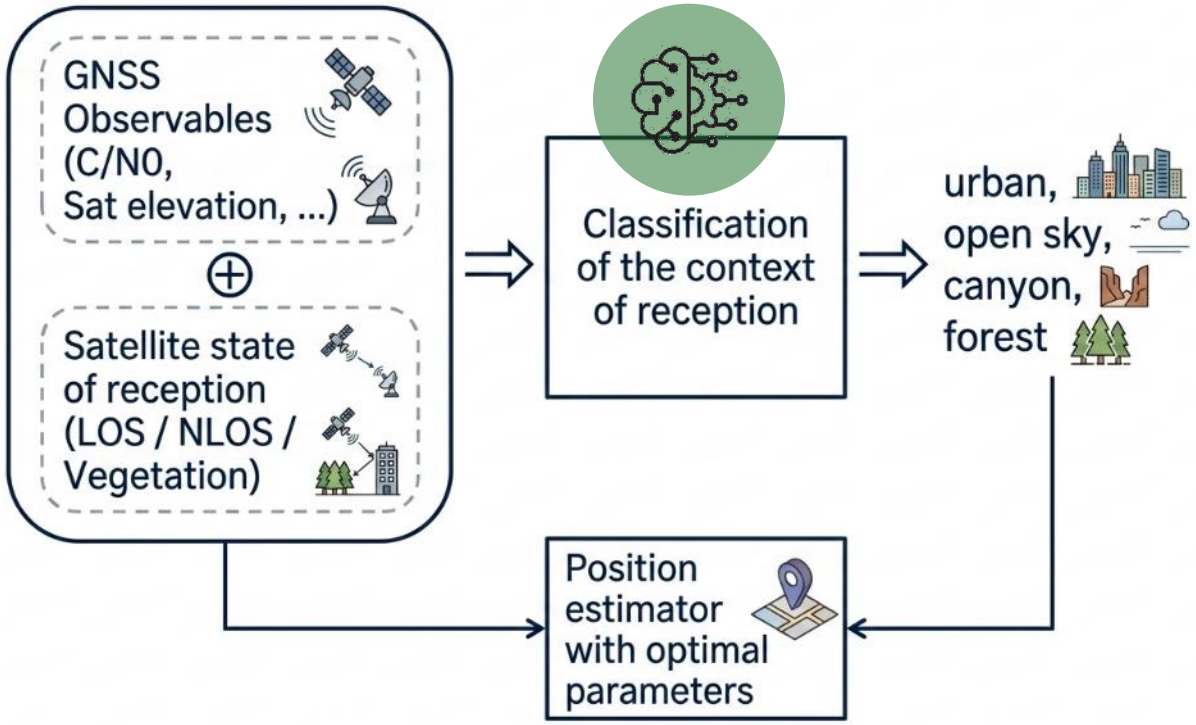

The MLP, KNN and RF models achieved high accuracy in distinguishing between the categories of open sky, urban area, canyon and trees.

Best Model : Random Forest (RF)

- Highest accuracy: 99.95%
- Confusion rate ~ 0
- Complete and robust identification of environments

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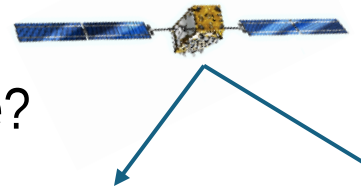
Yasmine Chaiben, Sébastien Ambellouis, Juliette Marais, Adaptive Pods positioning solution based on reception context and vehicle movement, ENC 2025, Mai, Wroclaw

Juliette Marais, Yasmine Chaiben, Syed Ali Kazim, Timothée Guillemaille, Adaptive robust navigation for safety-critical railway applications. EUSIPCO 2025, Palerme.

Magnetic localization

What if GNSS is unavailable?



blocked/jammed/spoofed

- Exploiting local features of the earth magnetic field
- Ferromagnetic material causes position-dependent variations
- Principle has been shown to apply for indoor and rail

- No data available to validate the principle for ropeways before the project

→ magnetic field measurements on ropeway in Cologne

Europe's Rail
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Measurement Campaign

- Measurements on different cabins
- Referenz Position: GNSS

- Sensors mounted on floor and wall

Europe's Rail

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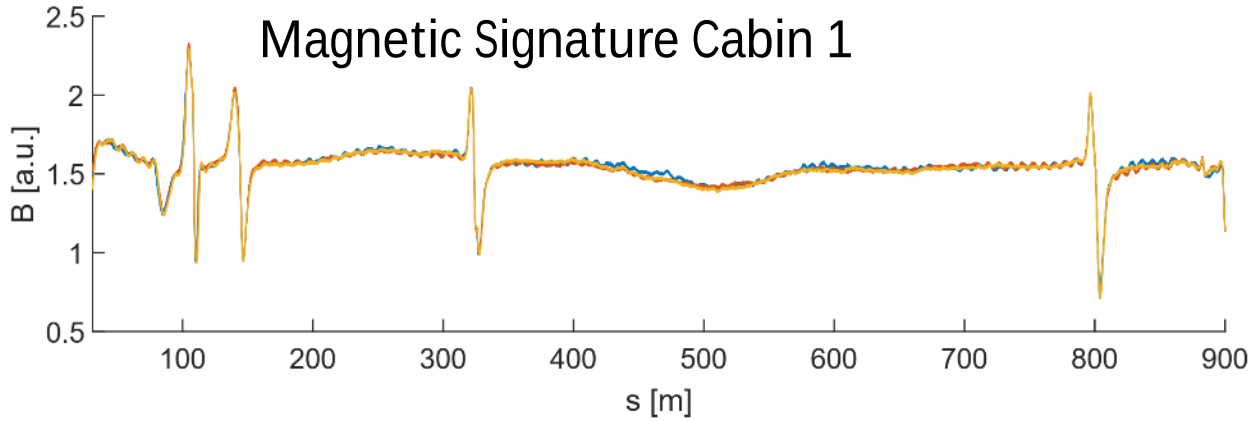
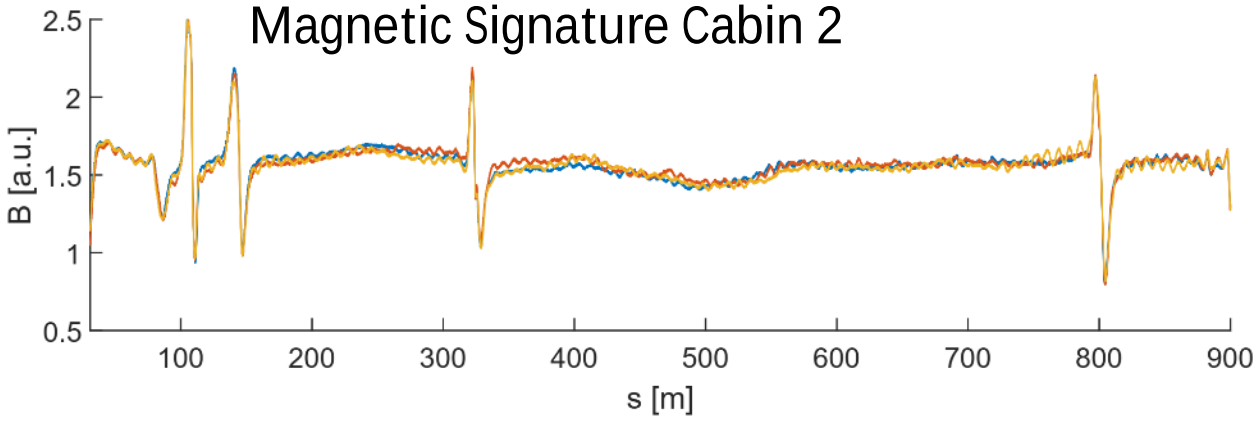
Results





- Magnetic field is position dependent and persistent over time
- Different cabins: linear transformation

→ similar to railcar

- Strong signature from masts
- Slight swaying of the cabin

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Conclusion and Outlook

- Concepts for context-aware GNSS localisation and multimodal magnetic field-based localisation have been formulated and the underlying principles have been validated
- Further research required for magnetic localisation on roads and ropeways

- Phase 2 (planned): lab-test evaluation of multimodal magnetic field-based localisation with measurement data (TRL 3/4) planned (in particular for road and ropeway)
  - Implementation with integration of additional sensors (e. g. odometers, IMUs)
  - Key performance indicators on reliability and accuracy

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How could operations be organised?

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1. Algorithms for operations (1/2)

KTH

- Multimodal operations
  - With integration of:
    - Demand to TU assignment
    - TU to CU assignment
- Local scope
  - Door-to-door

TU Delft

- Rail-based operations
  - 2 separate components:
    - TU to CU assignment
    - CU control
- Regional scope
  - Station-to-station

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1. Algorithms for operations (2/2)

KTH

- Multimodal operations
  - With integration of:
    - Demand to TU assignment
    - TU to CU assignment
- Local scope
  - Door-to-door

Key components

- Routing of:
  - TUs
  - CUs
- Can consider:
  - New demand along the way
  - Time windows
- Expandable with:
  - Repositioning of empty TUs/CUs
  - Analysing detours to pick-up/ drop-off demand

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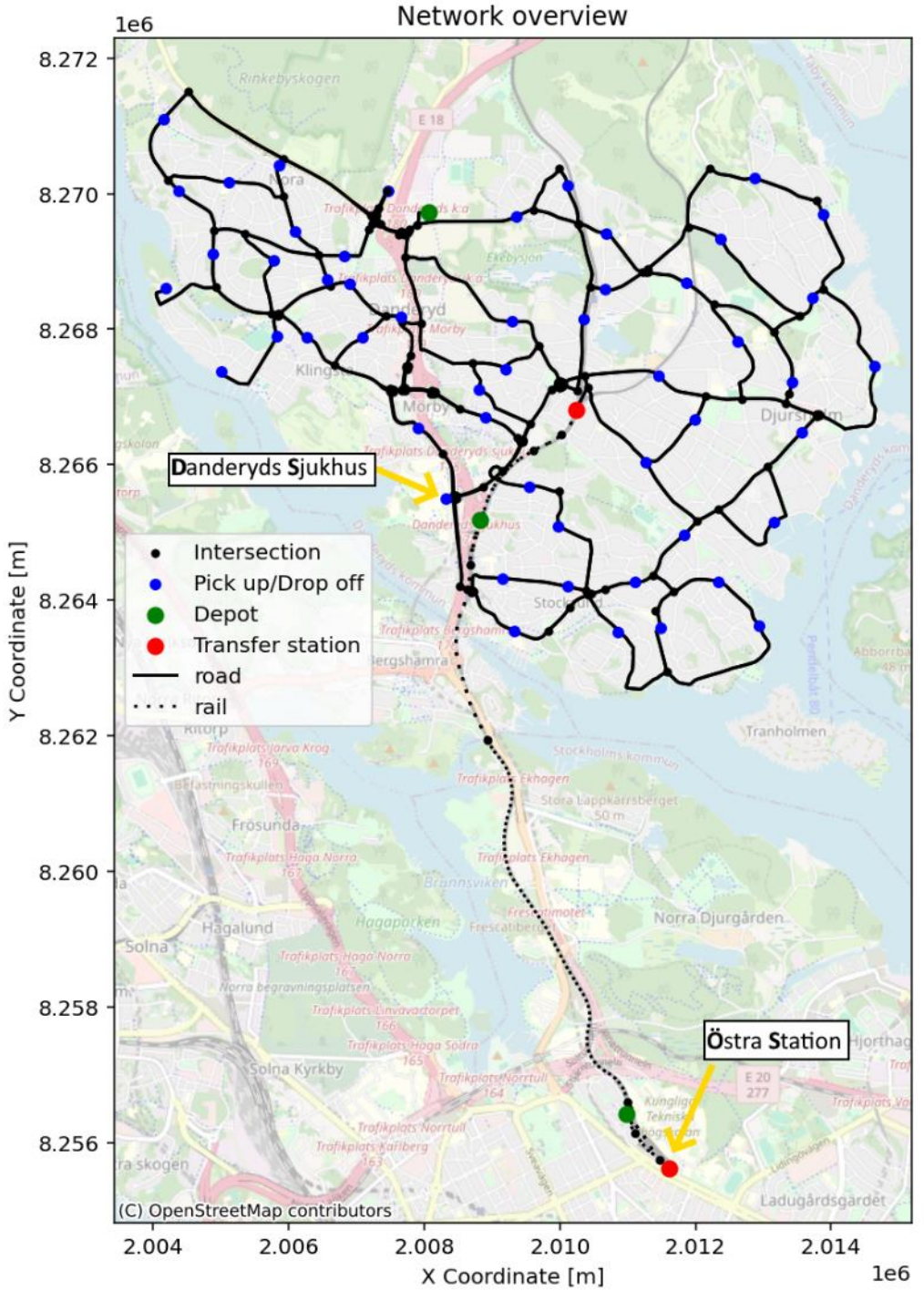
2. Animation of operations



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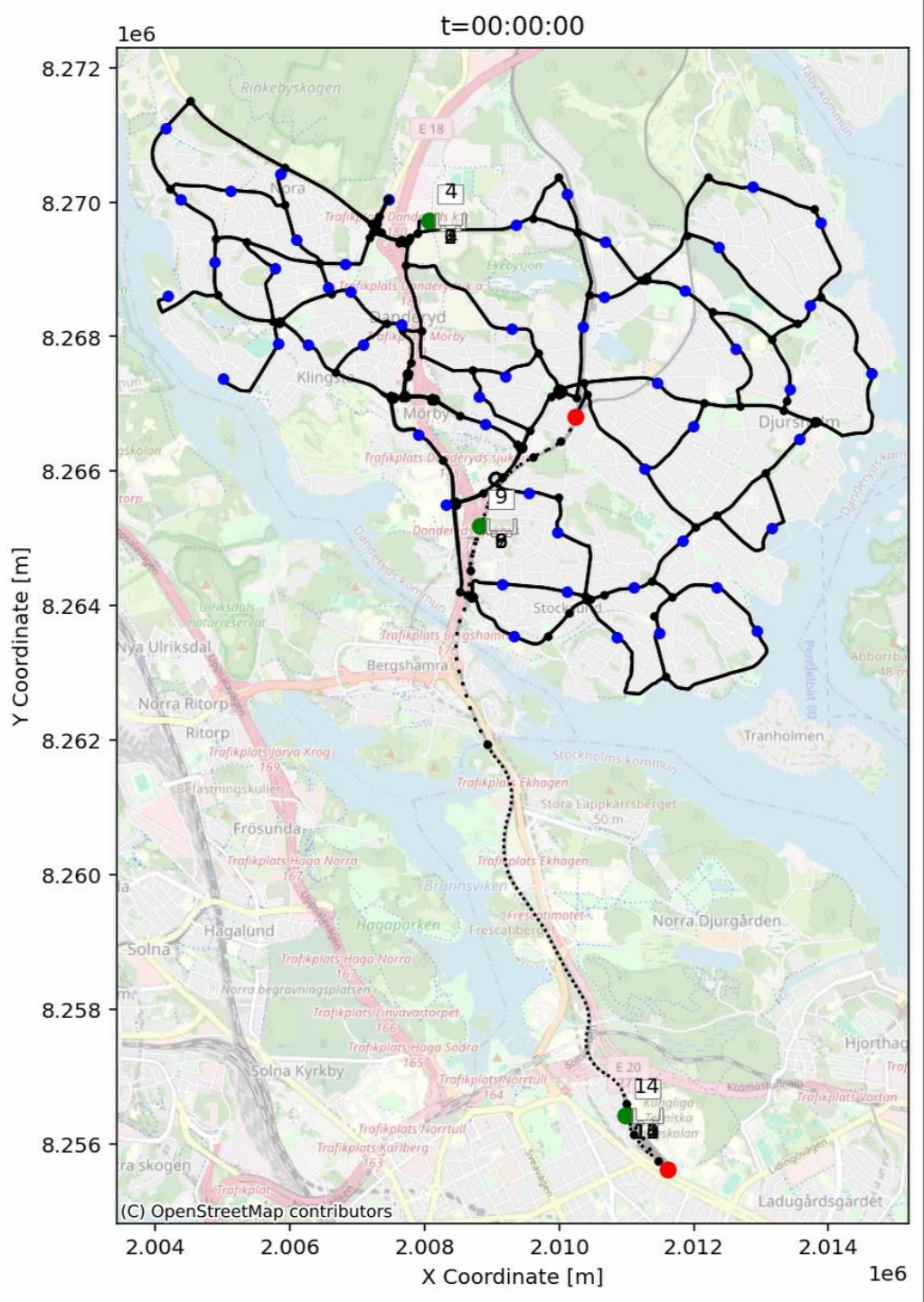

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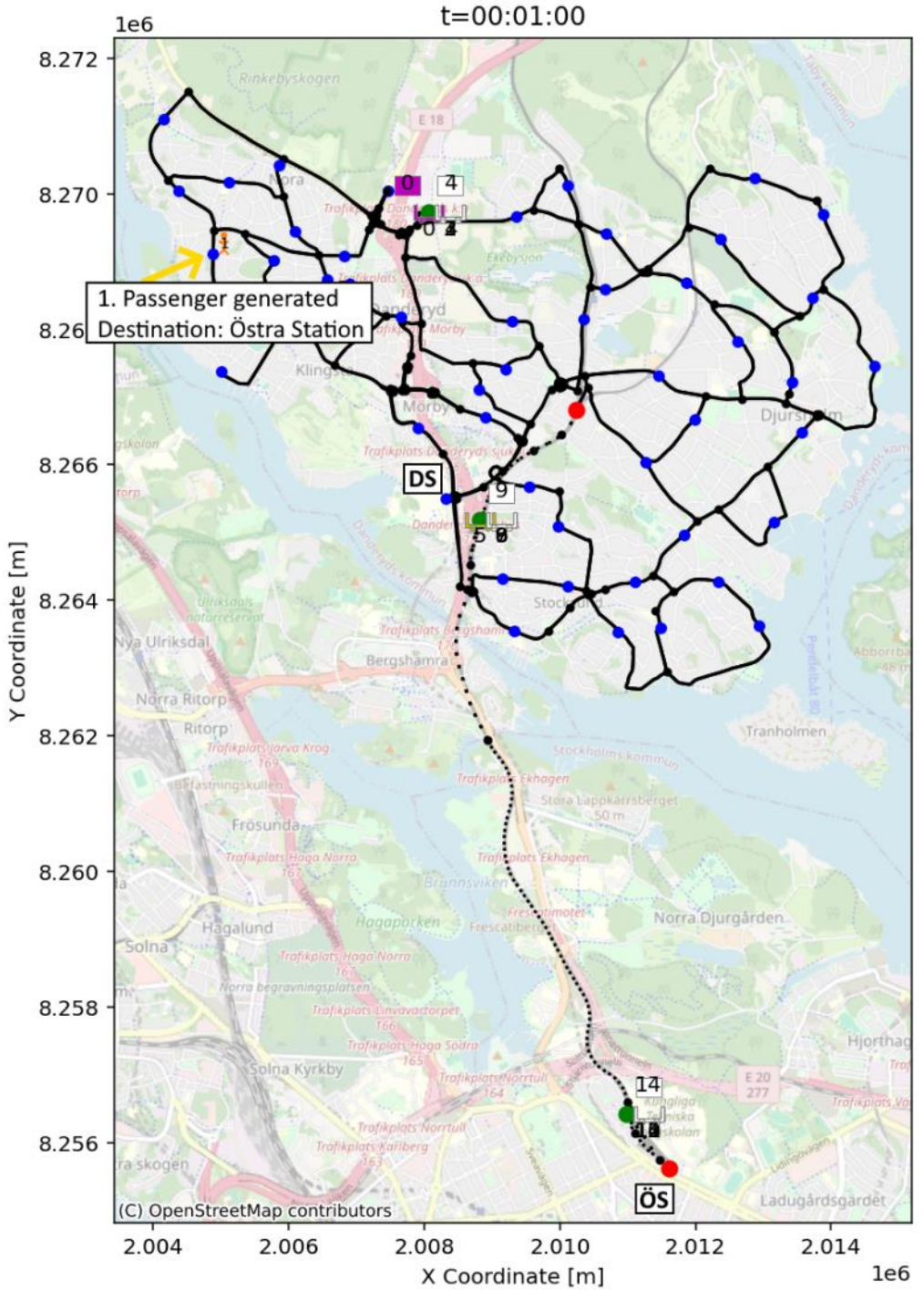

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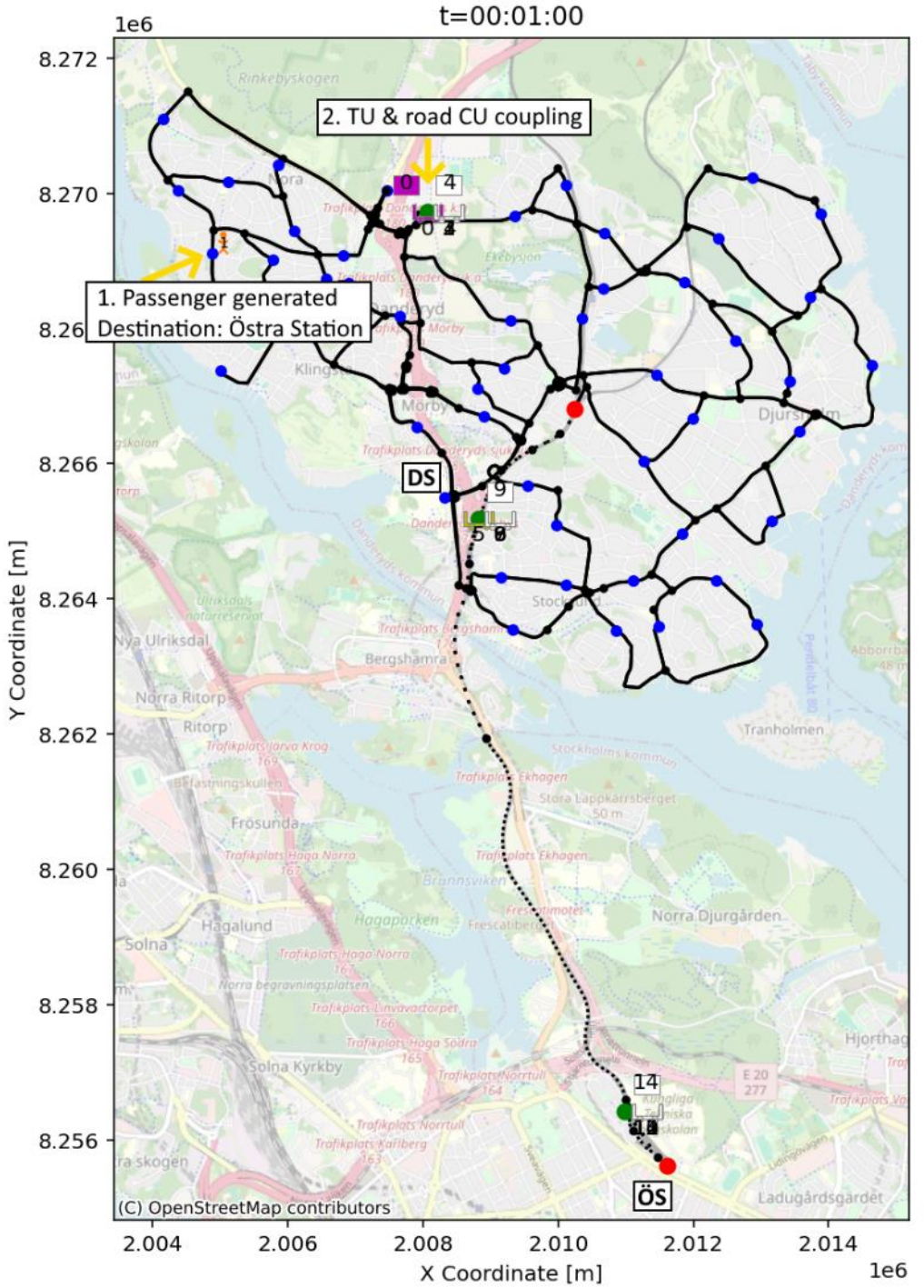

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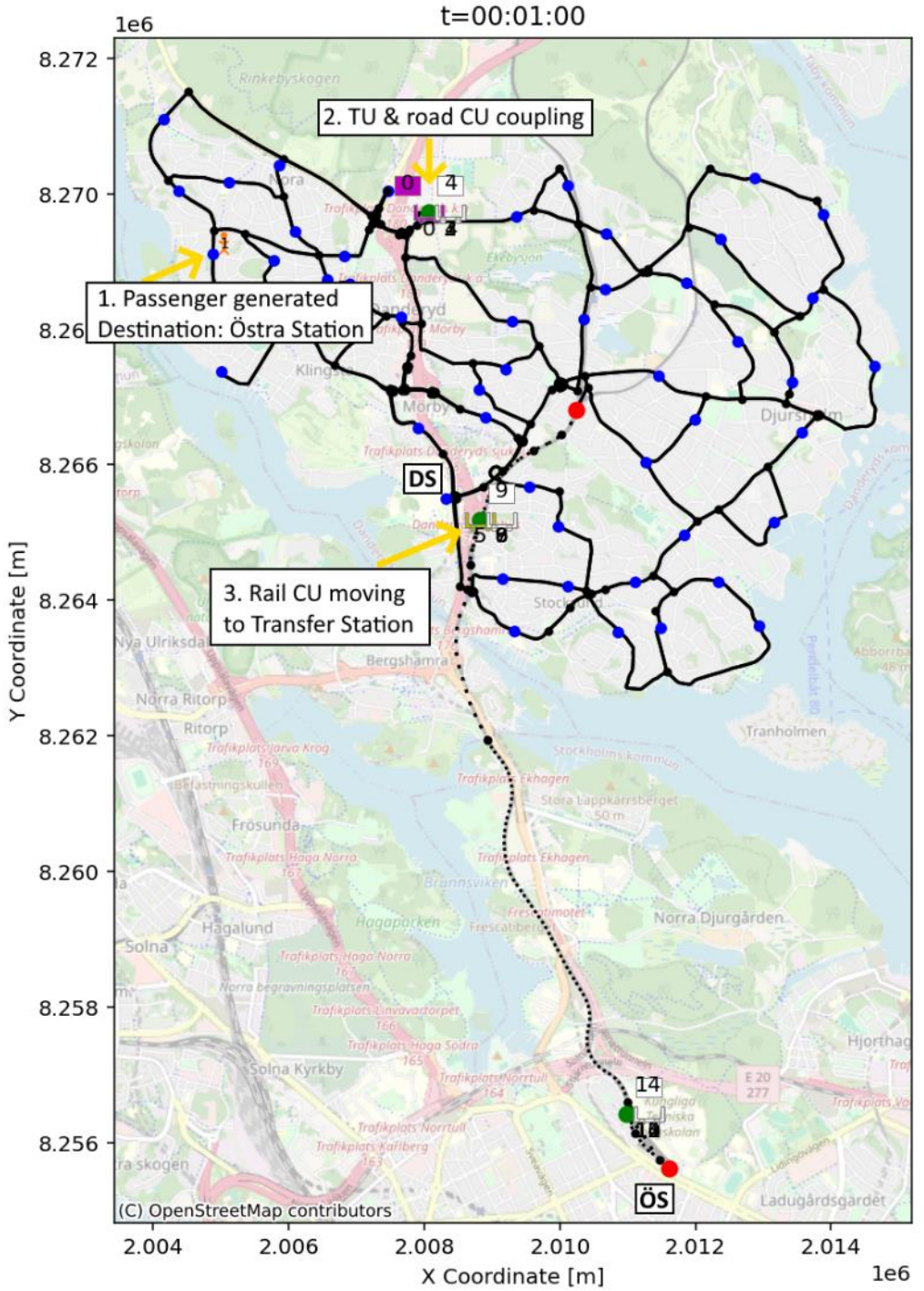

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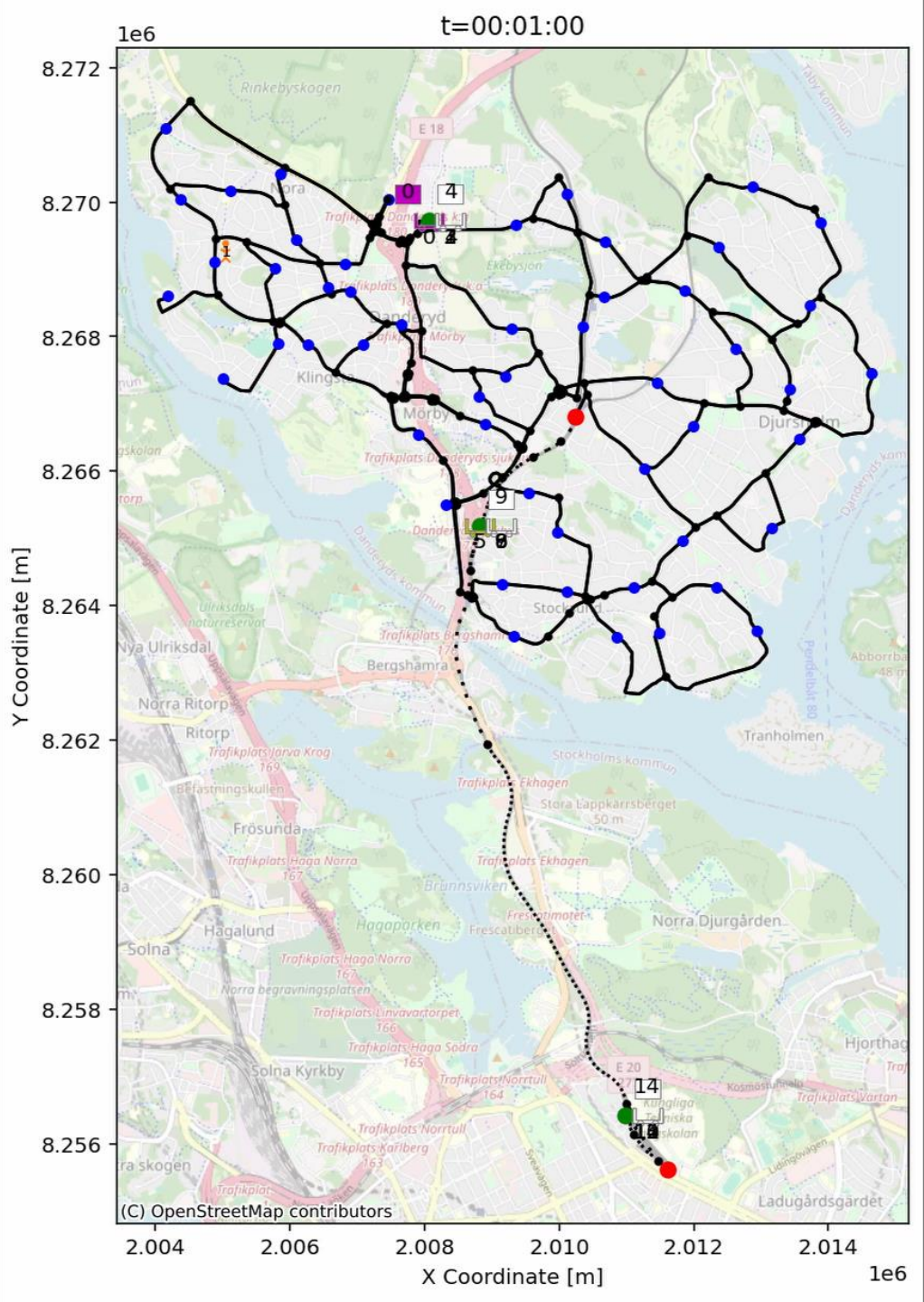

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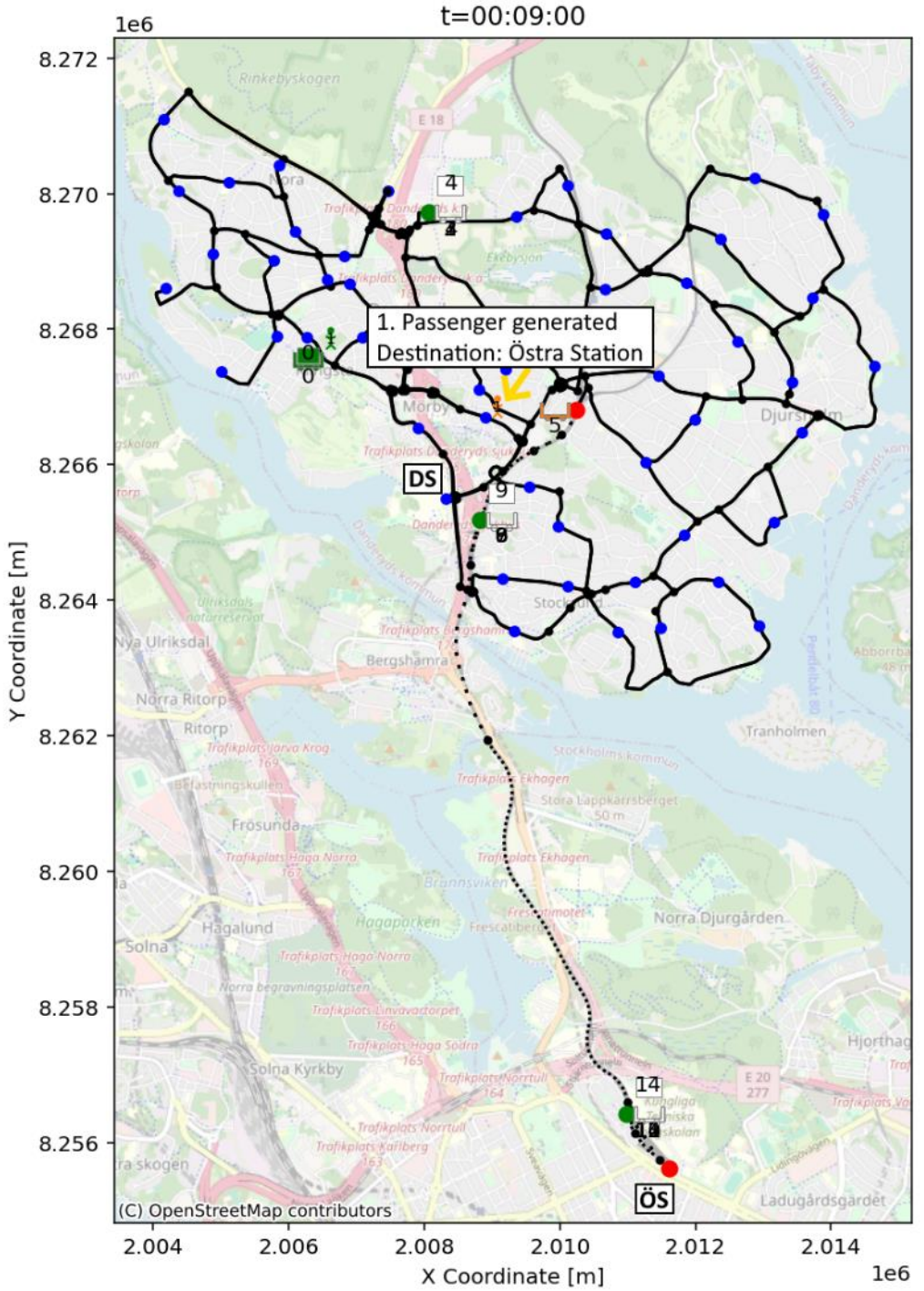

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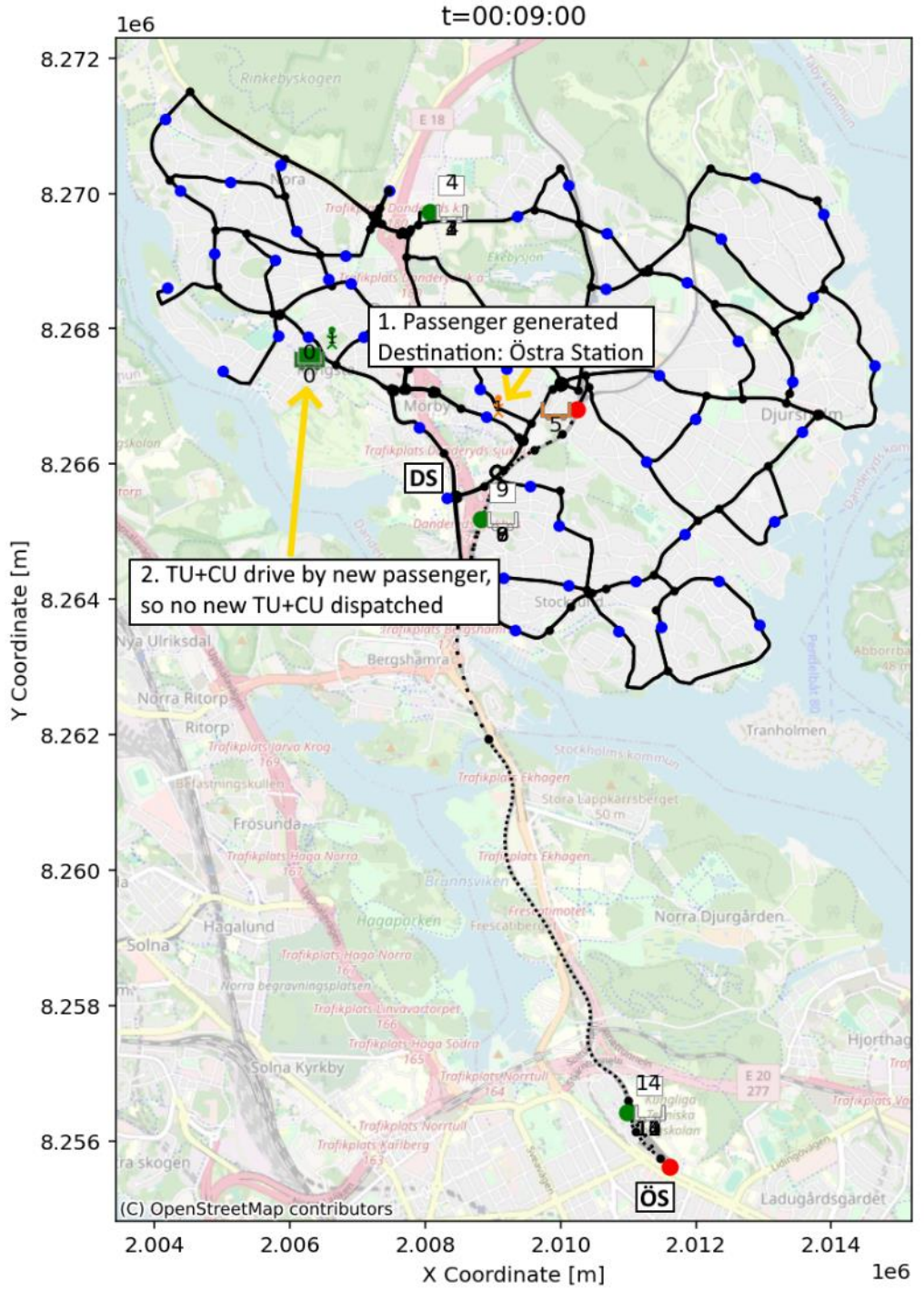

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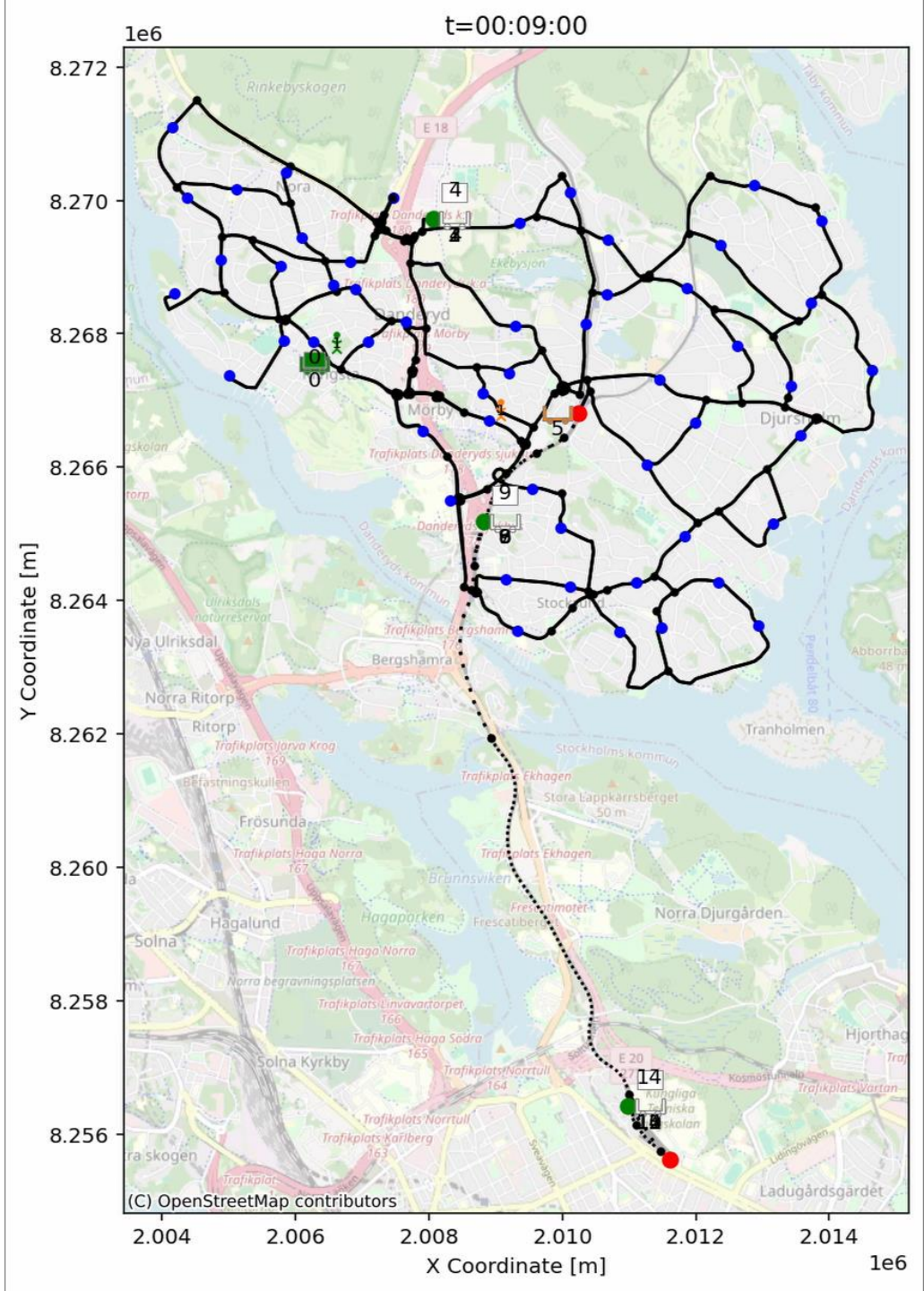

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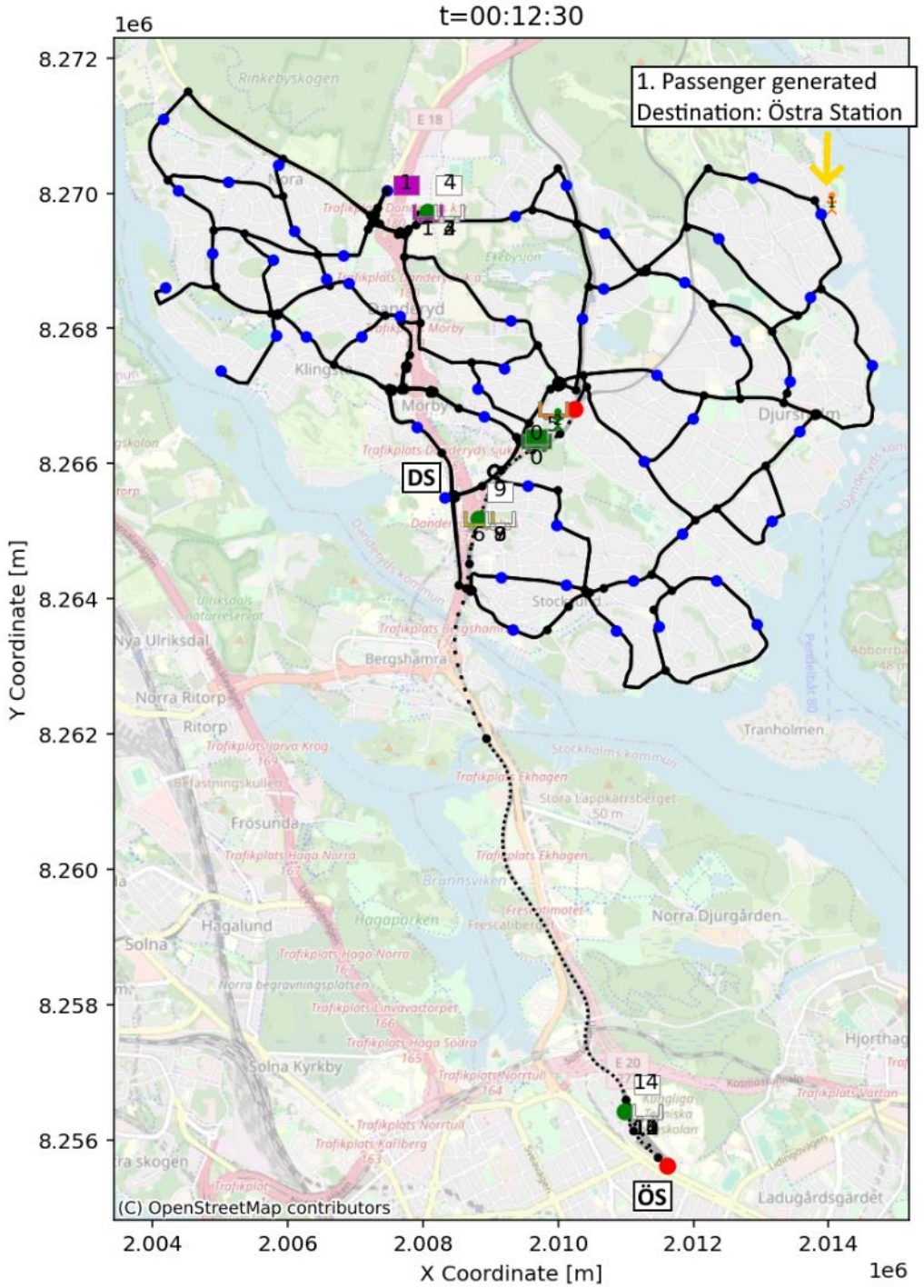

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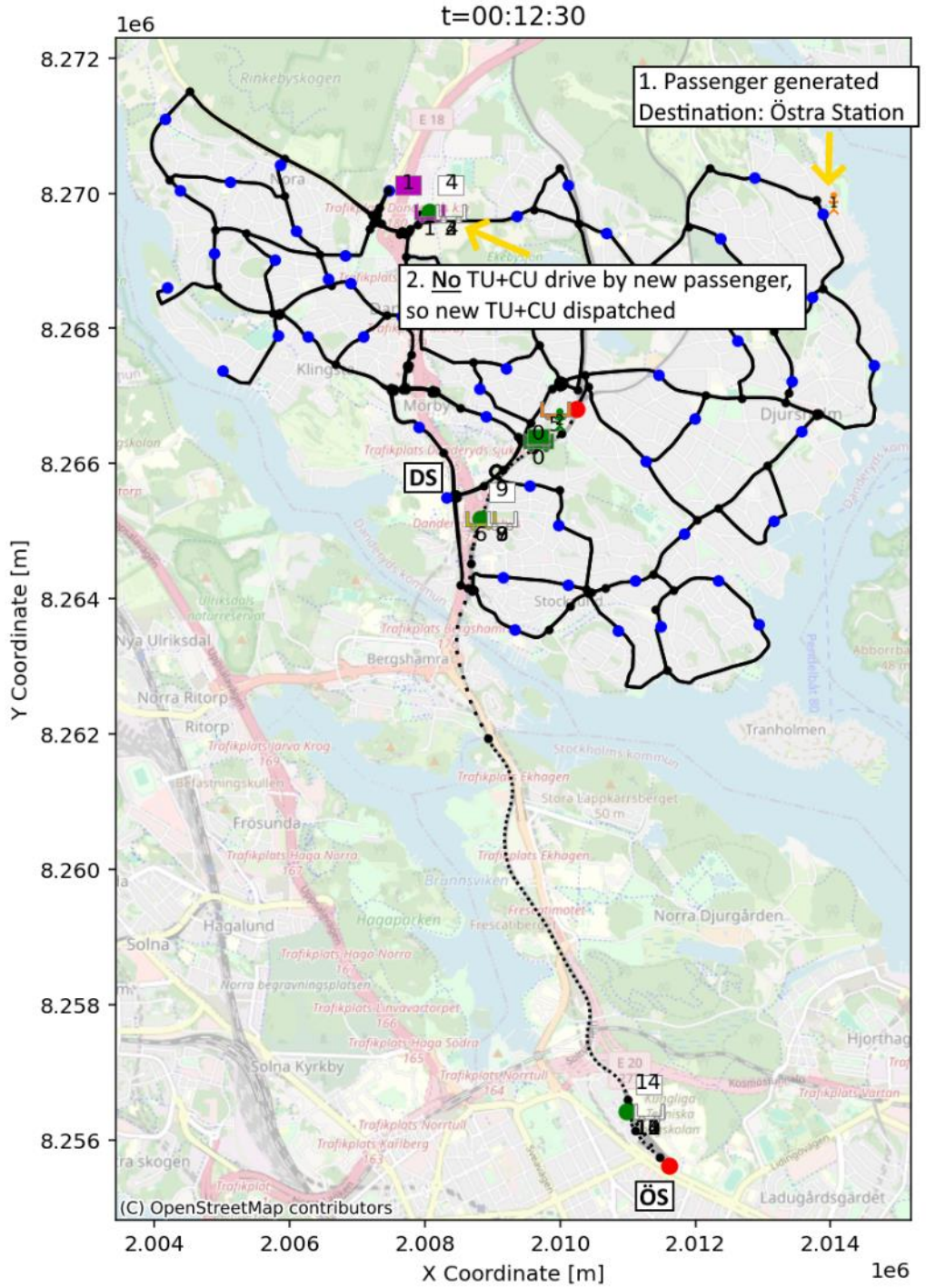

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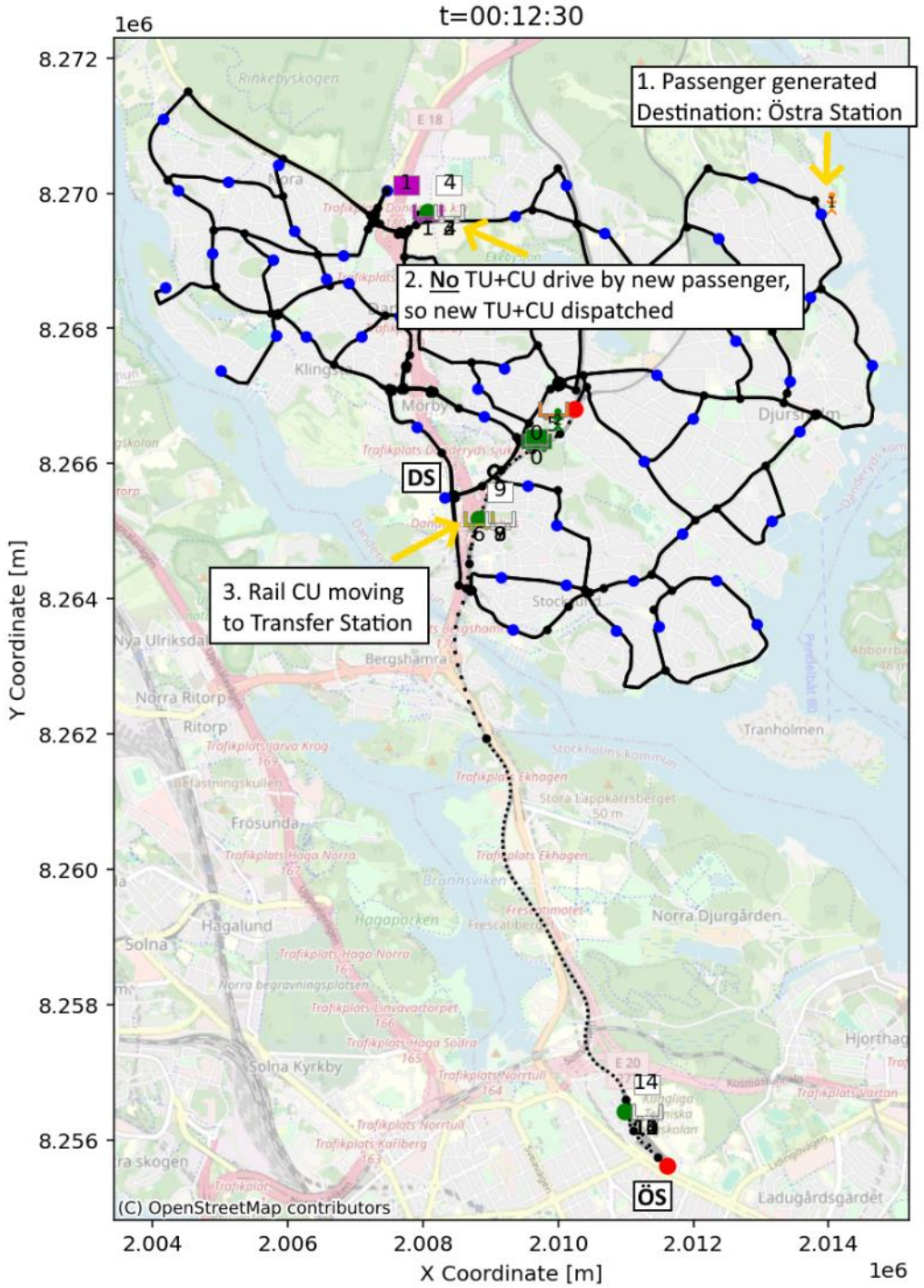

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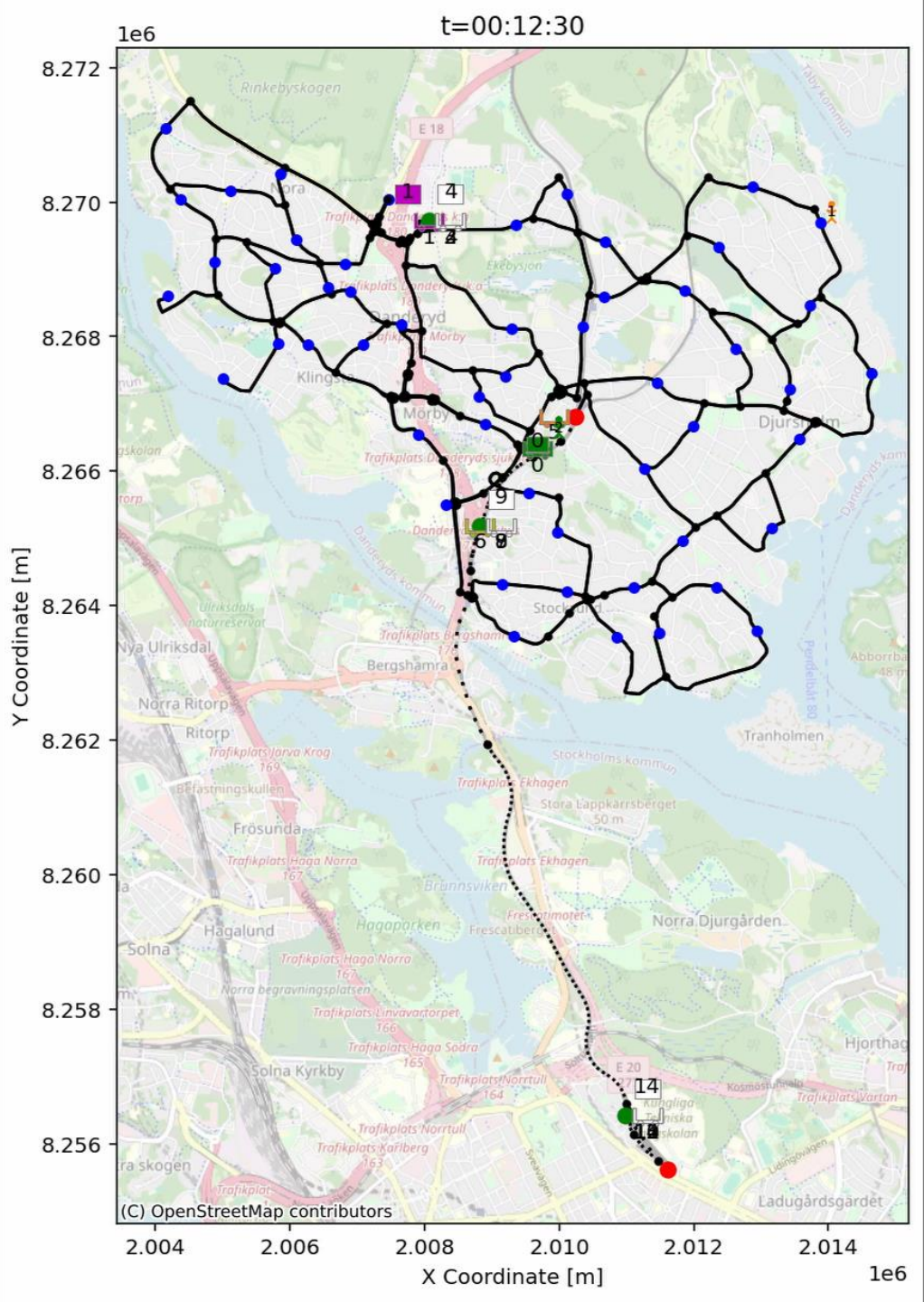

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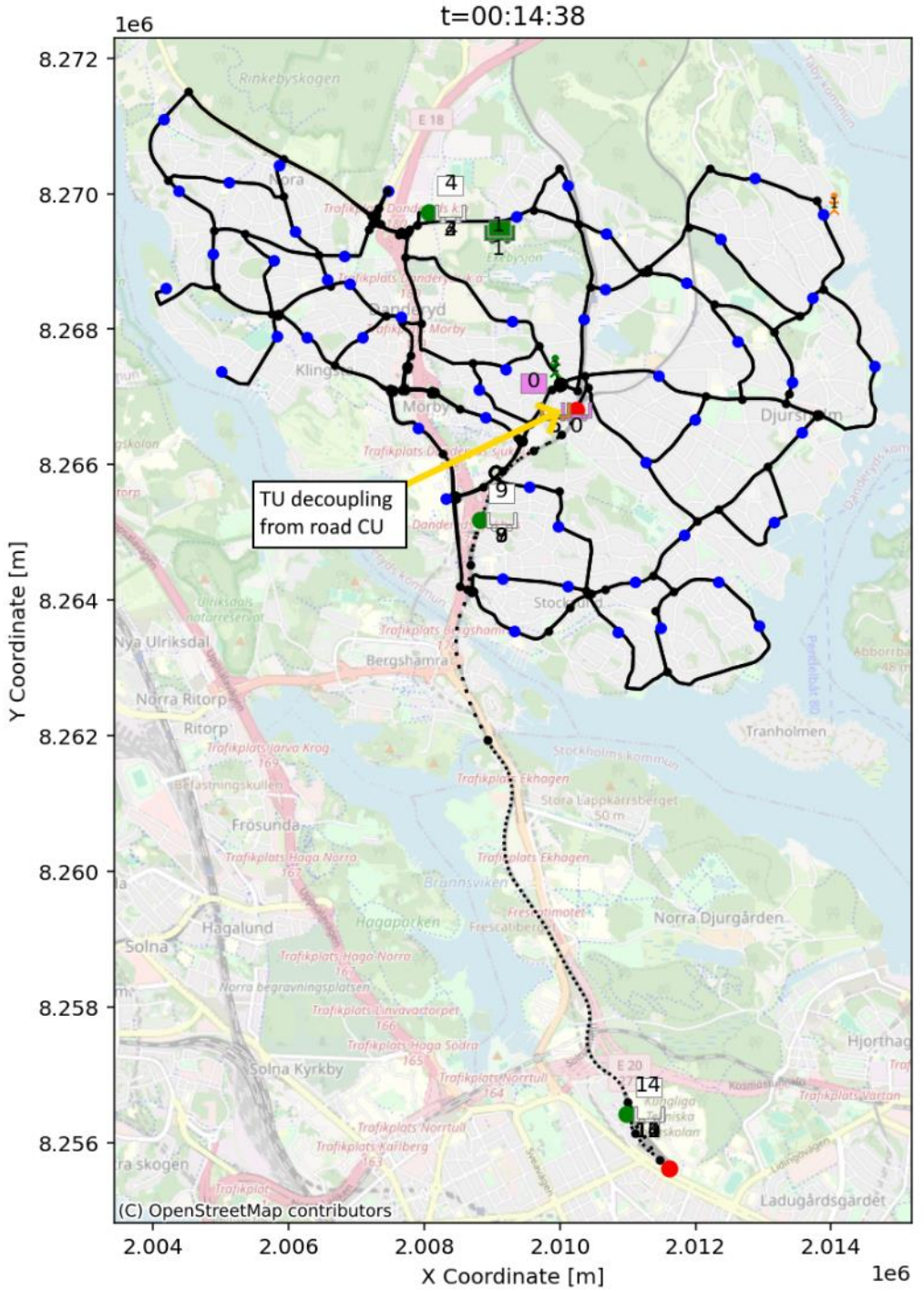

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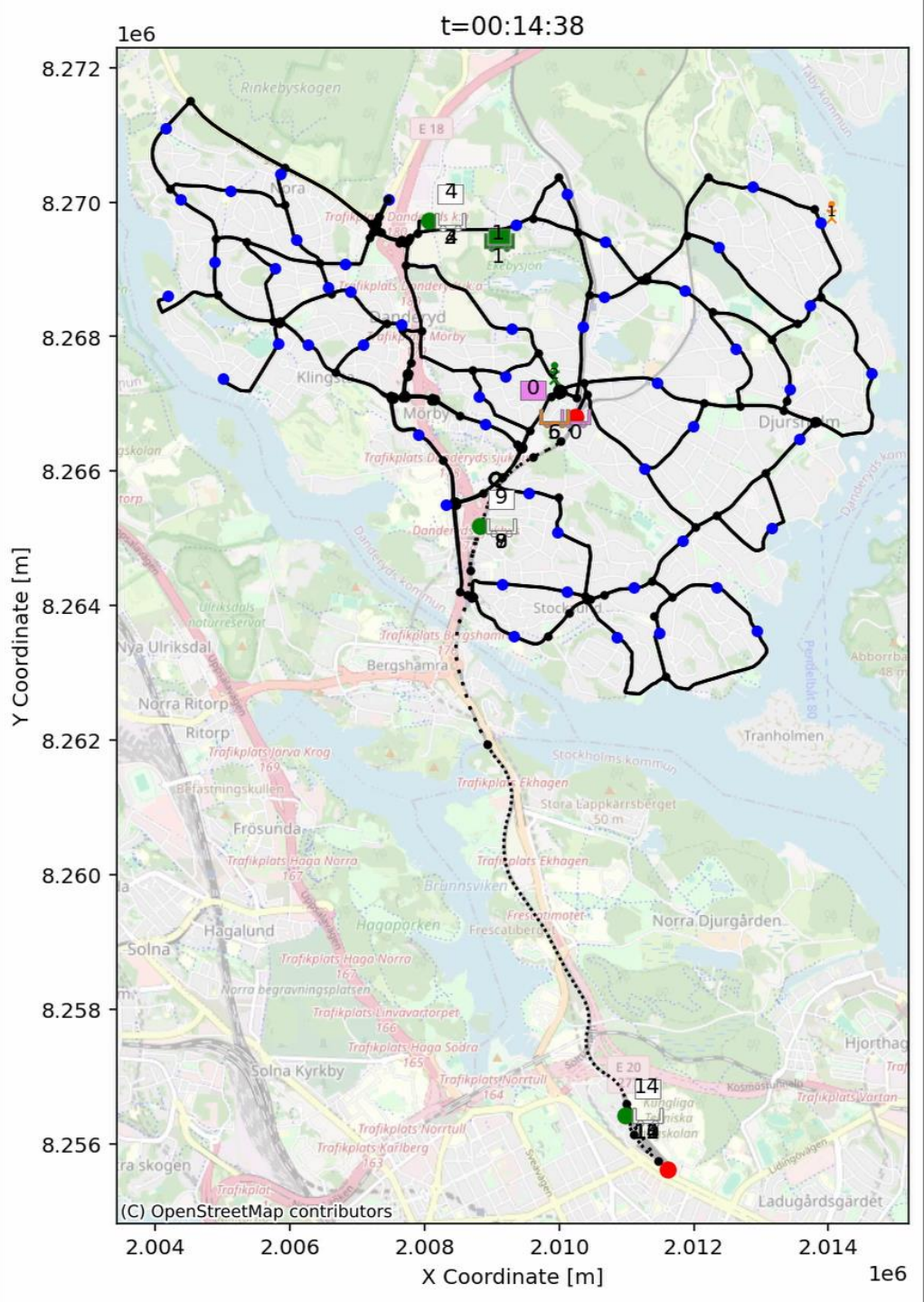

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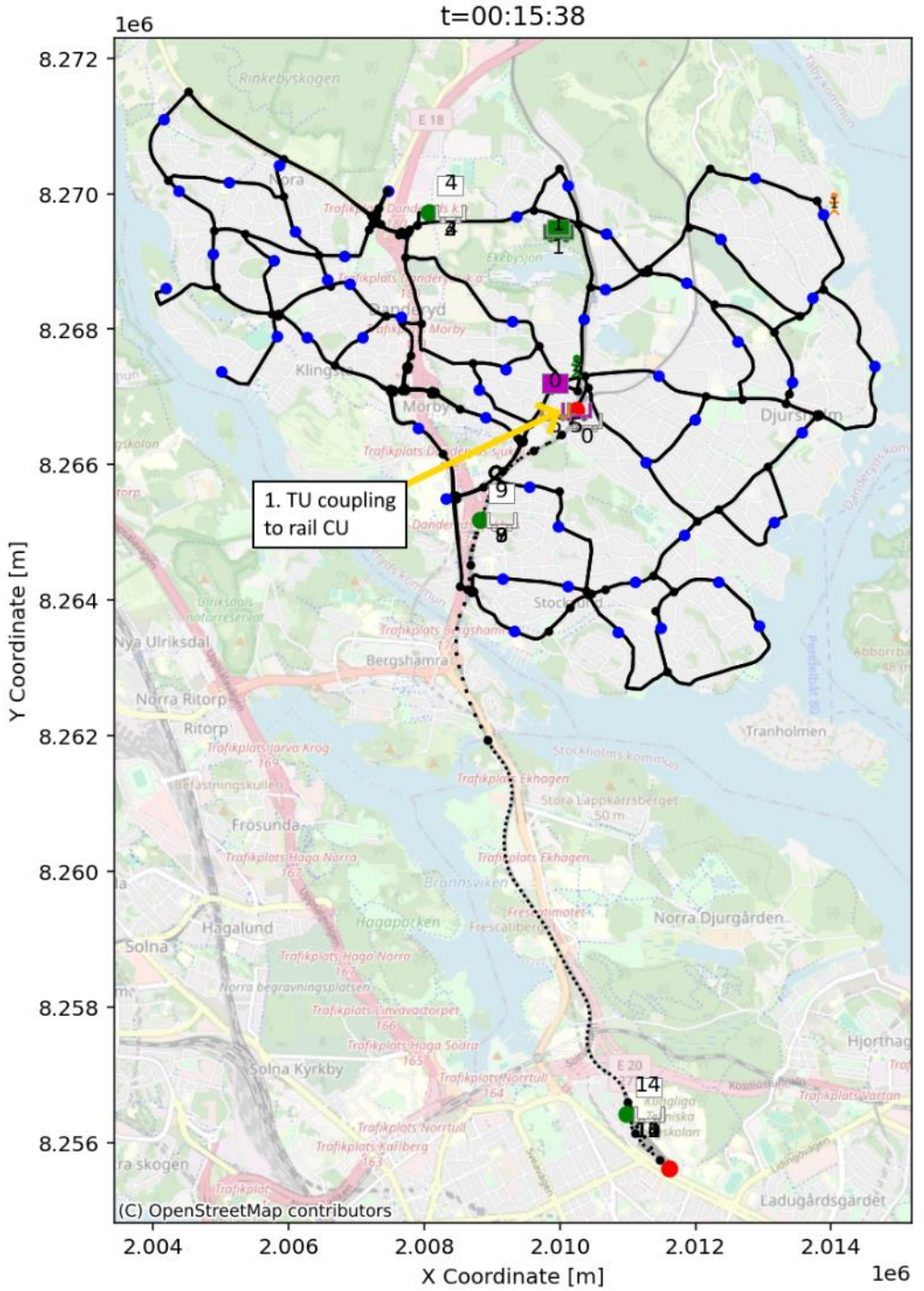

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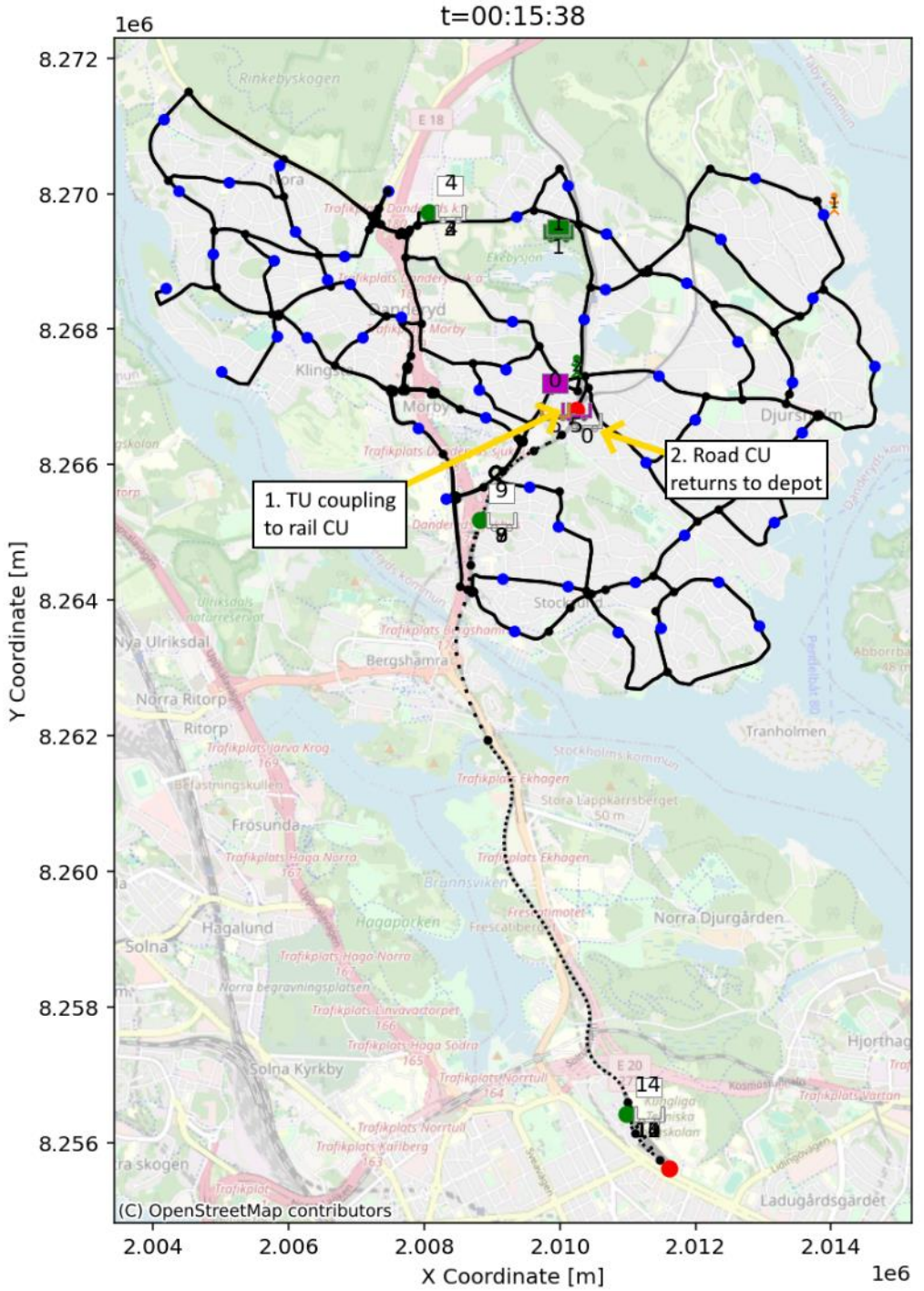

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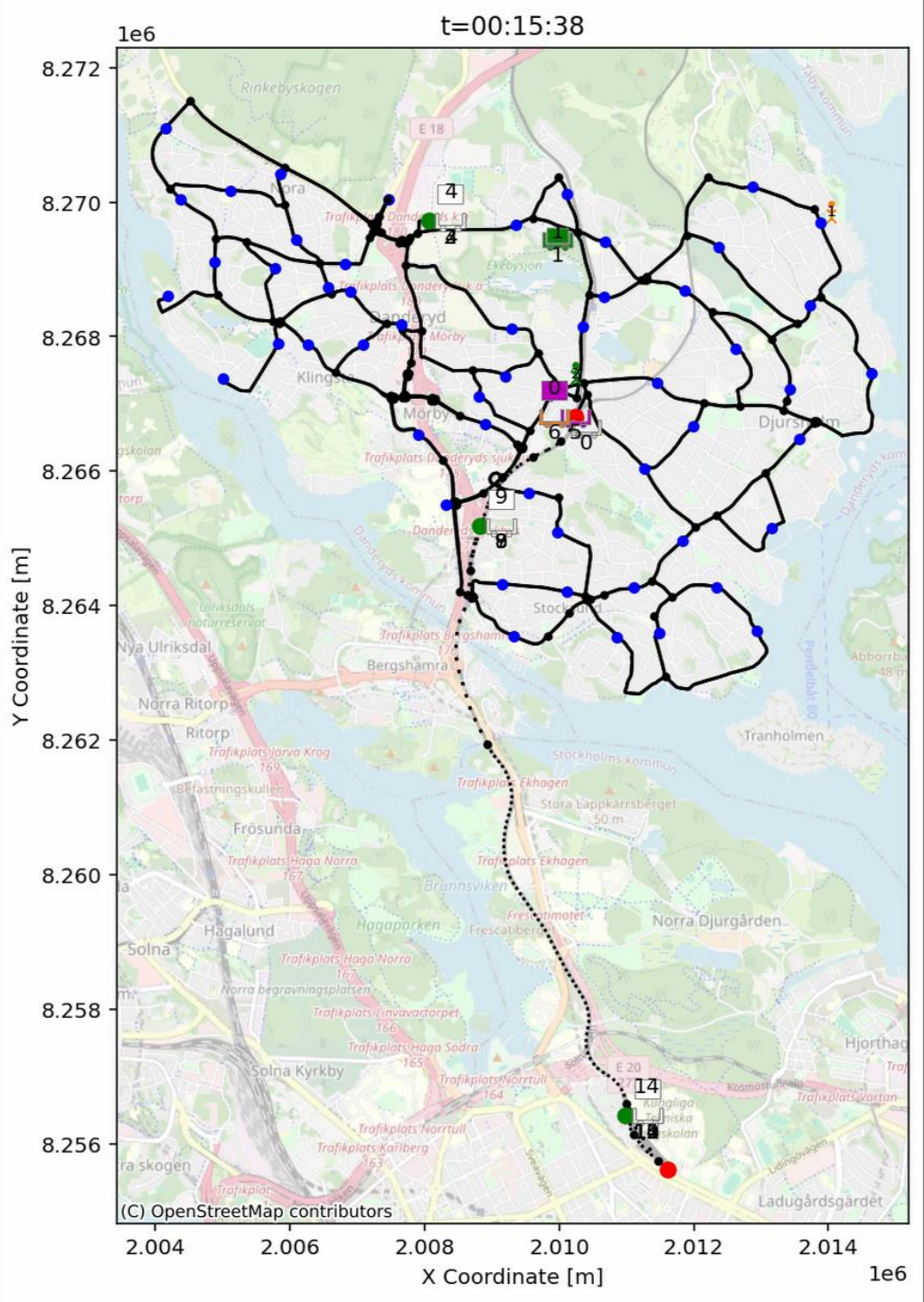

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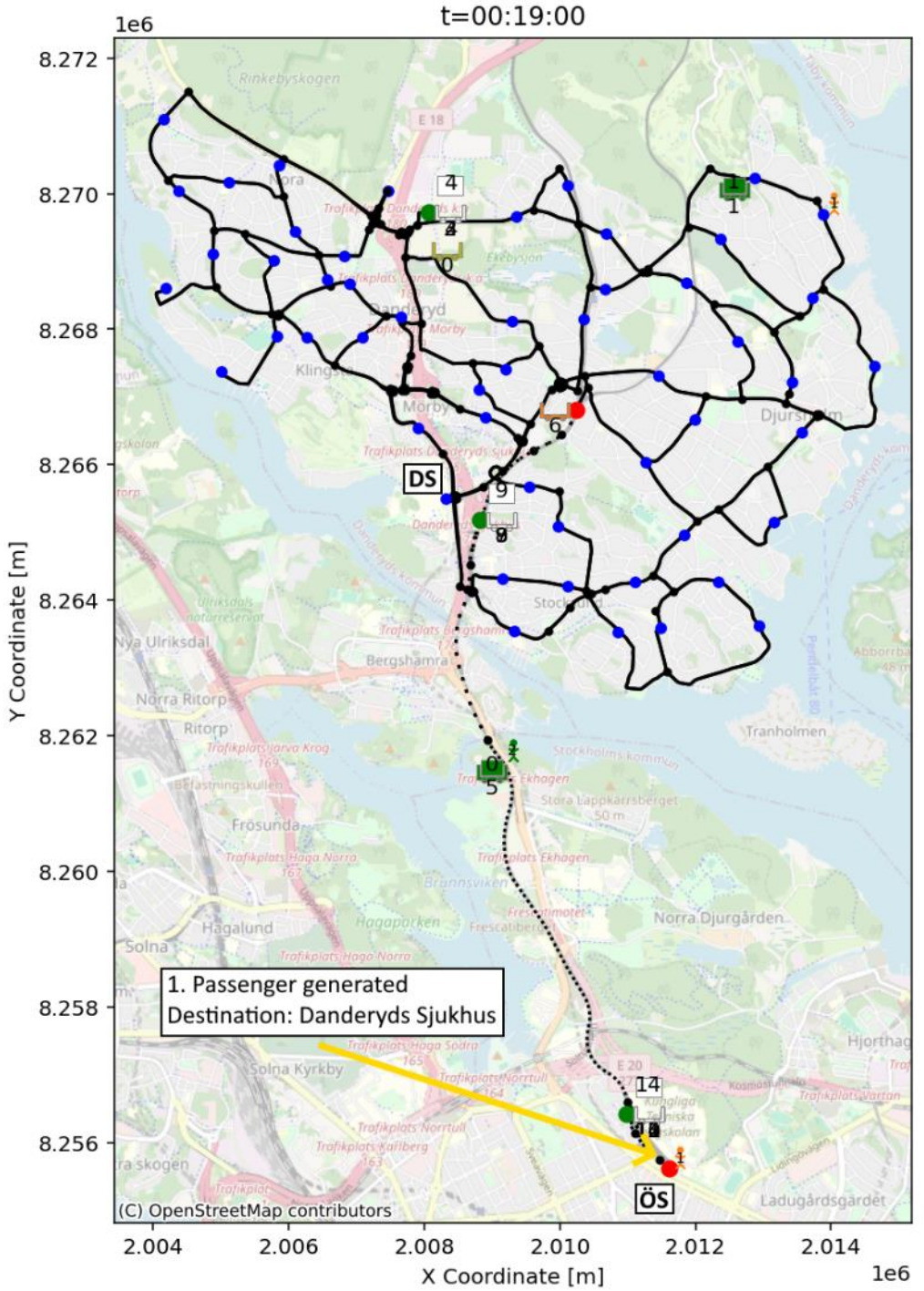

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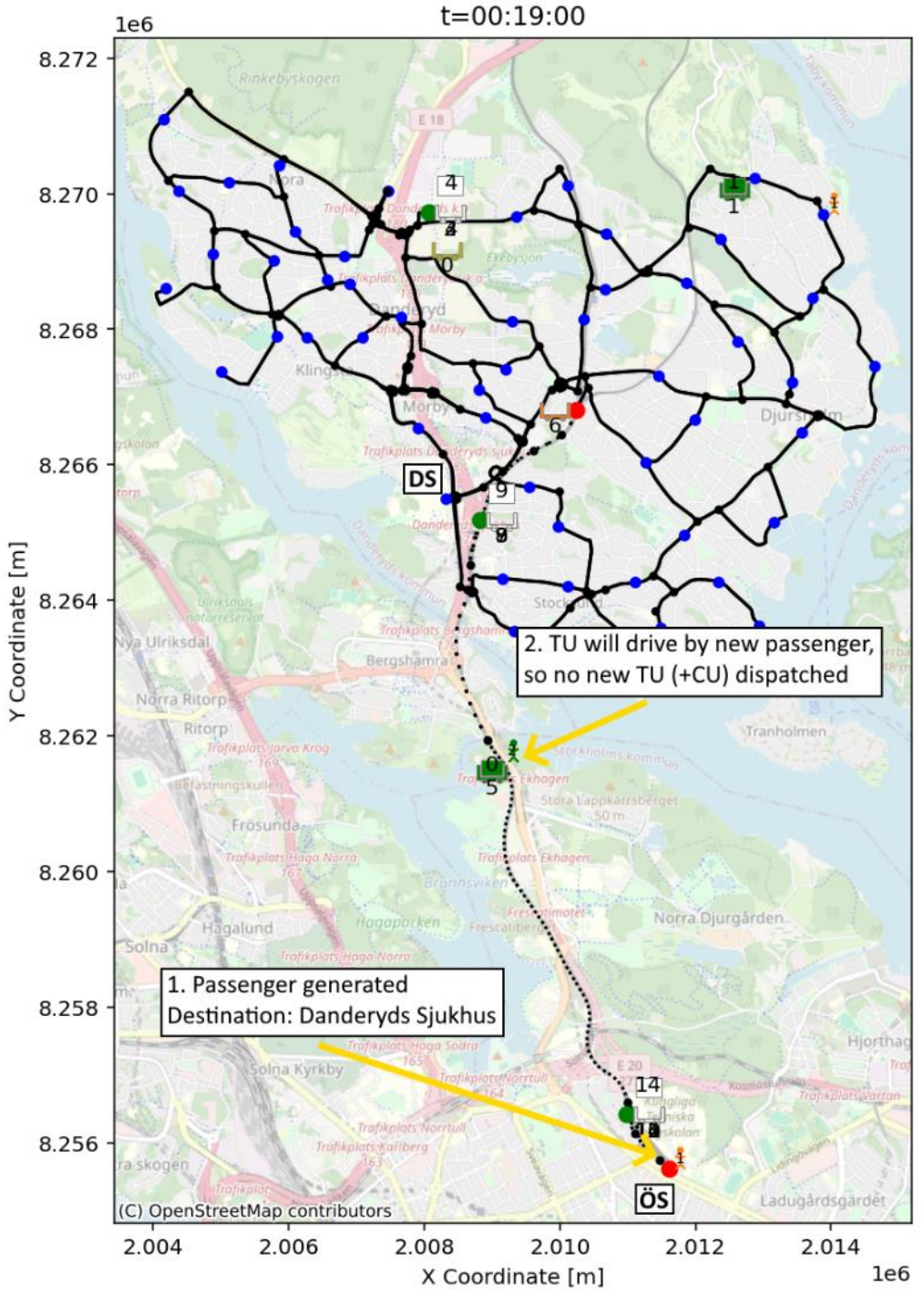

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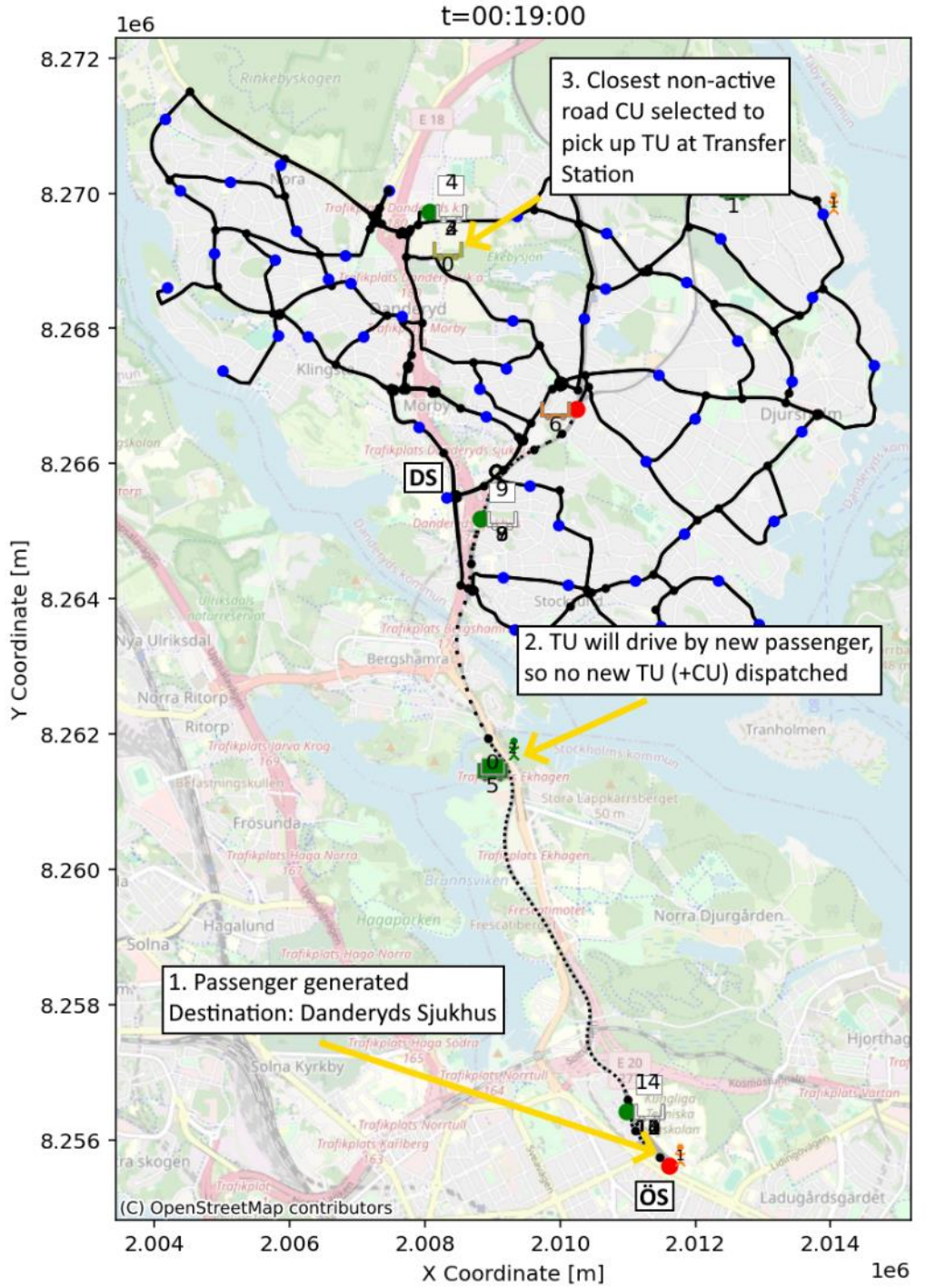

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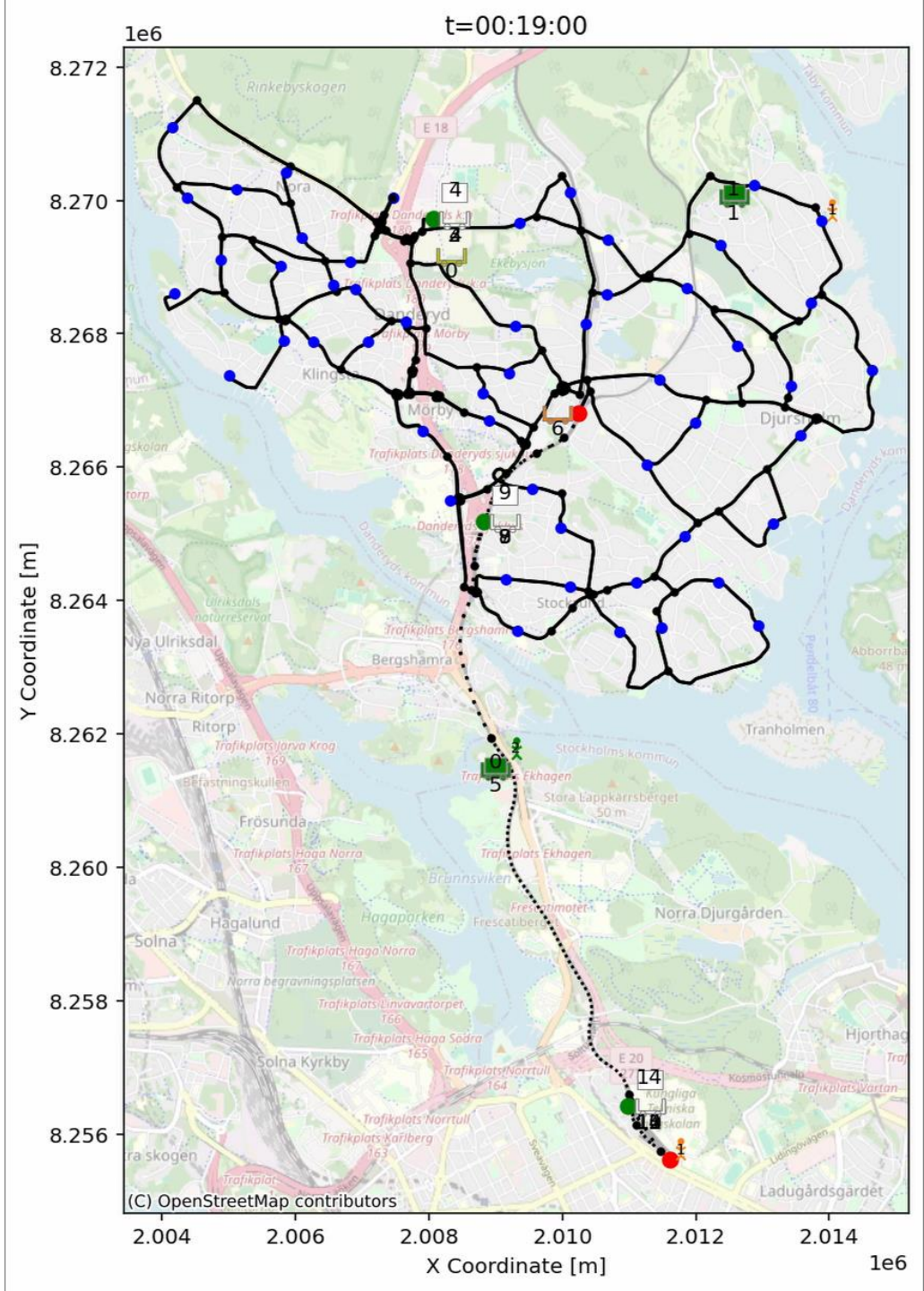

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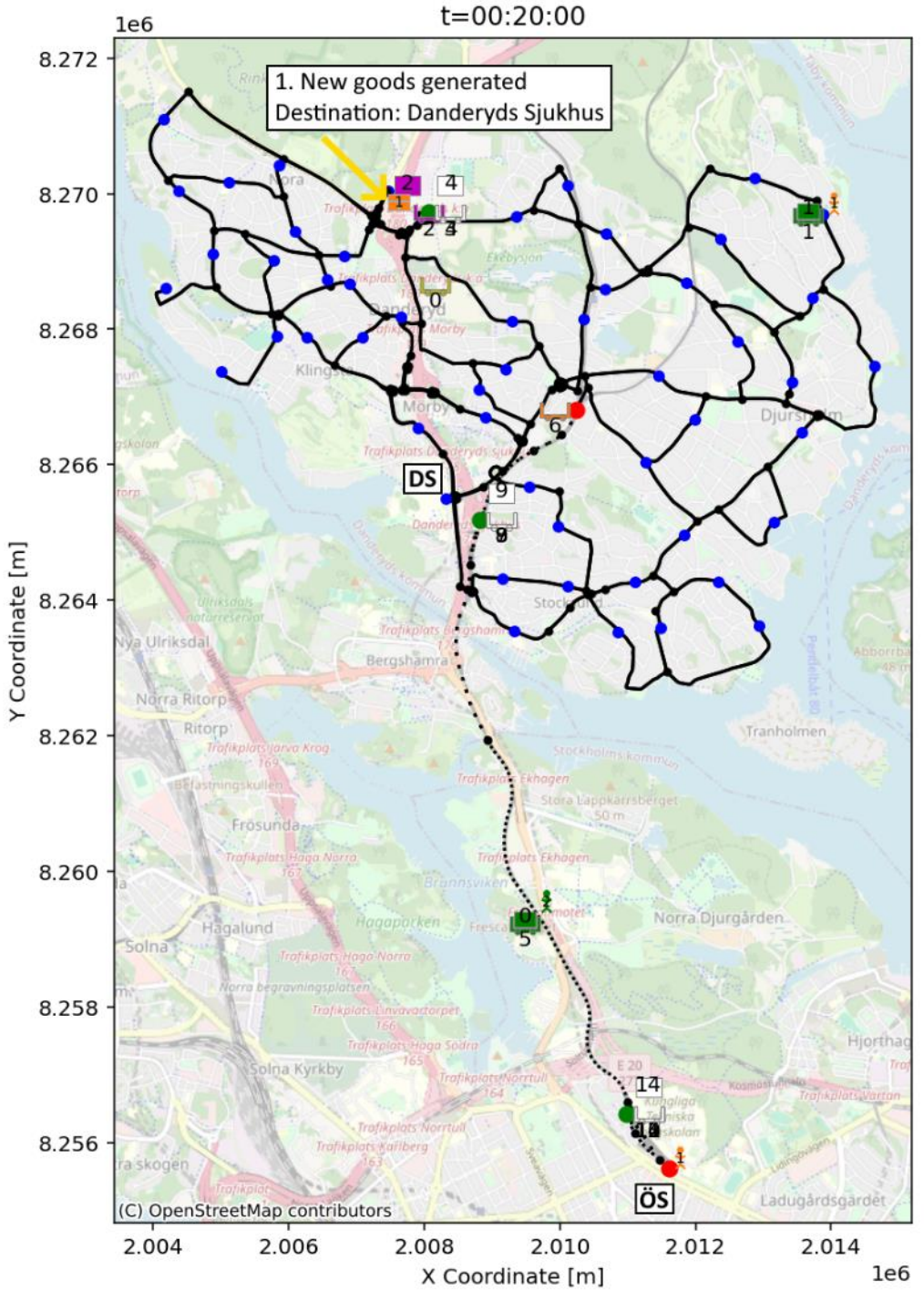

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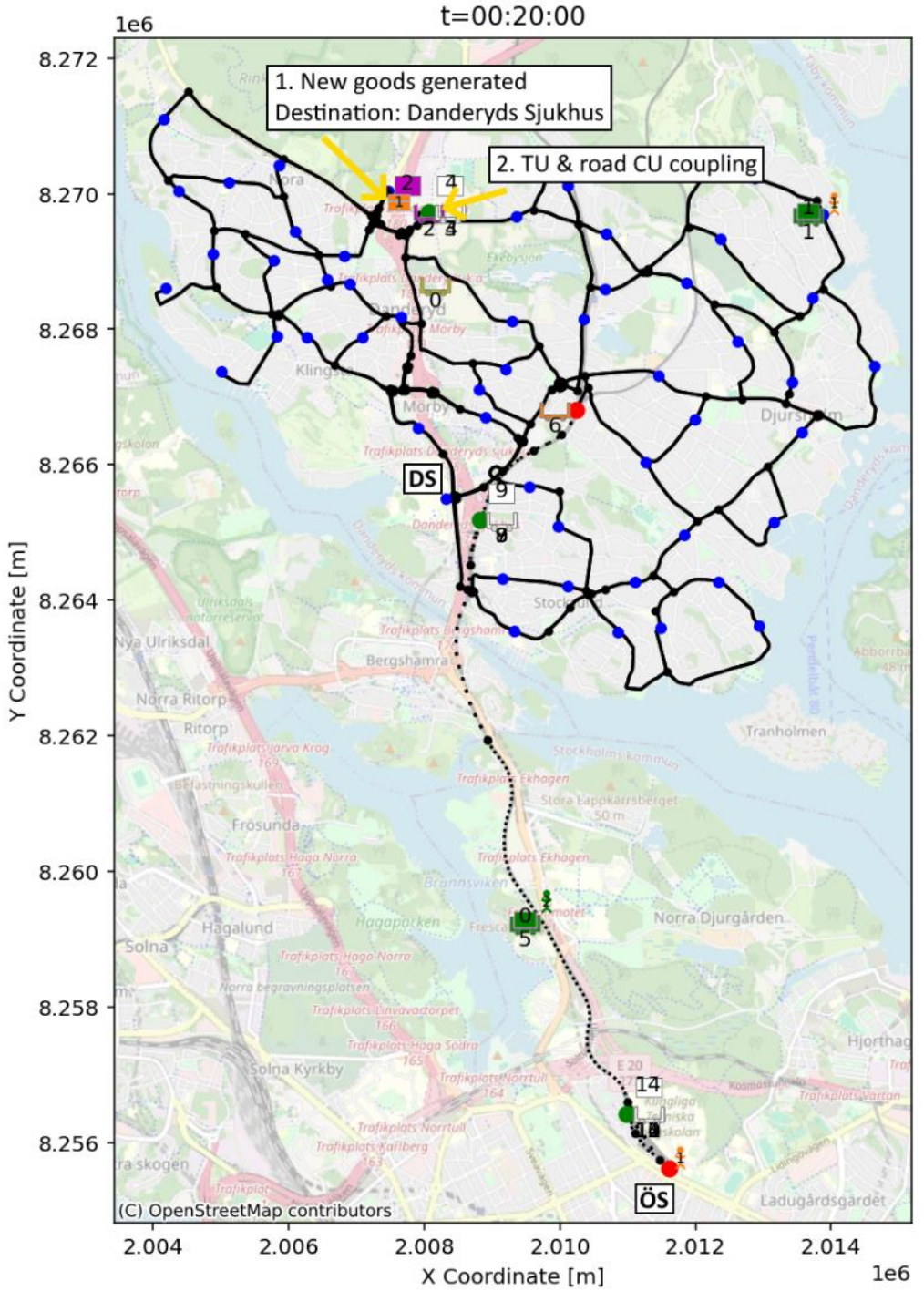

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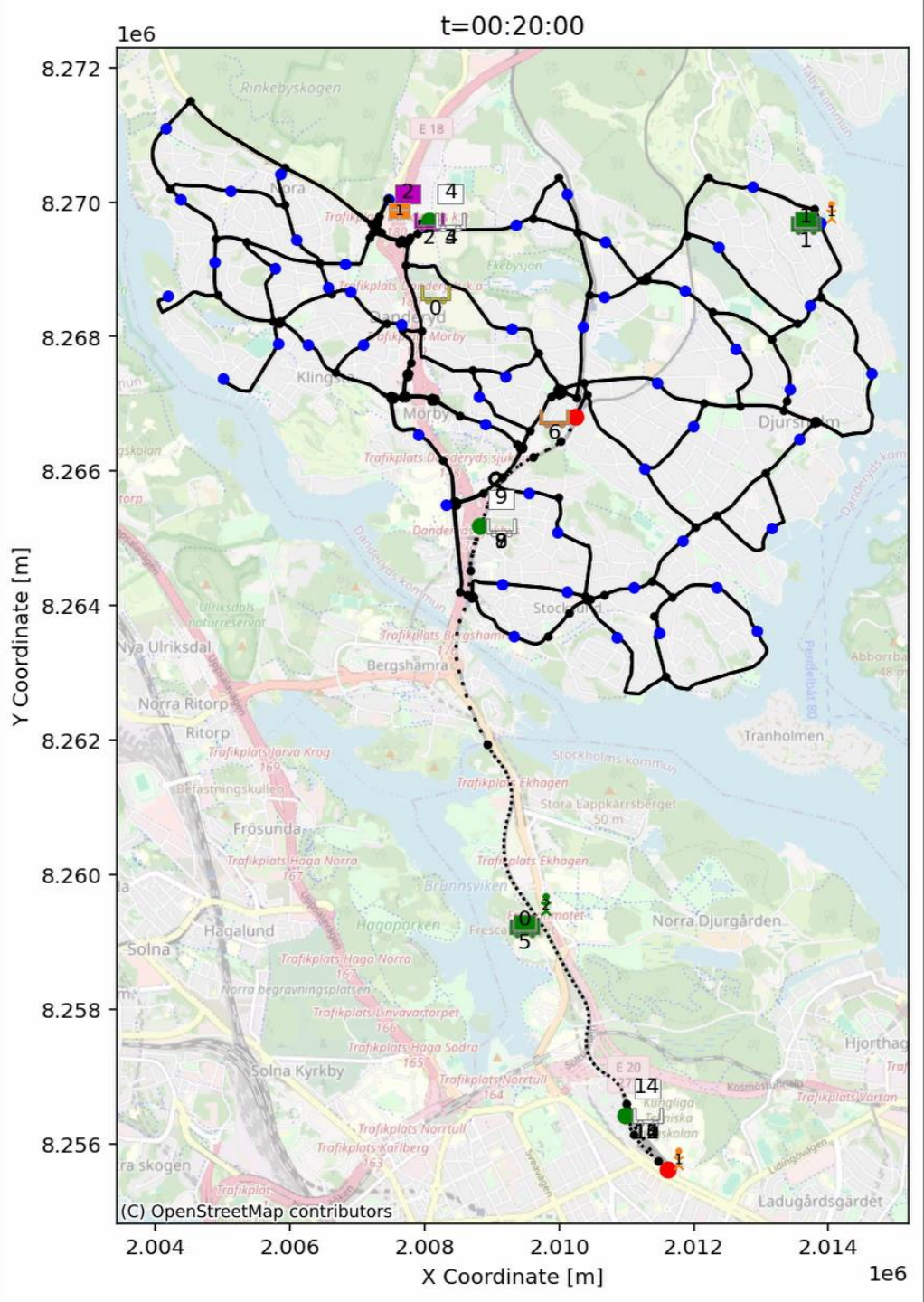

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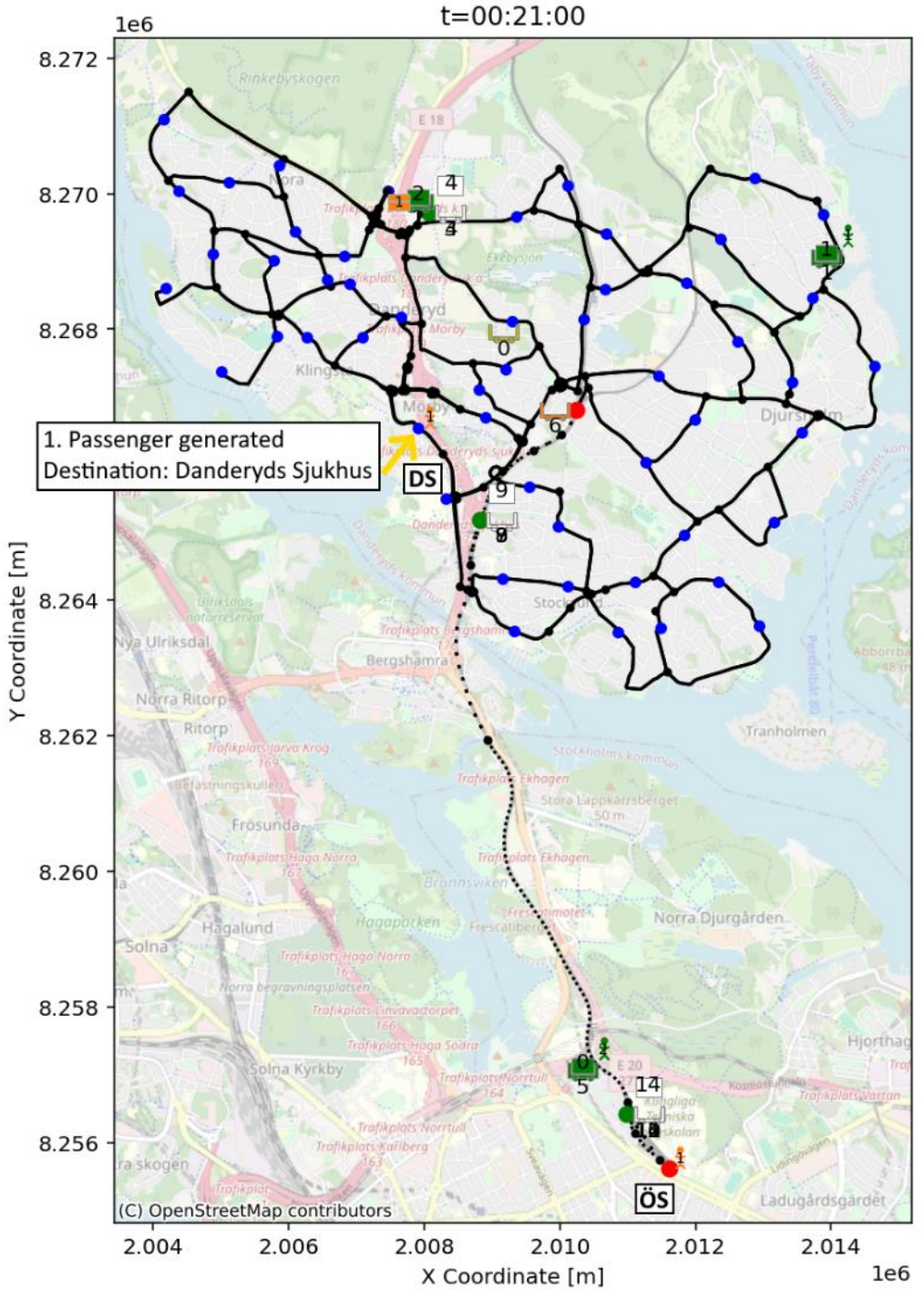

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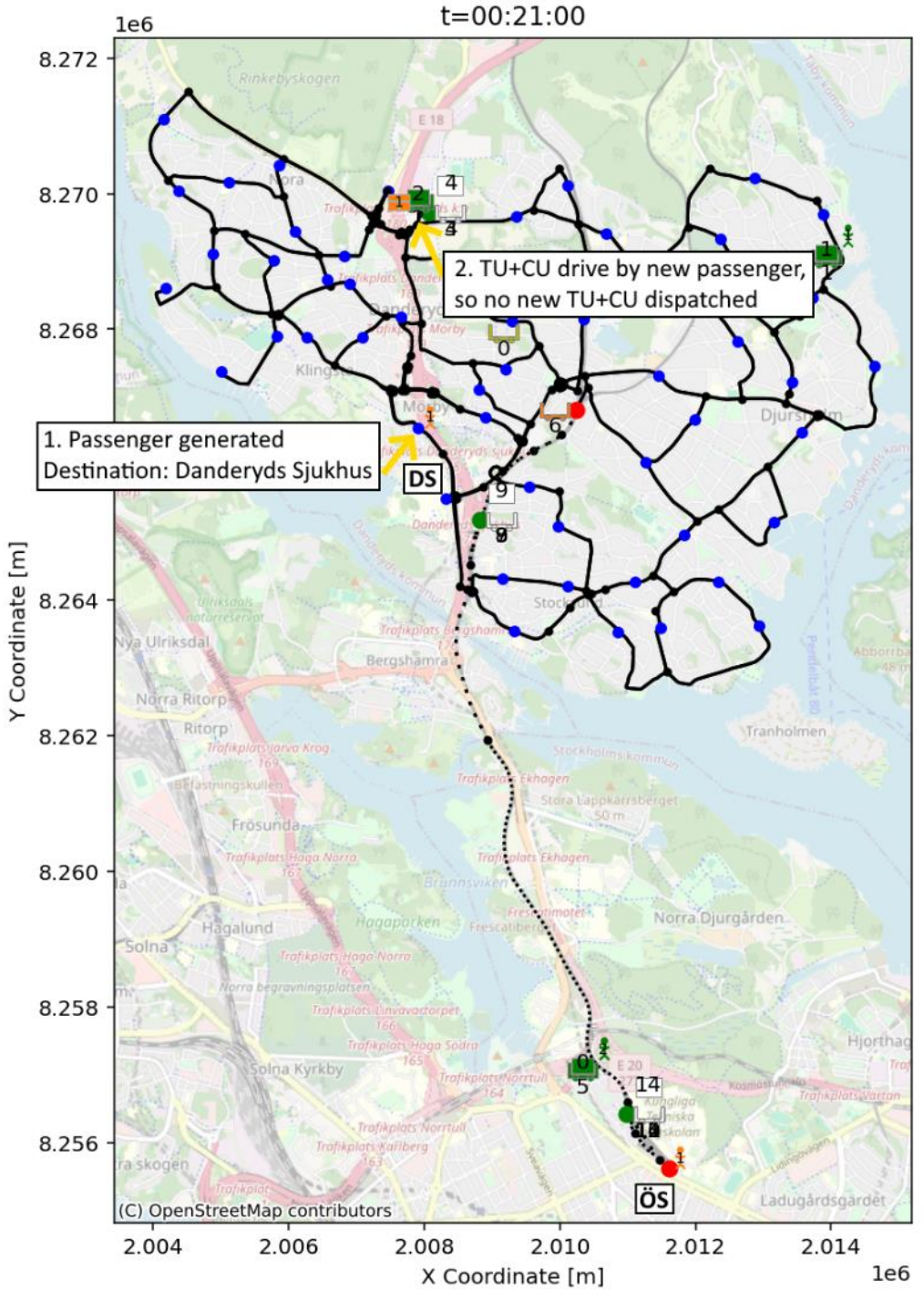

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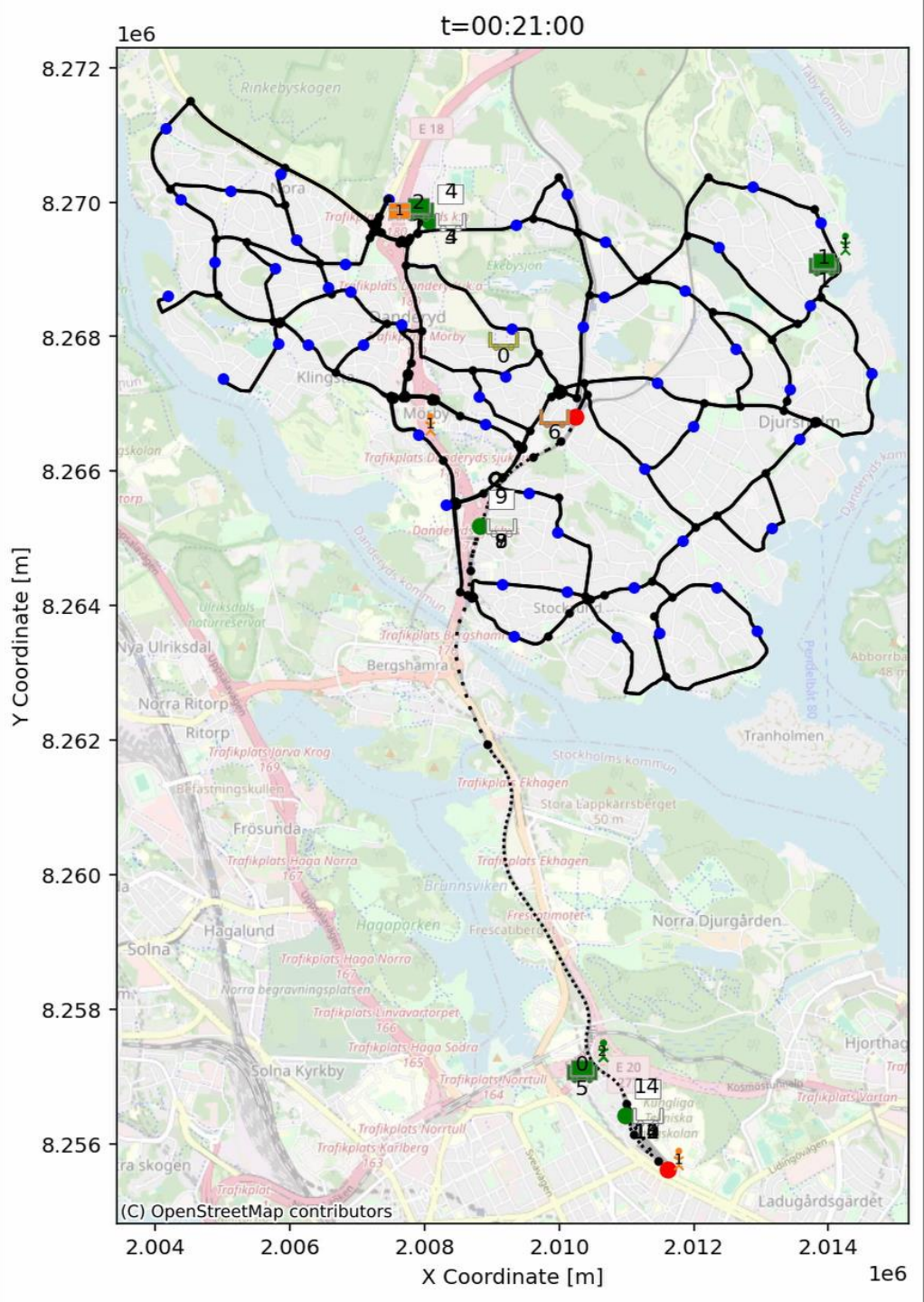
2. Animation of operations



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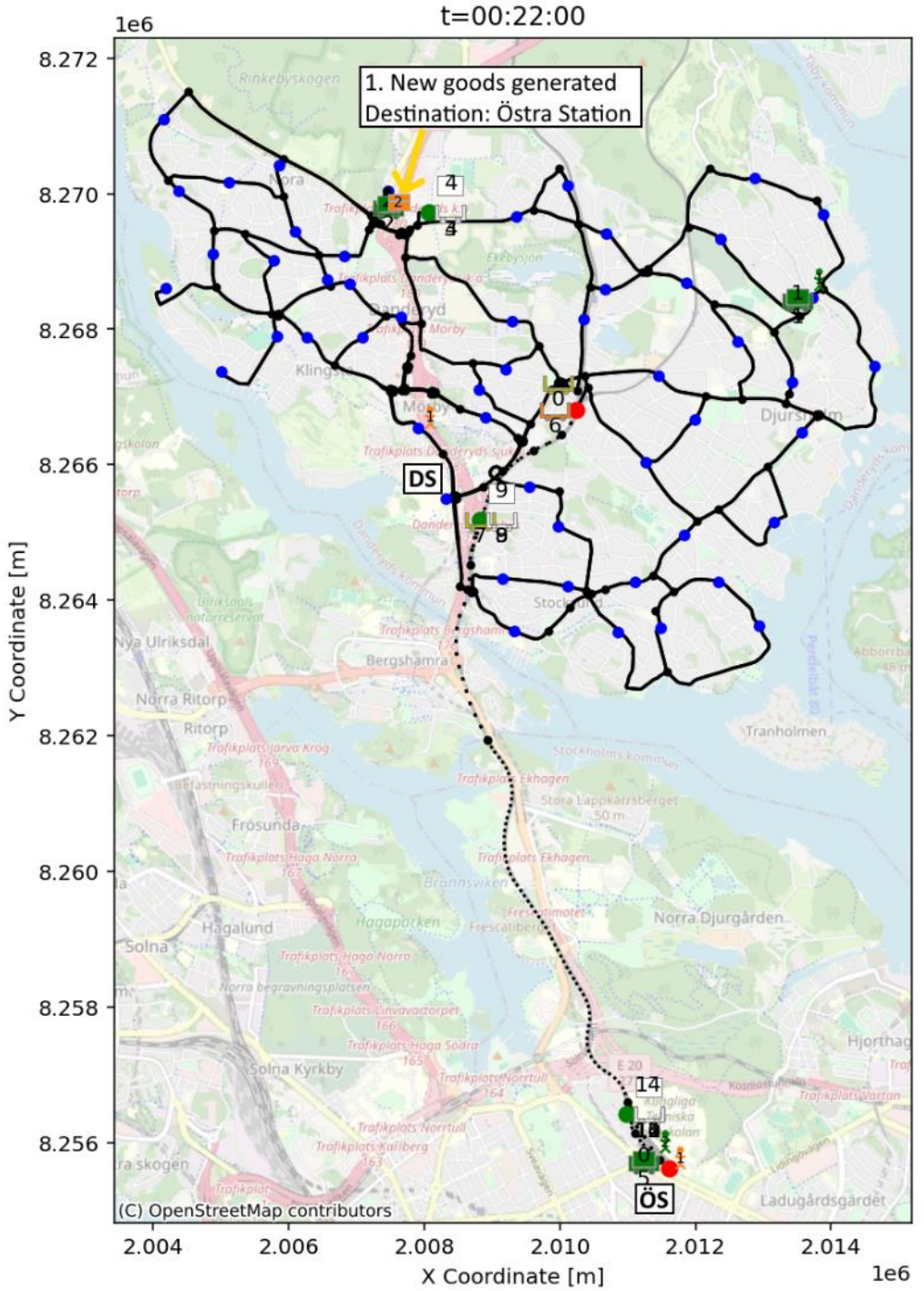
2. Animation of operations



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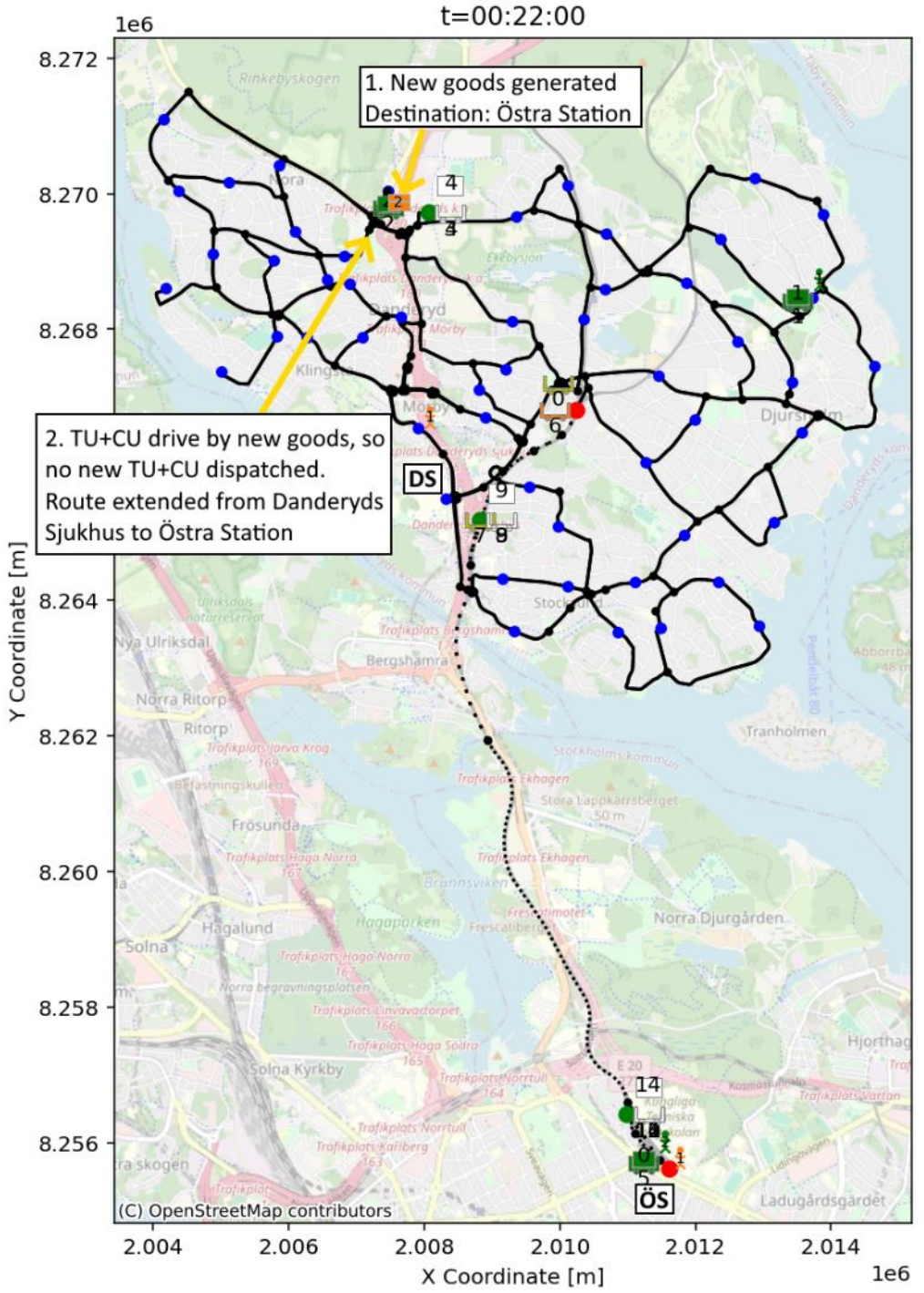

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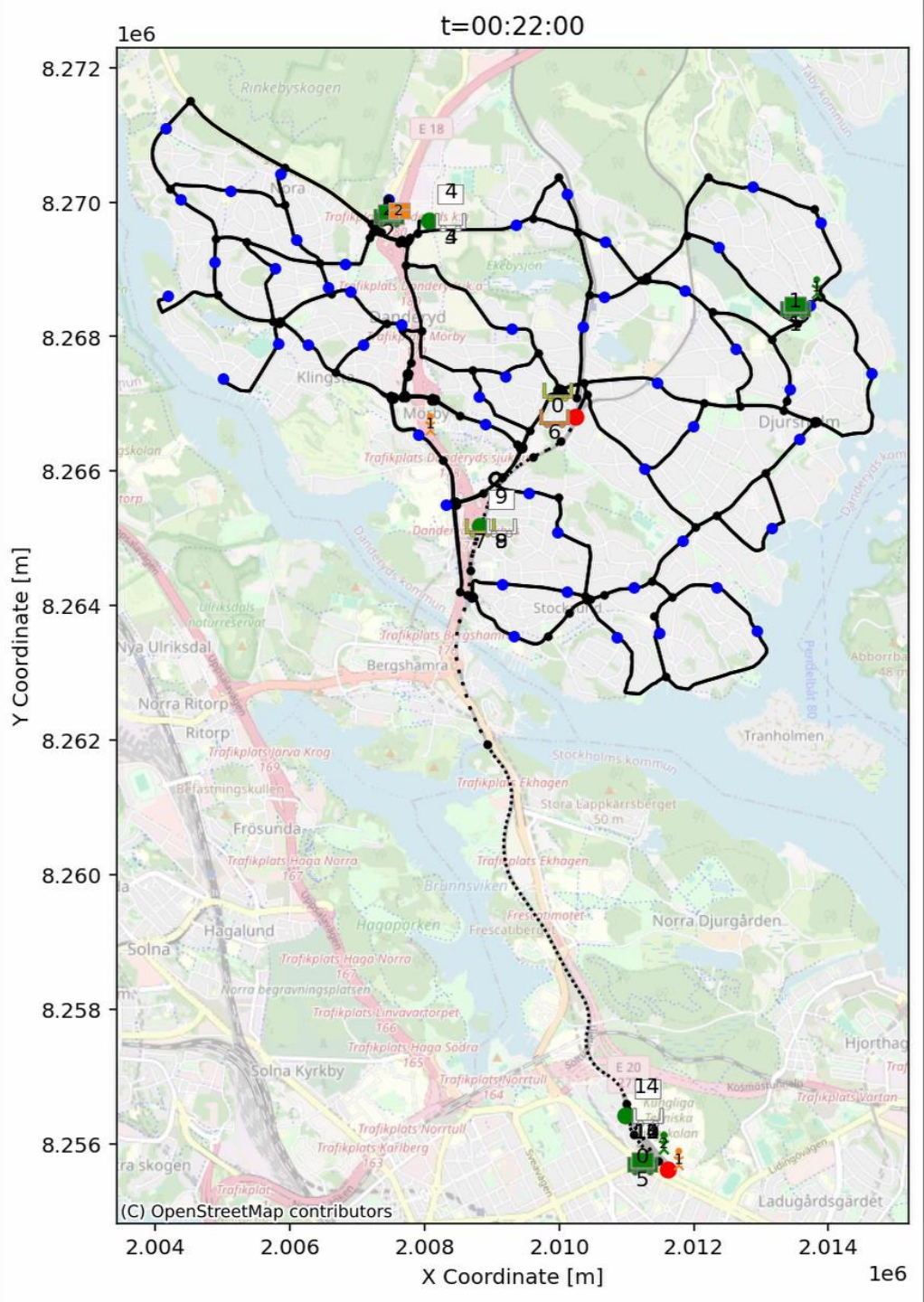
2. Animation of operations



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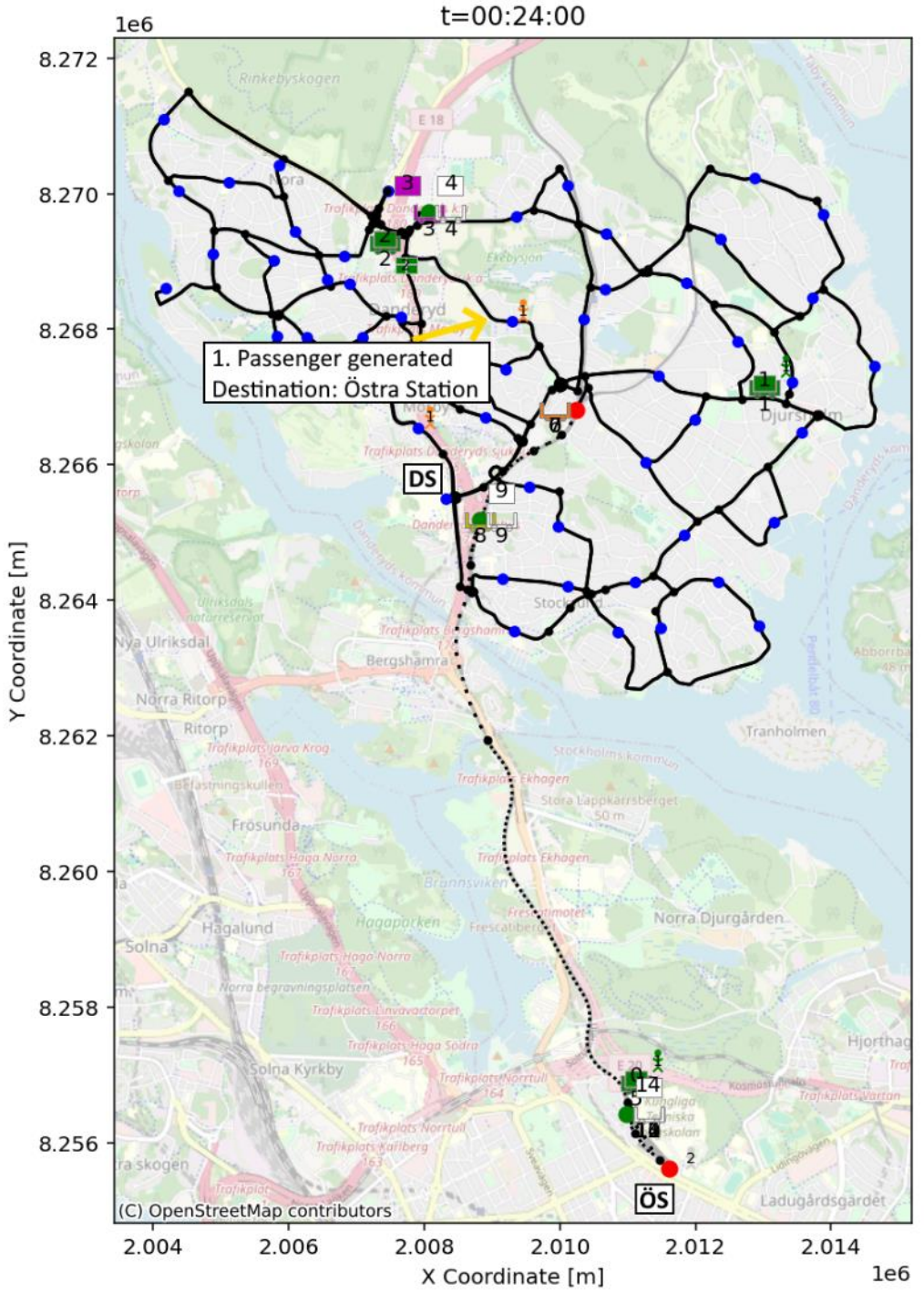
2. Animation of operations



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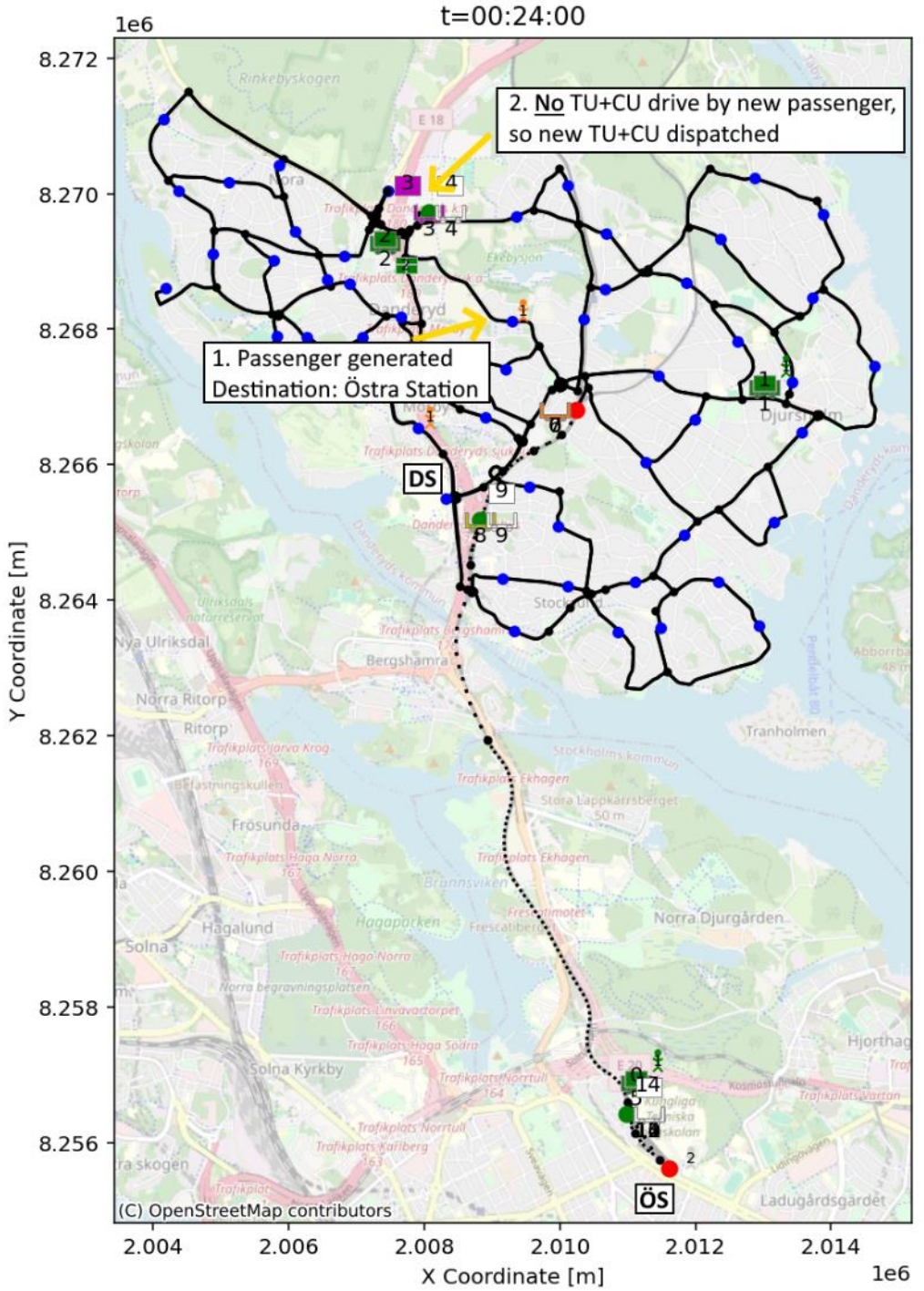
2. Animation of operations



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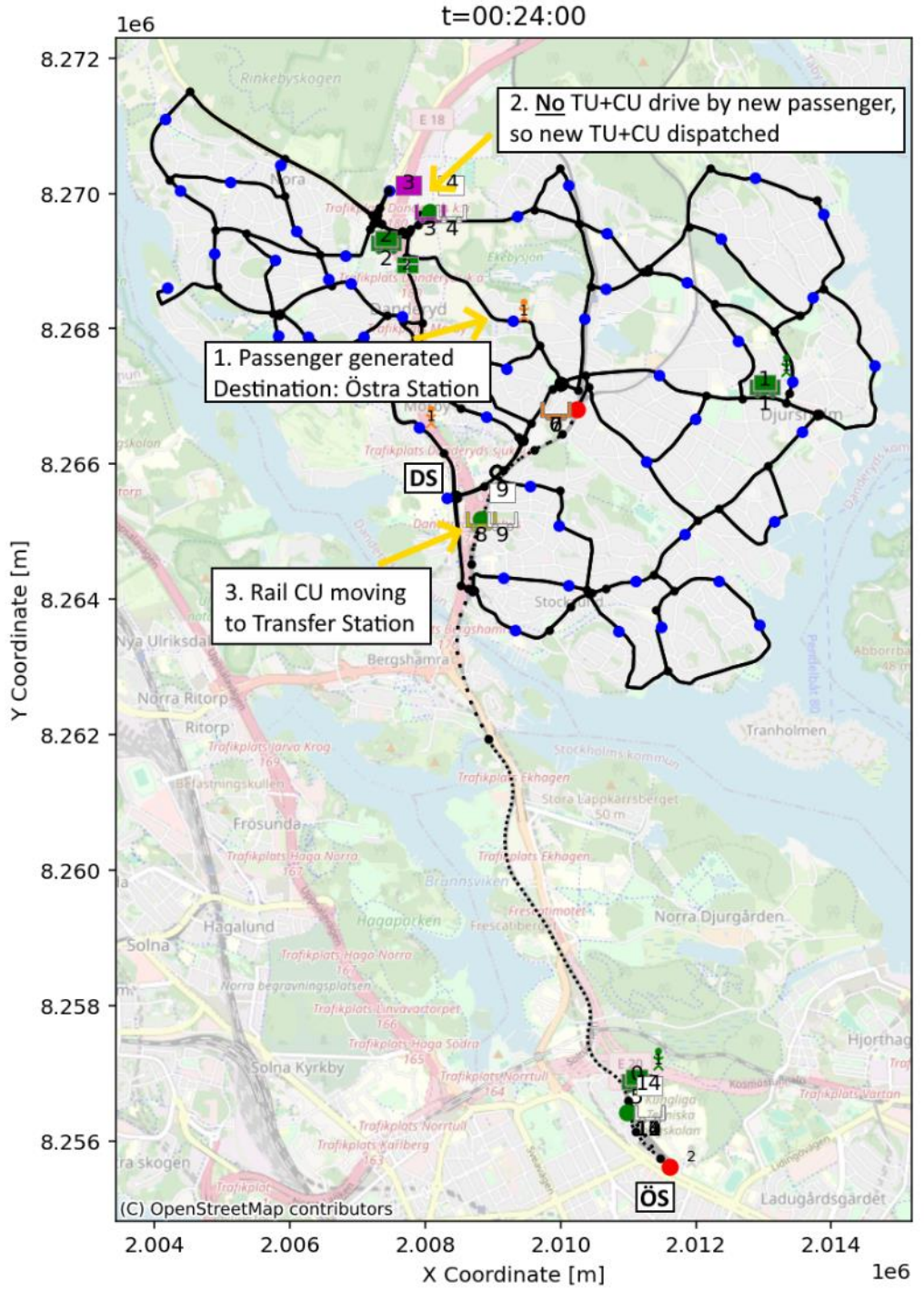

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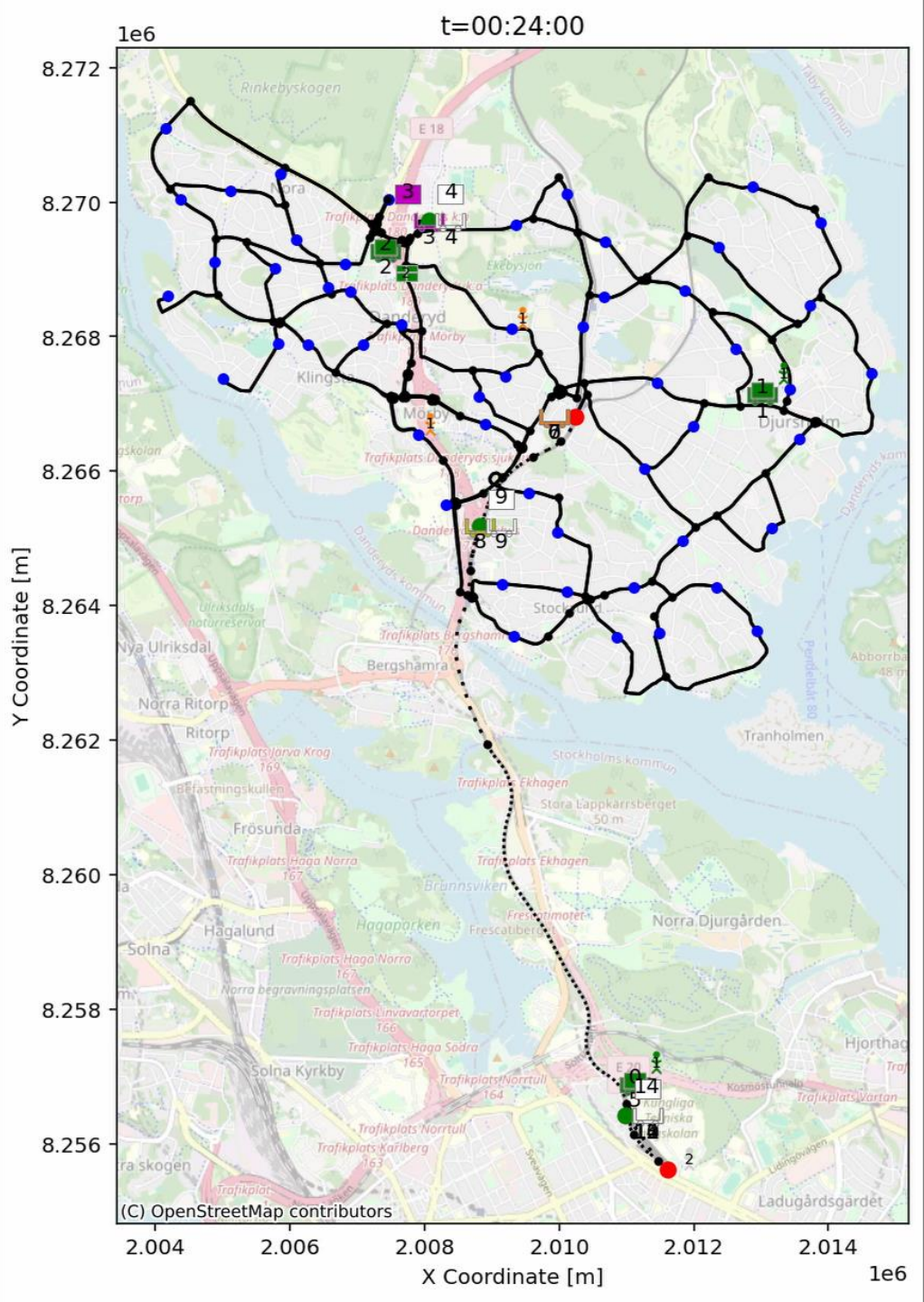
2. Animation of operations



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Thank You for Your Attention!

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