A novel metamodel-based framework for large-scale dynamic origin-destination demand calibration

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Origin-destination (OD) demand estimation & calibration

- OD demand estimation

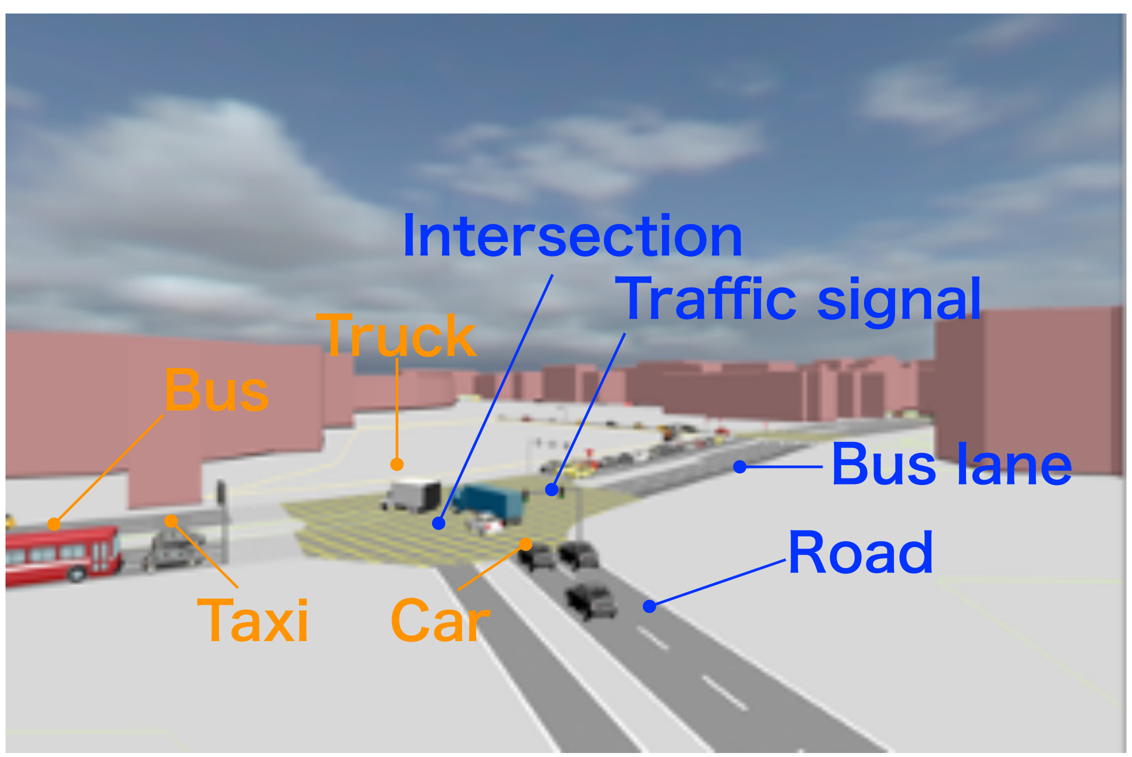
  Estimating general OD matrices for traffic planning and design

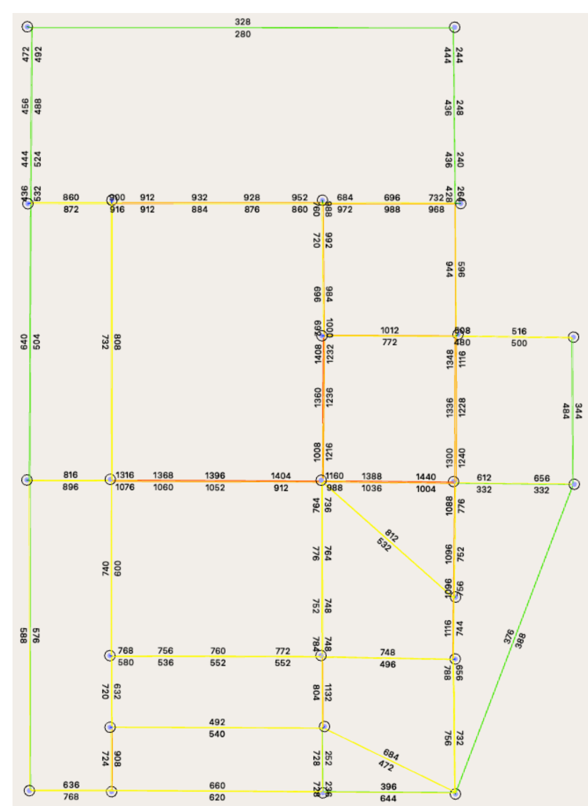
- OD demand calibration

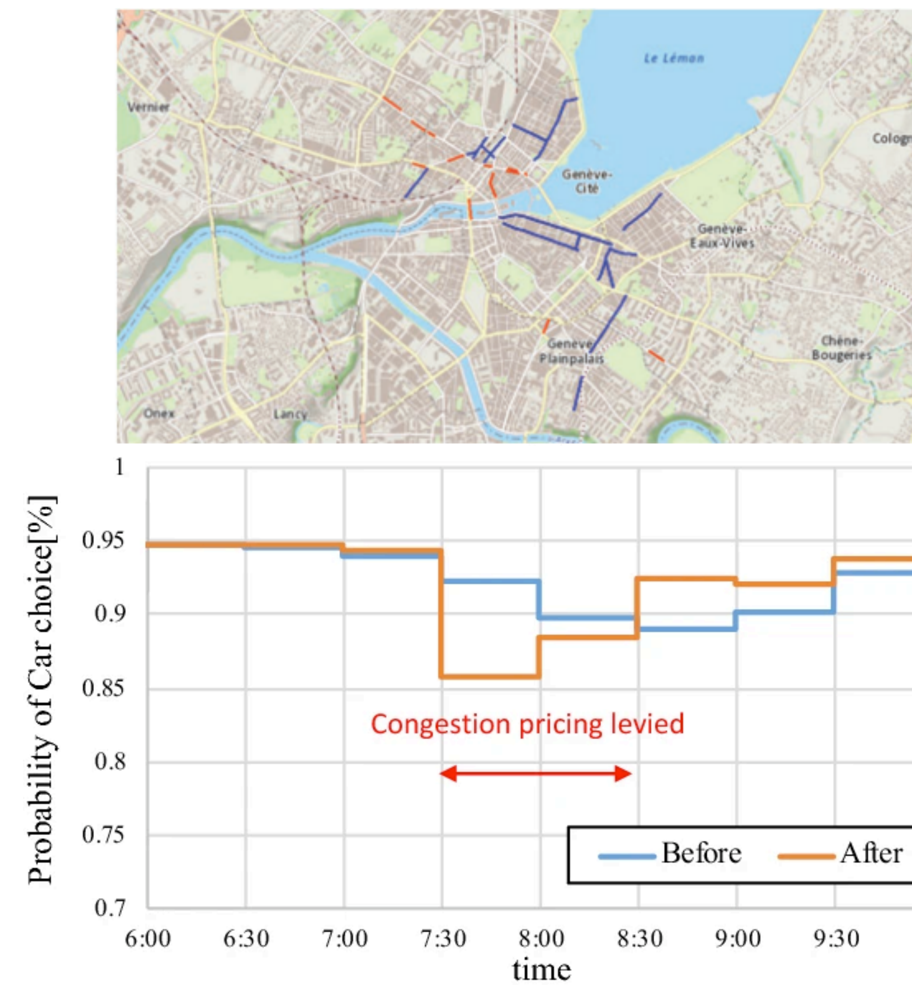
  Calibrating general OD matrices for a **stochastic traffic simulator**

Stochastic traffic simulation

- A tool to describe the complex interactions of many traffic components of the demand and supply sides
- What is **likely** to occur quantitatively
- Useful for policy makers to investigate the performance of the pre-determined policies

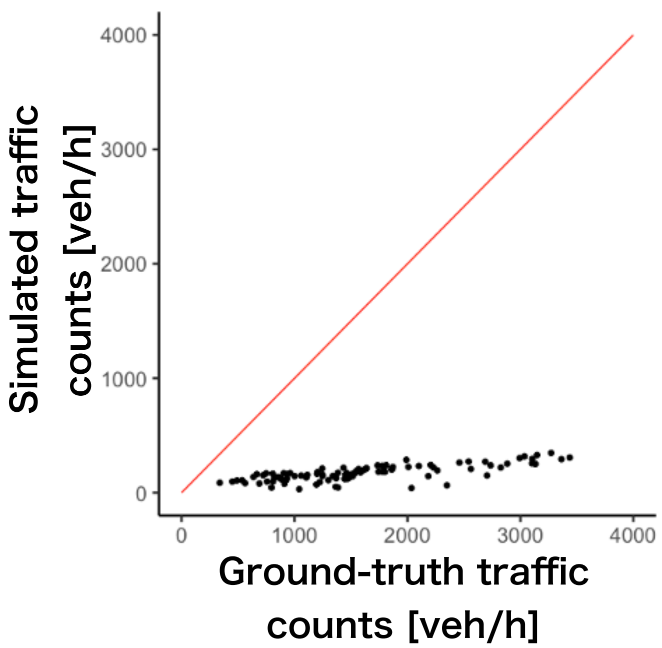






Zheng, Dantsuji, Wang and Geroliminis 2017, TRR
Dantsuji et al. 2021, Transportation

OD demand calibration

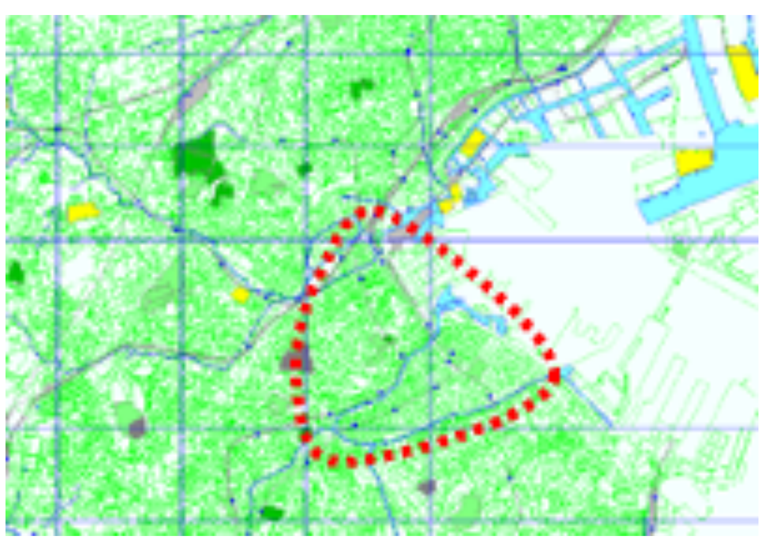


- The input for simulation (e.g., traffic demand) is a key component
    - Reliability of simulations
    - Calibration
- The general purpose algorithms (e.g., SPSA, GA, Kalman filter)
    - Applicable to a wide range of problems
    - The computational efficiency is not a priority
- Dynamic OD calibration for large-scale network is challenging
    - Computational efficiency
    - Scalability
- The lack of quantitatively methods to evaluate the calibration performance at large-scales
    - How to connect OD matrix with the complex traffic dynamics at aggregated levels

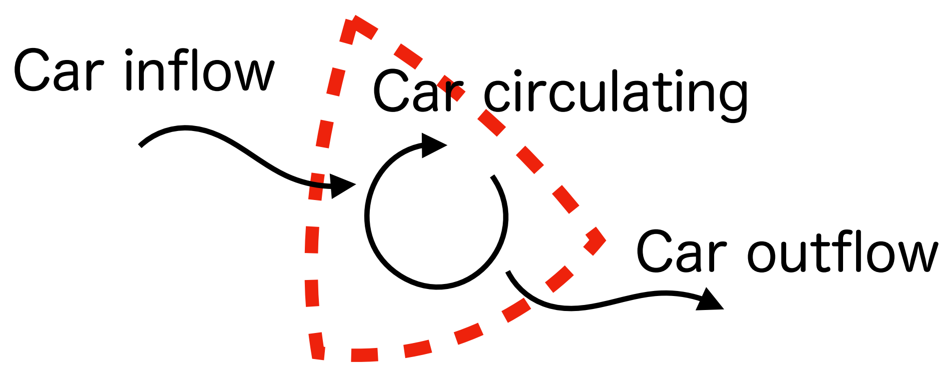
SPSA : Stochastic Perturbation Stochastic Approximation
GA : Genetic Algorithm

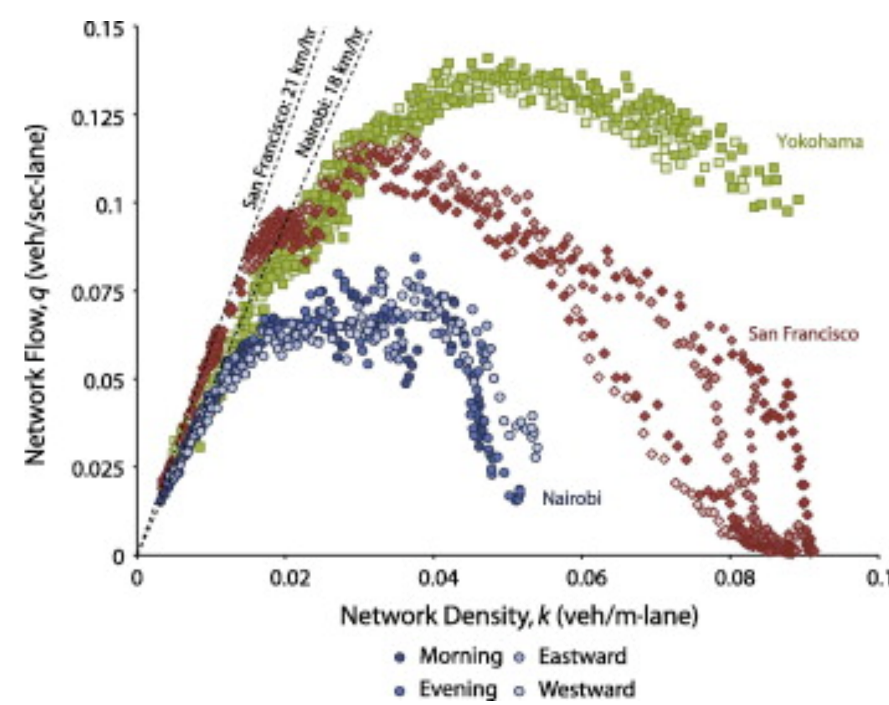
Macroscopic Fundamental Diagram (MFD)

- A traffic model at the network level
- The MFD relates the network flow to the network density (Daganzo, 2007)
- Some requirements for the well-defined MFD (Geroliminis and Daganzo, 2008)
    - Homogeneous congestion patter over space
    - Average trip length is constant over time



(Geroliminis and Daganzo, 2008)





(Gonzales et al., 2009)

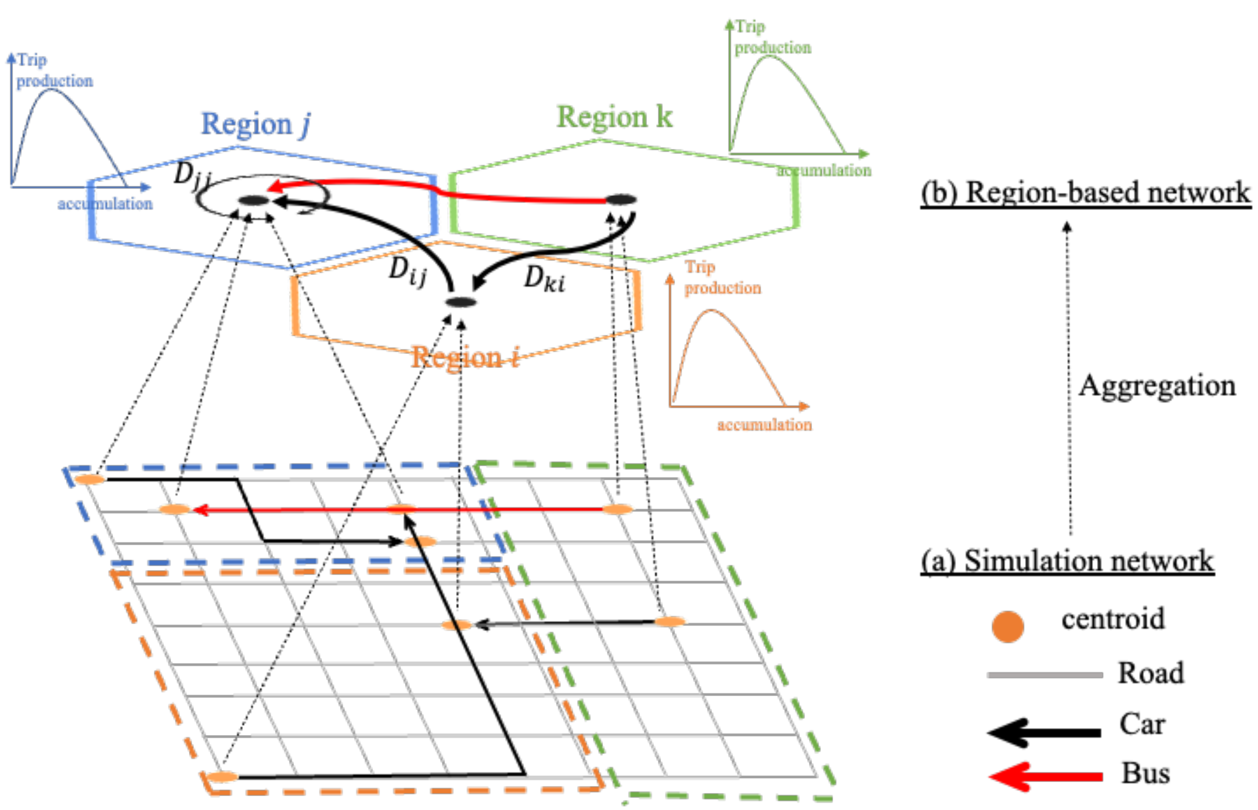
Contributions

- Propose a novel OD matrix calibration framework for large-scaled networks
    - aggregated traffic flow dynamics
    - metamodel optimization approach
- Utilize multiple data sources for deriving the ground-truth values
- Demonstrate the scalability, accuracy and efficiency

A simulation-based optimization with the MFD

- A simulation network is divided into N regions (e.g., Ji and Geroliminis, 2012)
- Traffic demand from centroids are aggregated to representative regional centroids
- Optimization problem for OD demand calibration

$$\min_{\mathbf{D}} \underbrace{\sum_{i\in I}\sum_{j\in I}\left(N_{i,t} - E[n^c_{i,t}(\mathbf{D}) + n^b_{i,t}(\mathbf{D})]\right)^2}_{\text{MSE in the total accumulations}} + \delta_1 \underbrace{\sum_{i\in I}\sum_{j\in I}(D^0_{i,j}(t) - D_{i,j}(t))^2}_{\text{Distance between initial and optimized demands}}$$



$\mathbf{D}$: vector of the regional car OD matrix

$N_{i,t}$: ground truth total accumulation in region i at time t

$n^c_{i,t}(\mathbf{D})$: Car accumulation in region i at time t from simulation with demand $\mathbf{D}$

$n^b_{i,t}(\mathbf{D})$: Bus accumulation in region i at time t from simulation with demand $\mathbf{D}$

$D^0_{i,j}(t)$: Initial demand generated in region i with final destination j at time t

$D_{i,j}(t)$: demand generated in region i with final destination j at time t

δ_1 : weight factor

High-dimensional problem

- Dimension as the size of the problem is $I \times I \times T$
  - I, T : number of regions, time steps
- Even for a small-scale network (e.g. 3 regions, 15 time steps), the dimension is 135
- Calibration of the aggregated OD matrices is still high-dimensional problem
- Running multiple replications of the simulation is expensive
- An efficient algorithm that require **a few iterations** has to be developed

Metamodel optimization

- A model of the models : simpler deterministic approximating function
- The proposed metamodel optimization

Simulation-based optimization $\min_{\mathbf{D}} \sum_{i \in I} \sum_{j \in I} \left(N_{i,t} - E[n^c_{i,t}(\mathbf{D}) + n^b_{i,t}(\mathbf{D})] \right)^2 + \delta_1 \sum_{i \in I} \sum_{j \in I} (D^0_{i,j}(t) - D_{i,j}(t))^2$

Metamodel parameter

Metamodel optimization $\min_{\mathbf{D}} \; f_1(\mathbf{D}; \beta) + \delta_1 \sum_{i \in I} \sum_{j \in I} (D^0_{i,j}(t) - D_{i,j}(t))^2$

analytical model

- The objective function estimate is produced with low computational burden

Metamodel Optimization

- Analytical macroscopic traffic flow model (Zheng and Geroliminis, 2013; Yildirimoglu et al., 2015)

$$f_1(\mathbf{D};\beta) = \sum_{i\in I}\sum_{t\in T}\left(N_{i,t} - \left(n_i^c(t) + n_i^b(t)\right)\right)^2$$

Number of vehicles

$$n_i^c(t) = \beta_{i,t}\sum_{j\in J} n_{i,j}^c(t)$$

Conservation law

$$n_{i,j}^c(t+1) = \begin{cases} n_{i,i}^c(t) + D_{i,i}(t) + \sum_{k\in V_i}\hat{M}_{k,i}^i(t) - O_{i,i}(t) & \text{if } i = j \\ n_{i,j}^c(t) + D_{i,j}(t) + \sum_{k\in V_i}\hat{M}_{k,j}^i(t) - \sum_{k\in V_k}\hat{M}_{i,j}^k(t) & \text{if } i \neq j \end{cases}$$

Capaciated inflow

$$\hat{M}_{i,j}^k(t) = \min[M_{i,j}^k(t), C_{i,k}(n_k^c(t), n_k^b(t))]$$

Inflow

$$M_{i,j}^k(t) = \sum_{r\in R} P_r(t) O_{i,j}(t)$$

Outflow

$$O_{i,j}(t) = \frac{n_{i,j}^c(t) v_i(t)}{L_i}$$

Regional choices probability

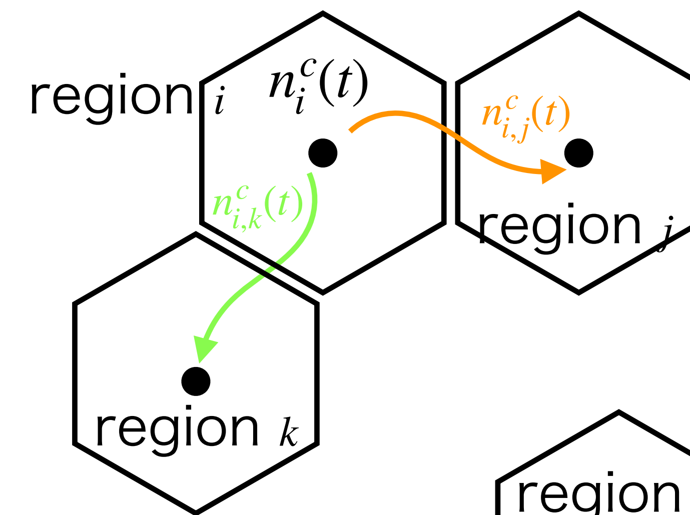
$$P_r(t) = \frac{e^{\theta TT_r(t)}}{\sum_{l\in L} e^{\theta TT_l(t)}}$$

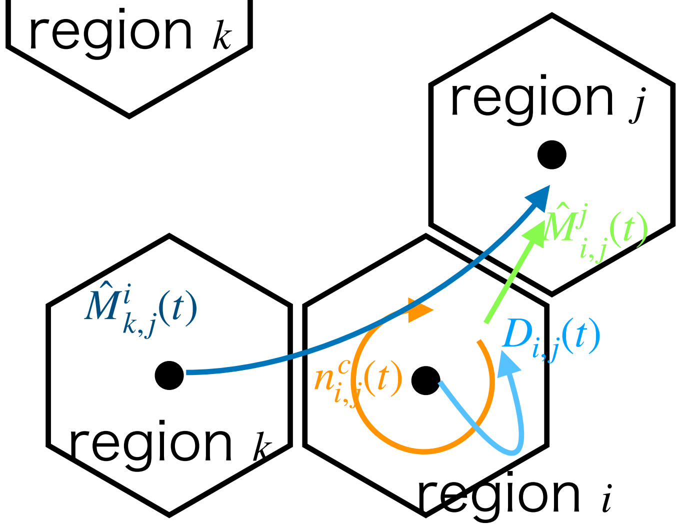
Average travel time

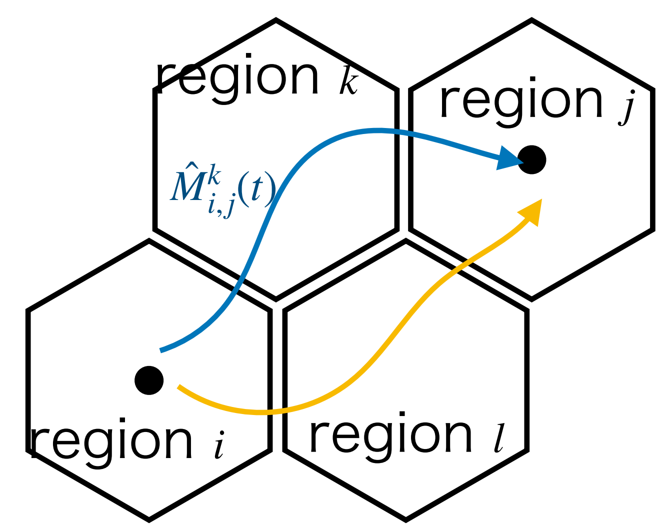
$$TT_i(t) = \frac{L_i}{v_i(t)}$$

Average travel speed

$$v_i(t) = a_i + a_i^c n_i^c(t) + a_i^b n_i^b(t)$$







Update of the metamodel parameters

- The heterogeneity exists in the trip lengths or congestion patterns over spaces

  (Buisson and Ladier, 2009; Mazloumian et al., 2010; Sun and Geroliminis, 2011)

- Gaps between the simulated and the analytical accumulations

- To fill the gaps, the metamodel parameters are adjusted

analytical accumulation of sample s

adjusting parameter at iteration h

$$\min_{\boldsymbol{\eta}^h} \sum_{s \in S} w_h(\mathbf{D}_s) \sum_{i \in I} \sum_{t \in T} \left(\eta_{i,t}^h \beta_{i,t}^{h-1} n_{i,s}^c(t) - E[n_{i,t}^c(\mathbf{D_s})] \right)^2 + w_0 \sum_{i \in I} \sum_{t \in T} (\eta_{i,t}^h - 1)^2$$

a set of samples — metamodel parameter at iteration $h-1$ — simulated accumulation of sample s

Subject to

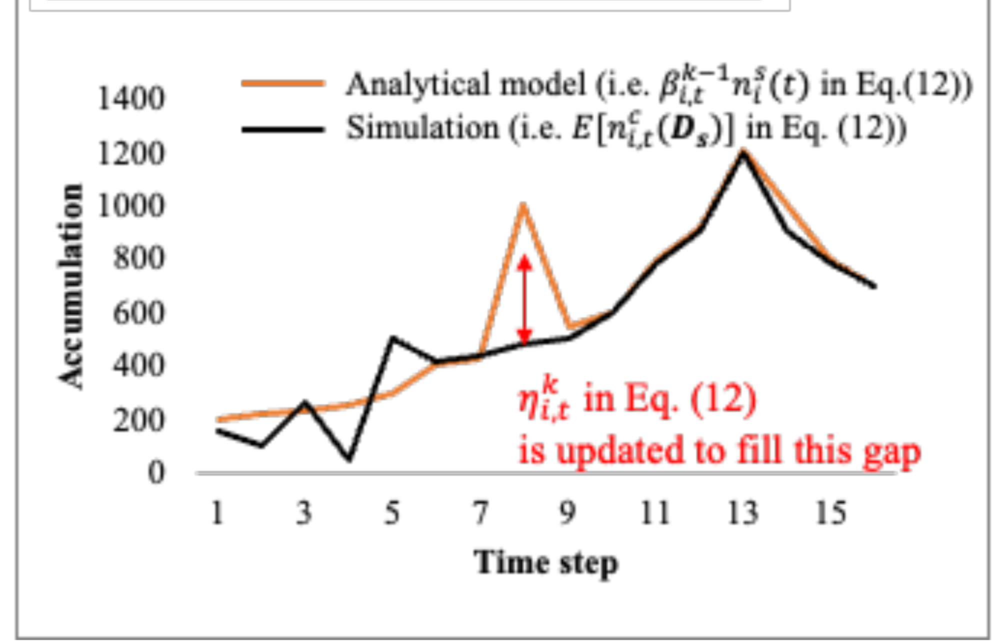
$$\beta_{i,t}^l \le \eta_{i,t}^h \beta_{i,t}^{h-1} \le \beta_{i,t}^u$$

metamodel parameter at next iteration

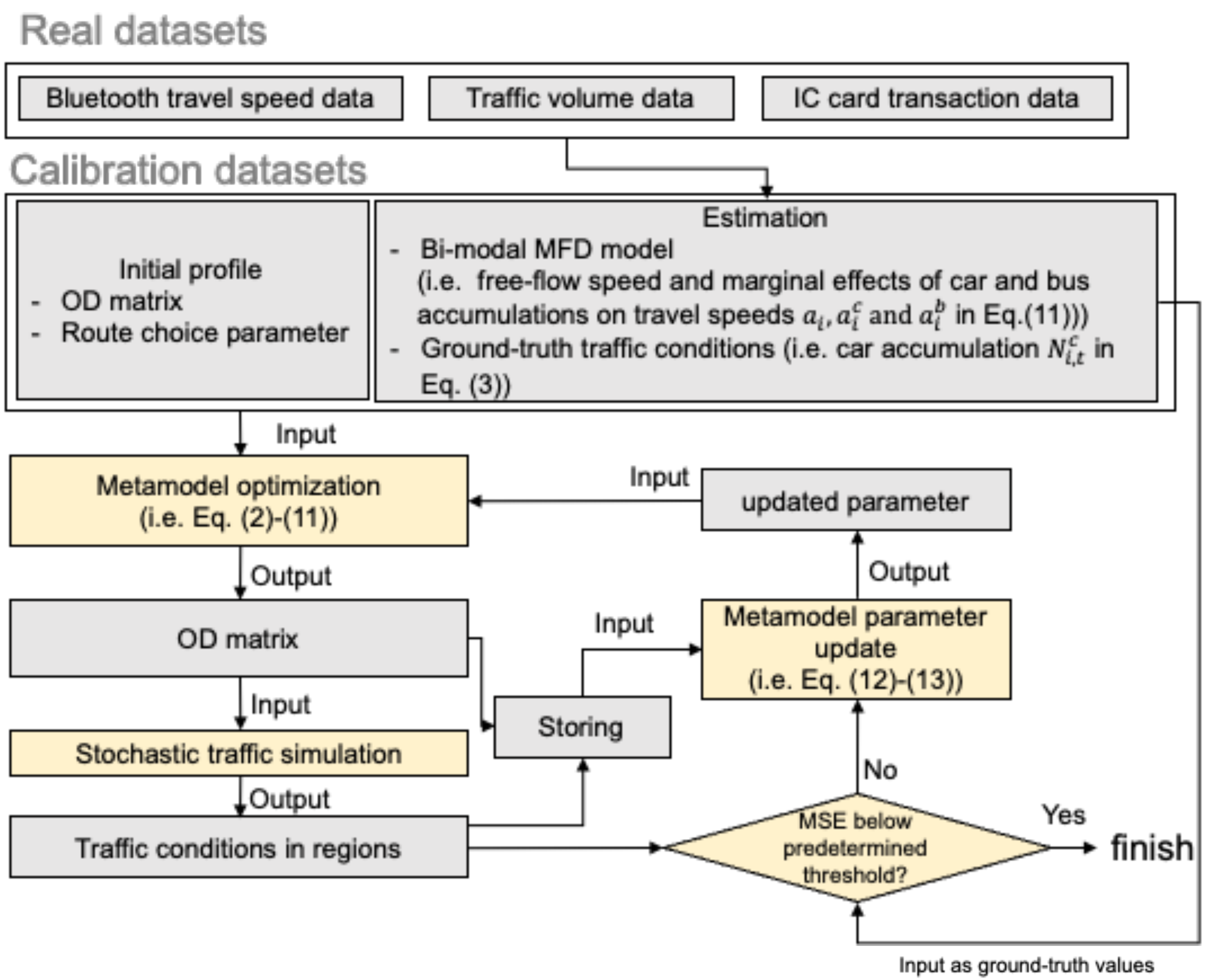
- Weight $w_h(\mathbf{D}_s)$

$$w_h(\mathbf{D}_s) = \frac{1}{1 + c\,||\mathbf{D}_s - \mathbf{D}_h||}$$

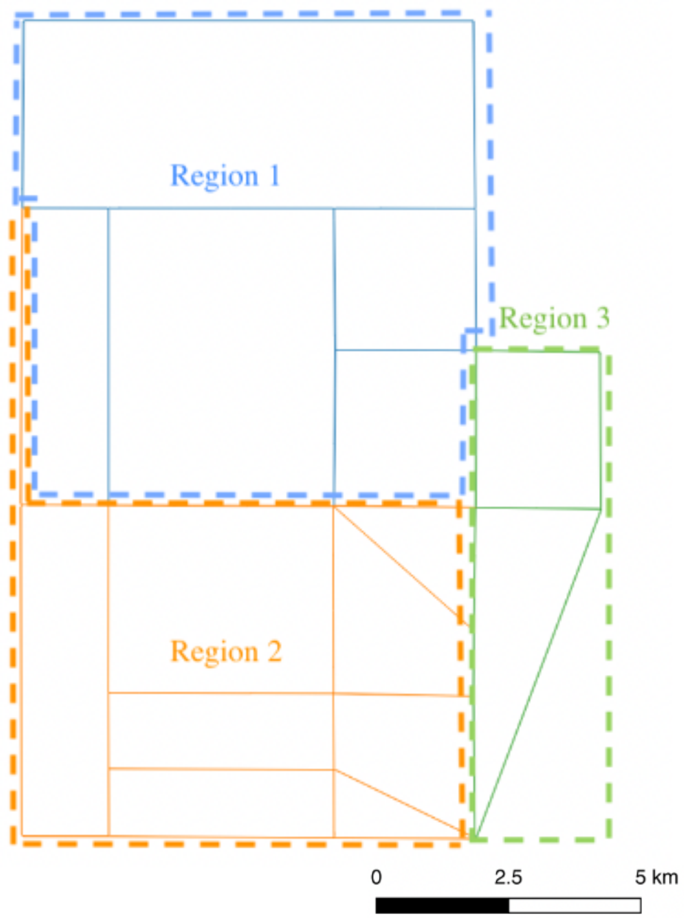
Concept of metamodel parameter update



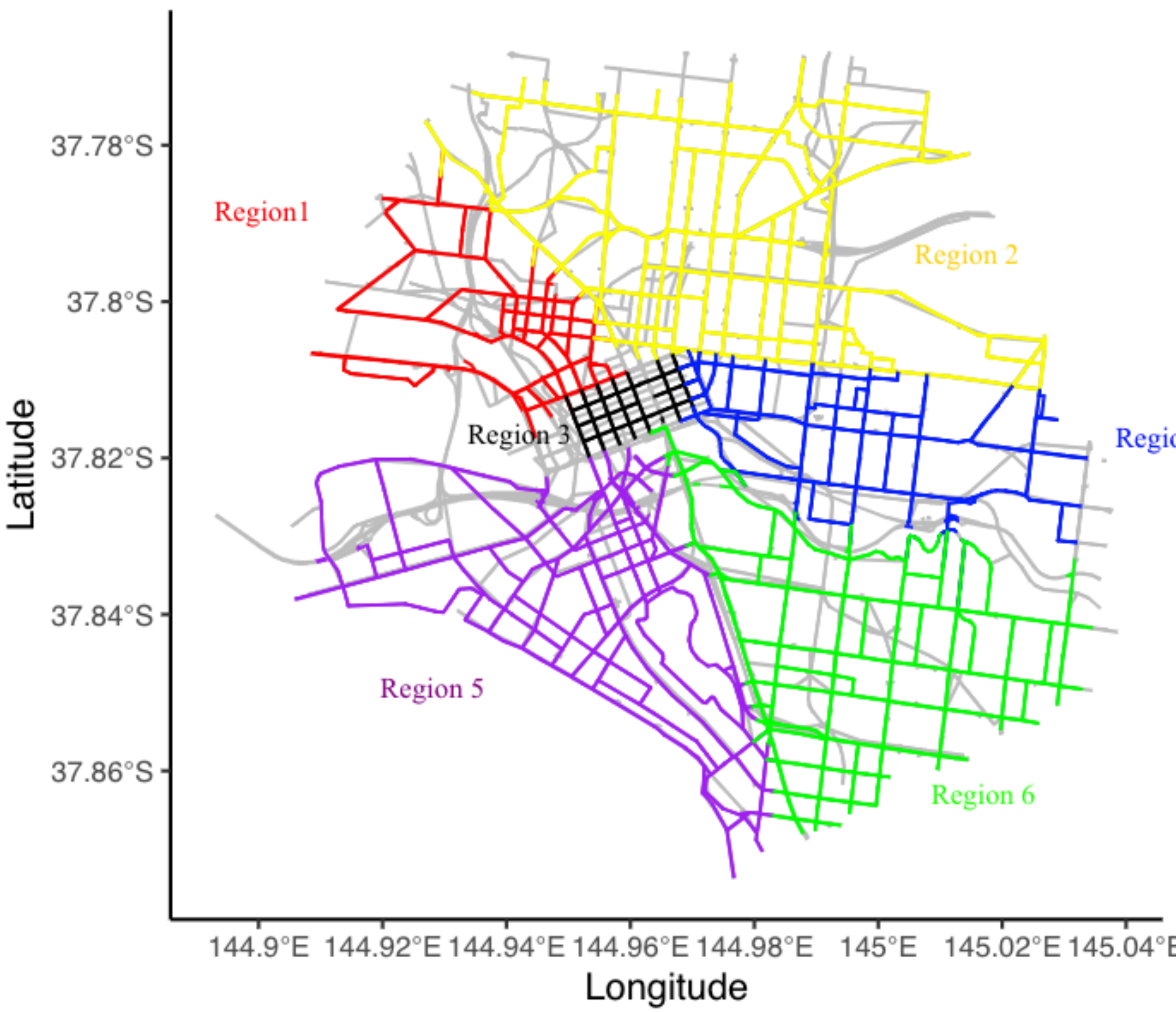
Calibration framework



Sioux-falls (SF) network



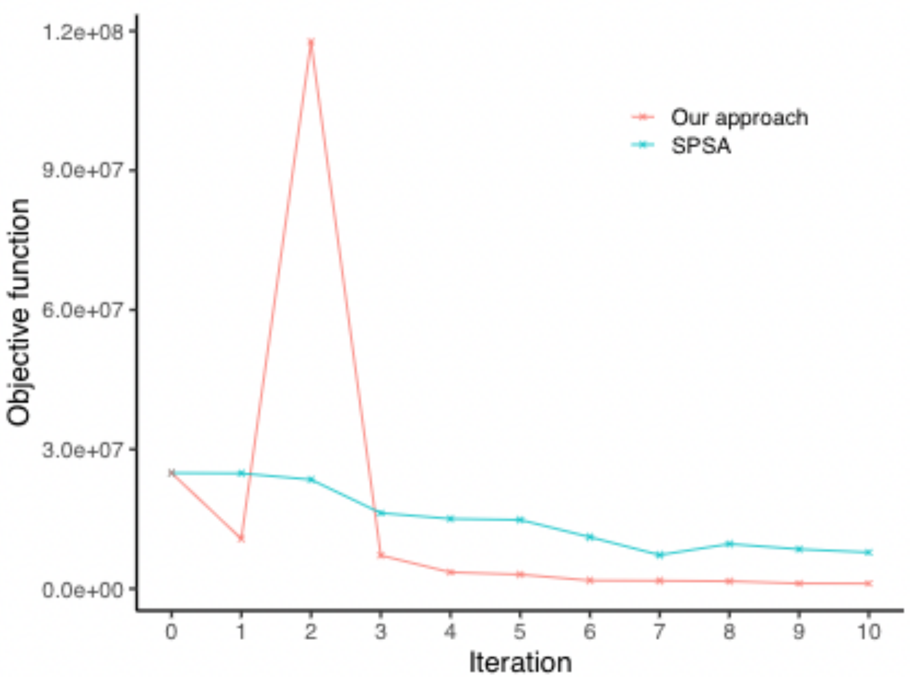
Melboune CBD network



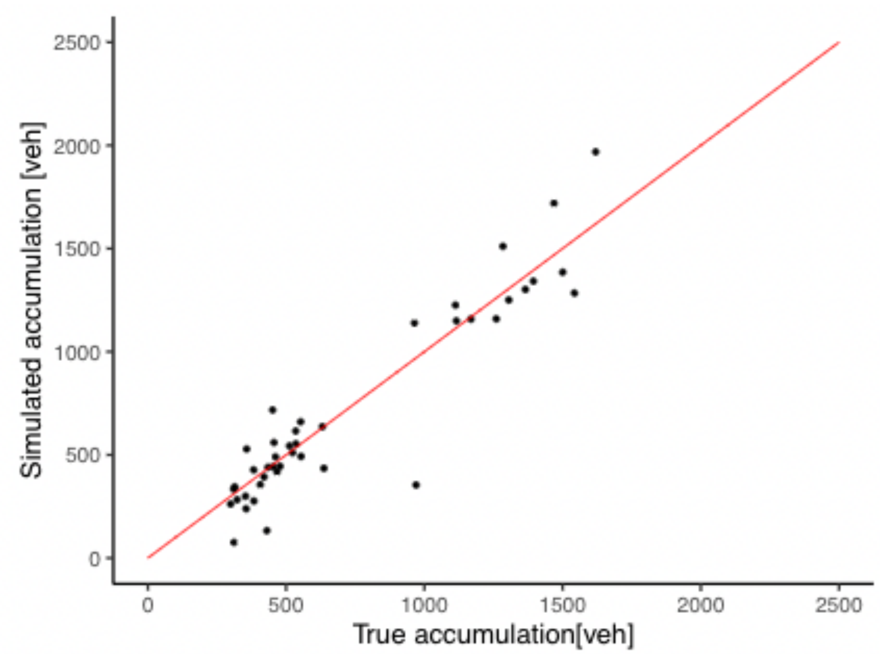
Validation with the SF network

- The performance of the proposed approach and SPSA
  - A few iterations are needed to understand the direction of parameters' adjustment
  - After 5th iteration, the objective function estimated becomes stable over iterations

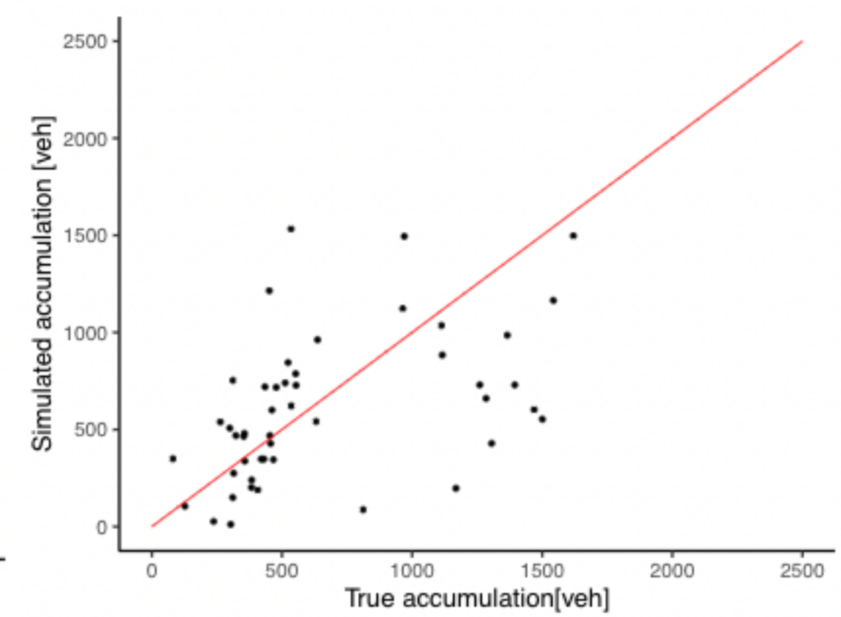
Obj. function estimated



The proposed approach

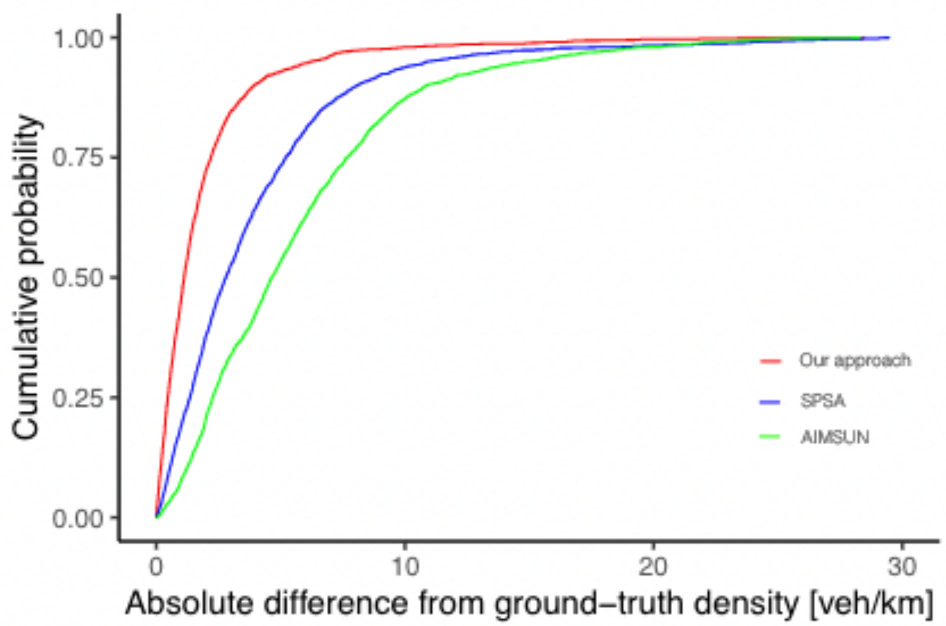


SPSA

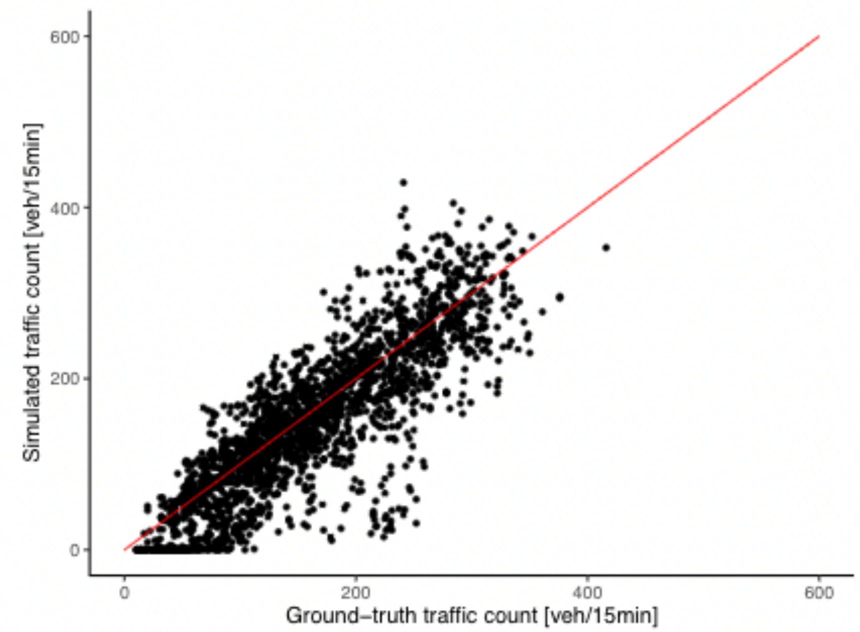


Validation with the SF network - link level comparison

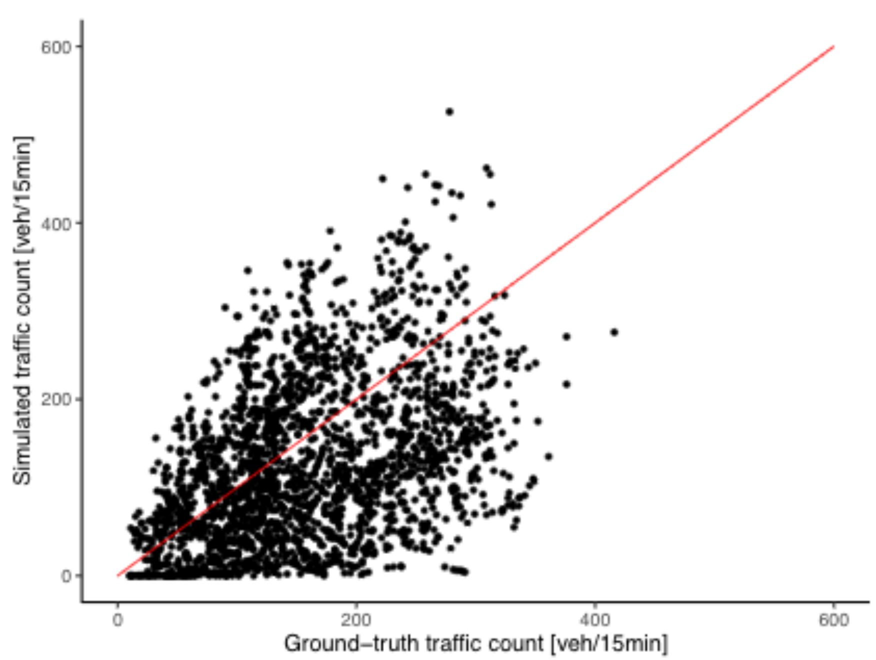
Comparison at 10 iteration



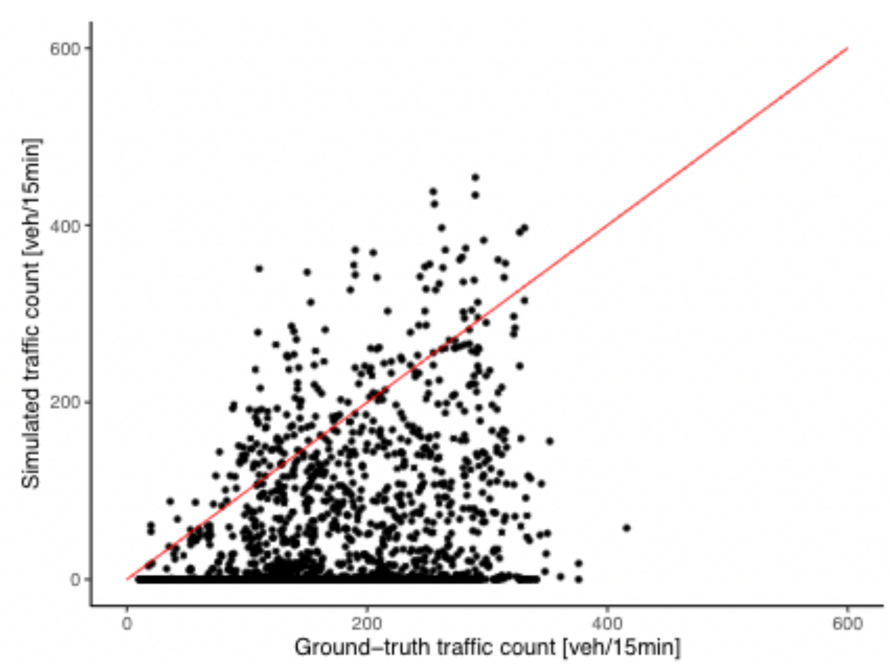
The proposed approach at 10th iteration



SPSA at 10th iteration

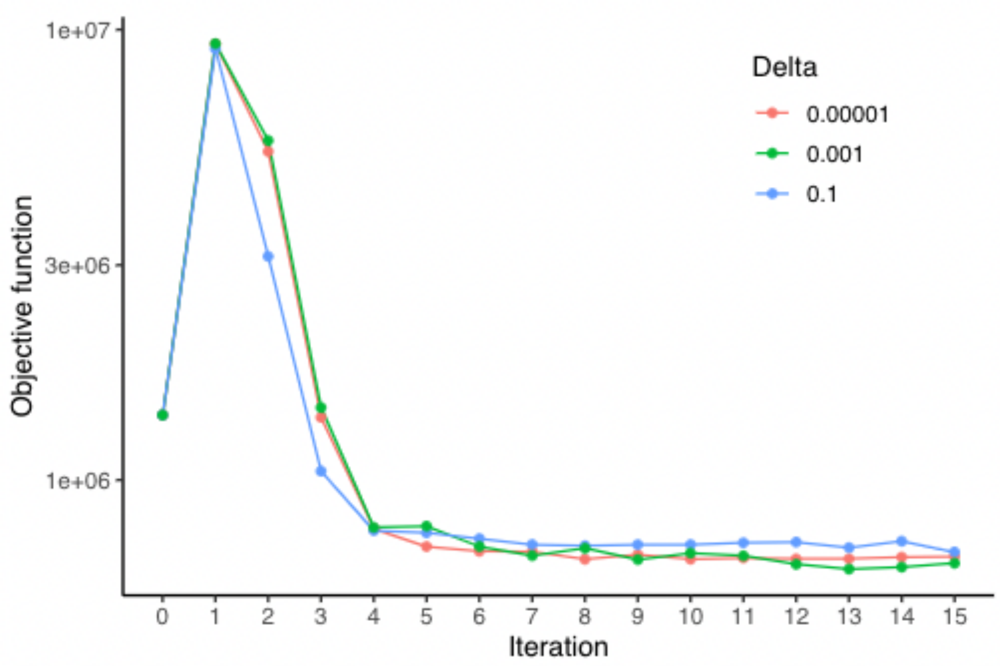


Aimsun at 10th iteration

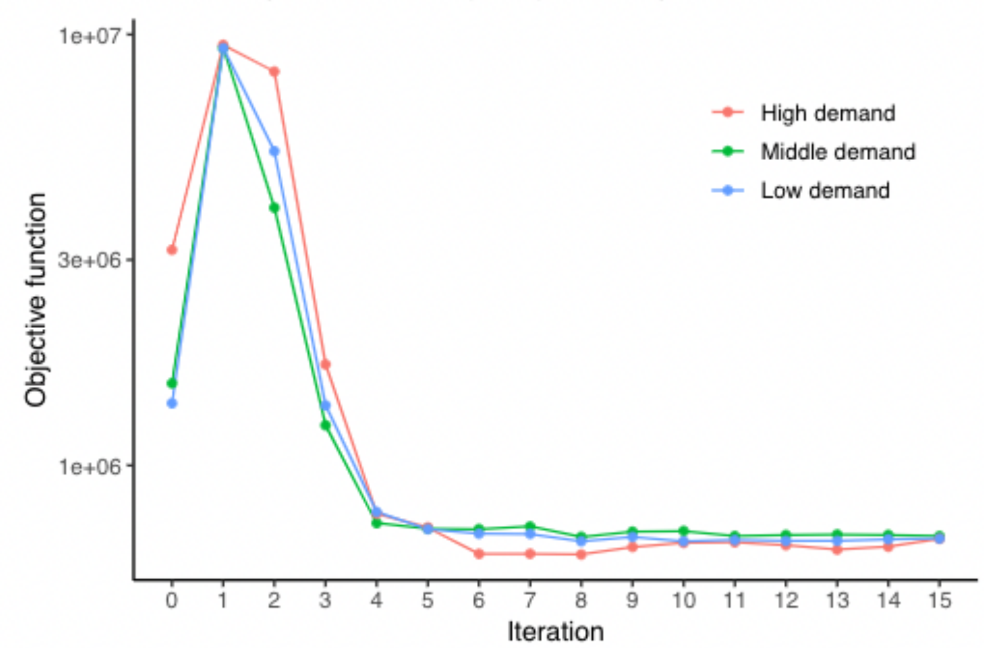


Sensitivity analysis with the SF network

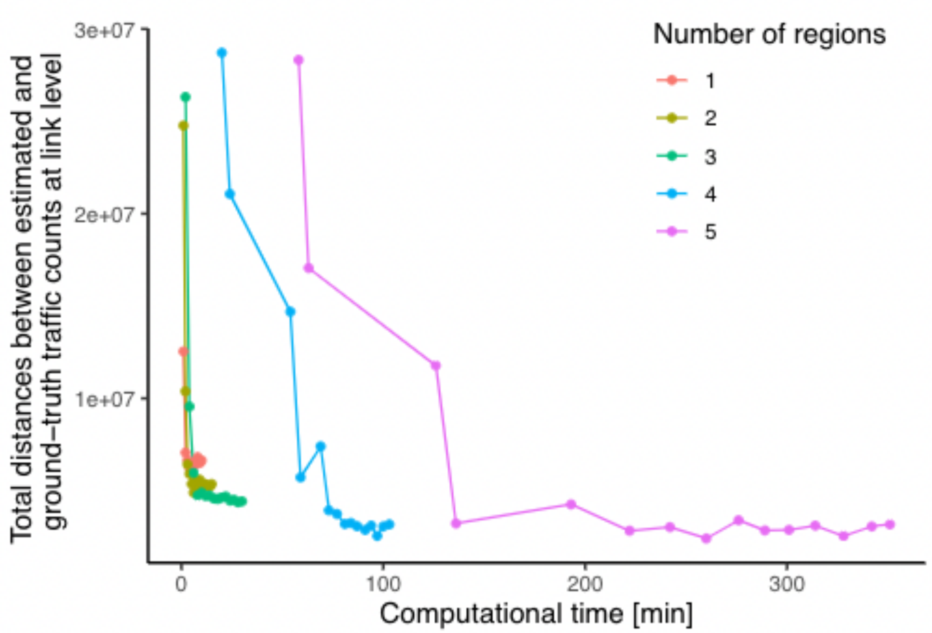
Sensitivity analysis on weight factor



Sensitivity analysis on initial demand



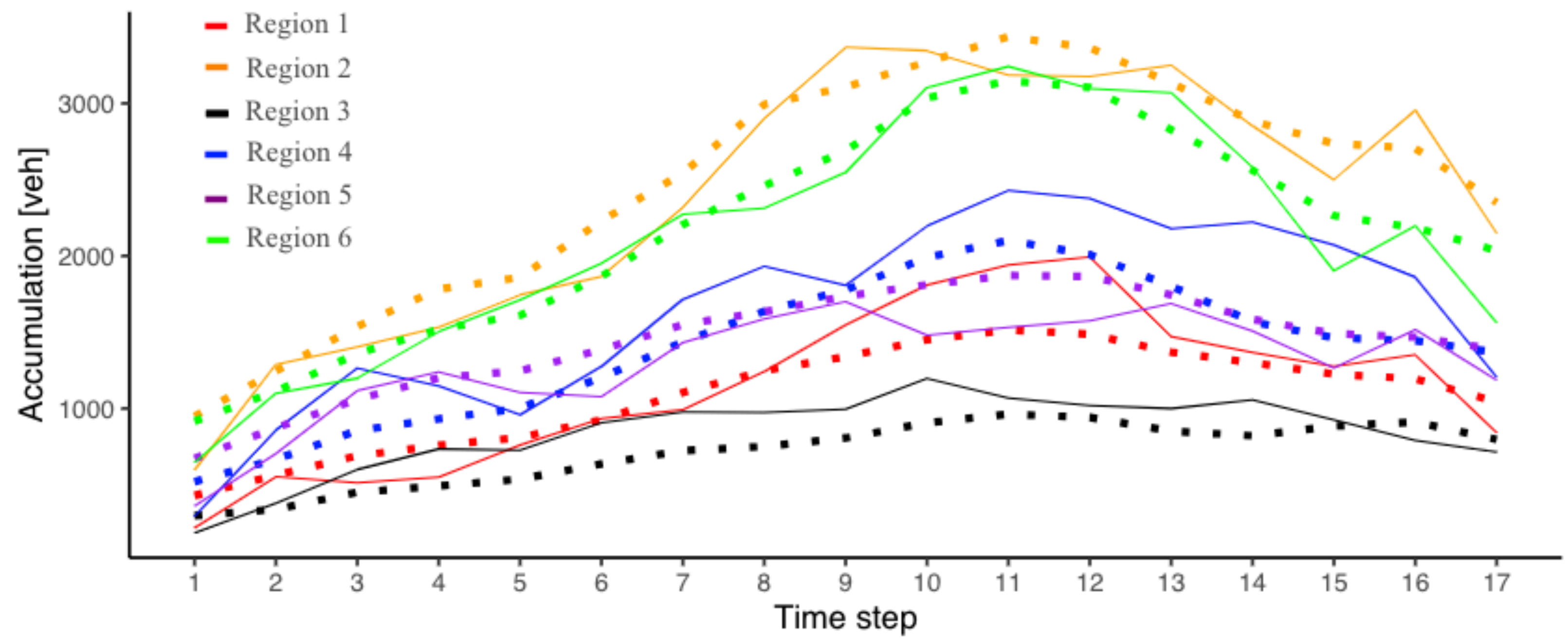
Sensitivity analysis on number of regions



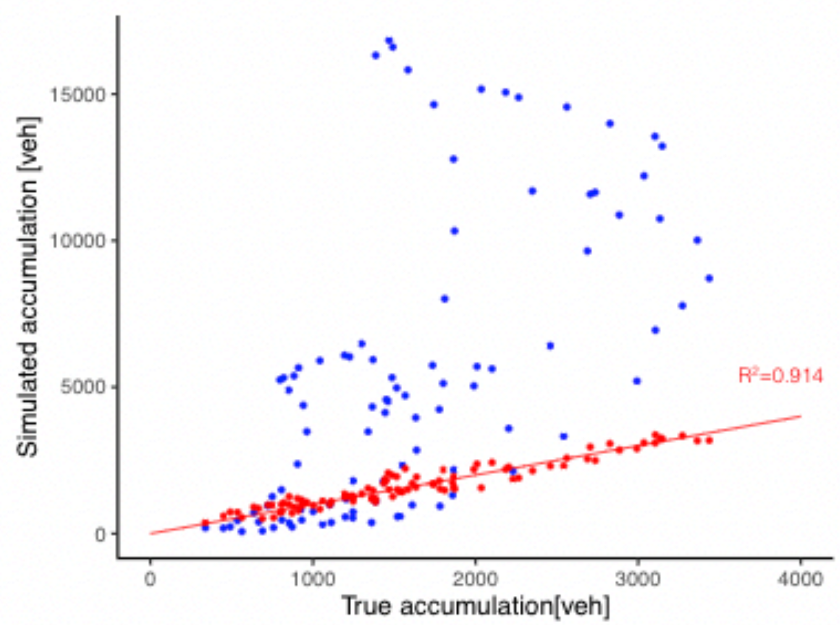
Case study - Melbourne CBD

- Data for grand-truth values
  - SCATS data
  - Bluetooth travel time
  - IC smart card (Myki data)

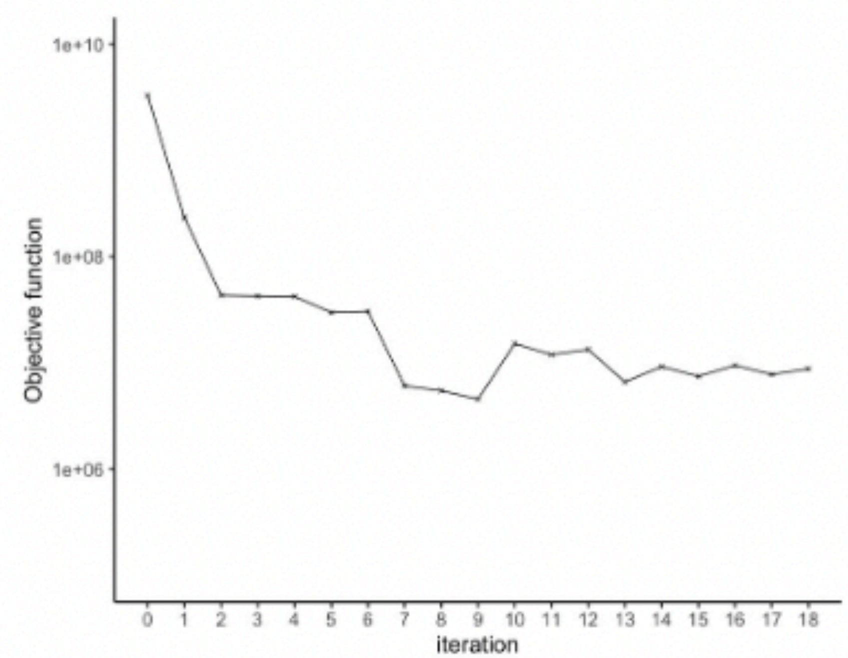
Ground-truth (dotted) and simulated (solid) accumulations



Initial (blue) & simulated (red)



Obj. function estimated



Conclusions & future directions

Conclusions

- Developed a computationally efficient metamodel optimization framework for the OD demand calibration of large-scaled networks
- Utilized the region-based traffic dynamics as an analytical model of the metamodel
- Tested the proposed approach with two case studies

Future directions

- Extend to other optimization problems such as dynamic congestion pricing

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