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

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 pattern over space
  - Average trip length is constant over time

(Geroliminis and Daganzo, 2008)
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

\[
\min_{\mathbf{D}} \sum_{i \in I} \sum_{j \in I} \left( N_{i,t} - E[n_{i,t}^c(\mathbf{D}) + n_{i,t}^b(\mathbf{D})] \right)^2 + \delta_1 \sum_{i \in I} \sum_{j \in I} (D_{i,j}^0(t) - D_{i,j}(t))^2
\]

**MSE in the total accumulations**

**Distance between initial and optimized demands**

**D** : vector of the regional car OD matrix
- \( N_{i,t} \) : ground truth total accumulation in region \( i \) at time \( t \)
- \( n_{i,t}^c(\mathbf{D}) \) : Car accumulation in region \( i \) at time \( t \) from simulation with demand \( \mathbf{D} \)
- \( n_{i,t}^b(\mathbf{D}) \) : Bus accumulation in region \( i \) at time \( t \) from simulation with demand \( \mathbf{D} \)
- \( D_{i,j}^0(t) \) : 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 \( t \)
- \( \delta_1 \) : 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

\[
\min_D \sum_{i \in I} \sum_{j \in I} \left( N_{i,t} - E[n_{i,t}^c(D) + n_{i,t}^b(D)] \right)^2 + \delta \sum_{i \in I} \sum_{j \in I} (D_{i,j}(t) - D_{i,j}(t))^2
\]

Metamodel optimization

\[
\min_D f_1(D; \beta) + \delta_1 \sum_{i \in I} \sum_{j \in I} (D_{i,j}^0(t) - D_{i,j}(t))^2
\]

- 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)

\[
f_i(\mathbf{D}, \beta) = \sum_{i \in I} \sum_{t \in T} \left( N_{i,t} - \left( n^c_{i,t}(t) + n^b_{i,t}(t) \right) \right)^2
\]

\[
n^c_{i,t}(t) = \beta_{i,t} \sum_{j \in J} n^c_{i,j}(t)
\]

\[
n^c_{i,t}(t + 1) = \begin{cases} n^c_{i,i}(t) + D_{i,i}(t) + \sum_{k \in V_i} \hat{M}^k_{i,k}(t) - O_{i,i}(t) & \text{if } i = j \\ n^c_{i,j}(t) + D_{i,j}(t) + \sum_{k \in V_i} \hat{M}^k_{i,j}(t) - \sum_{k \in V_i} \hat{M}^k_{j,i}(t) & \text{if } i \neq j \end{cases}
\]

\[
\hat{M}^k_{i,j}(t) = \min[M^k_{i,j}(t), C_{i,k}(n^c_{i,k}(t), n^b_{i,k}(t))]
\]

\[
M^k_{i,j}(t) = \sum_{r \in R} P_r(t) O_{i,j}(t)
\]

\[
O_{i,j}(t) = \frac{n^c_{i,j}(t)v_i(t)}{L_i}
\]

\[
P_r(t) = \frac{e^{\theta T T_i(t)}}{\sum_{l \in L} e^{\theta T T_i(t)}}
\]

\[
T T_i(t) = \frac{L_i}{v_i(t)}
\]

\[
v_i(t) = a_i + a^c n^c_i(t) + a^b n^b_i(t)
\]
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

  \[
  \min_{\eta^h} \sum_{s \in S} w_h(D_s) \sum_{i \in I} \sum_{t \in T} \left( \eta^h_{i,t} \beta_i^{h-1} n^c_{i,s}(t) - E[n^c_{i,t}(D_s)] \right)^2 + w_0 \sum_{i \in I} \sum_{t \in T} (\eta^h_{i,t} - 1)^2
  \]

  Subject to

  \[
  \beta^l_{i,t} \leq \eta^h_{i,t} \beta_i^{h-1} \leq \beta^u_{i,t}
  \]

  . Weight \( w_h(D_s) \)

  \[
  w_h(D_s) = \frac{1}{1 + c \left| ||D_s - D_h|| \right|}
  \]
Calibration framework

Real datasets
- Bluetooth travel speed data
- Traffic volume data
- IC card transaction data

Calibration datasets
- Initial profile
  - OD matrix
  - Route choice parameter
- Estimation
  - Bi-modal MFD model
    (i.e. free-flow speed and marginal effects of car and bus accumulations on travel speeds $a^c_t$, $a^b_t$ and $a^b_t$ in Eq.(11)))
  - Ground-truth traffic conditions (i.e. car accumulation $N^{c}_{i,t}$ in Eq. (3))

Input
- Metamodel optimization
  (i.e. Eq. (2)-(11))

Output
- OD matrix

Input
- Stochastic traffic simulation

Output
- Traffic conditions in regions

Input
- Metamodel parameter update
  (i.e. Eq. (12)-(13))

Storing

MSE below predetermined threshold?

Yes
- finish

No

Input as ground-truth values
Case studies

Sioux-falls (SF) network

Melbourne CBD 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**

- Delta
  - 0.00001
  - 0.001
  - 0.1

**Sensitivity analysis on initial demand**

- High demand
- Middle demand
- Low demand

**Sensitivity analysis on number of regions**

- Number of regions
  - 1
  - 2
  - 3
  - 4
  - 5

Objective function vs Iteration graphs for each scenario.
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
References