Dynamics of congested urban rail transit: a macroscopic model with demand and supply interaction

需要供給統合化マクロモデルを用いた都市鉄道の混雑ダイナミクス解析

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1. Background & Objective

- **Urban rail transit: severe congestion & chronic delays**
  - Delay and passenger congestion can easily develop into vicious circle during peak hours (chronic delays)
- **Necessity of flattening concentrated demand**
  - To enhance system supply of rail transit becomes very difficult in many cases
- **Lack of appropriate model considering interaction between demand & supply**
  - Most studies treated demand as given information
- **Objectives**
  1. To comprehensively understand passenger congestion influence on rail transit operation
  2. To build a macroscopic model estimating equilibrium distribution of passenger arrivals
  3. To derive insights into effectiveness of probable management strategies by proposed model

2. Model Formulation

- Passenger travel cost UC

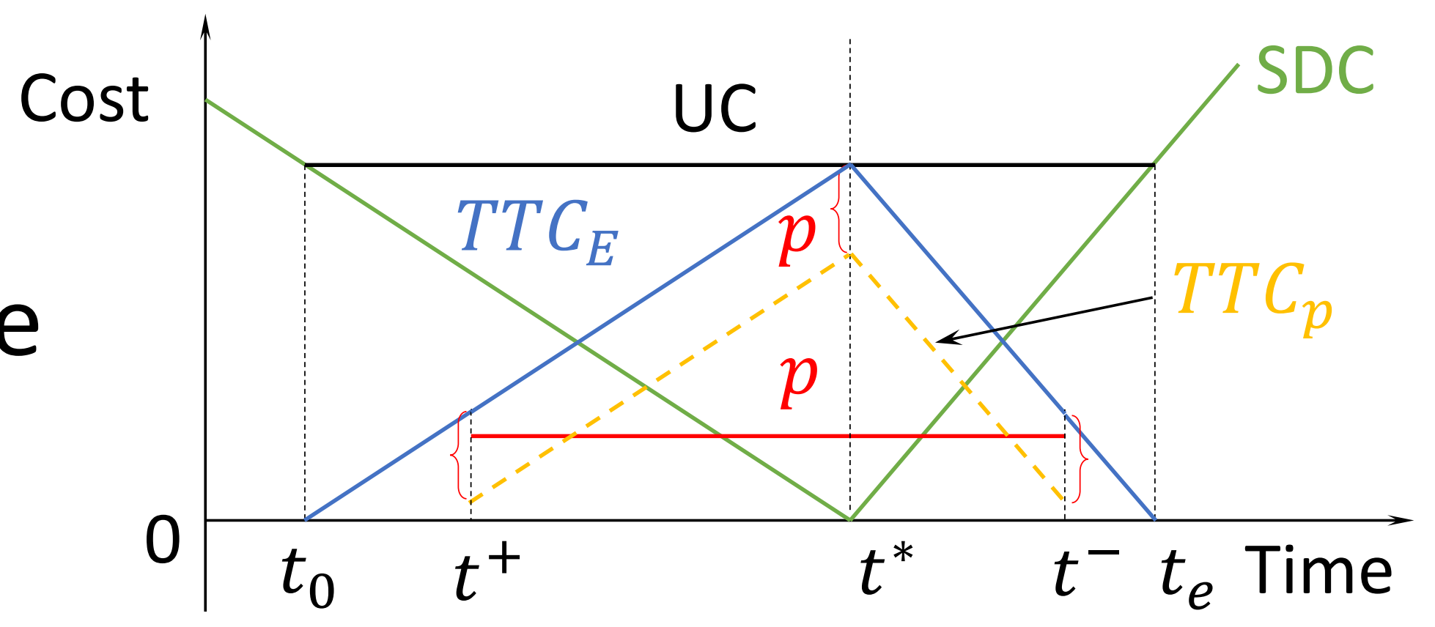
$$UC(t,t_i^*)=\underbrace{\alpha\left(T(t)-T_0\right)}_{\text{Travel time cost (TTC)}}+\underbrace{s\left(t,t_i^*\right)}_{\text{Schedule delay cost (SDC)}}+\underbrace{p(t)}_{\text{Monetary cost}}$$

- Equilibrium state

$$\frac{\partial UC}{\partial t}\left(t_i,t_i^*\right)=0$$

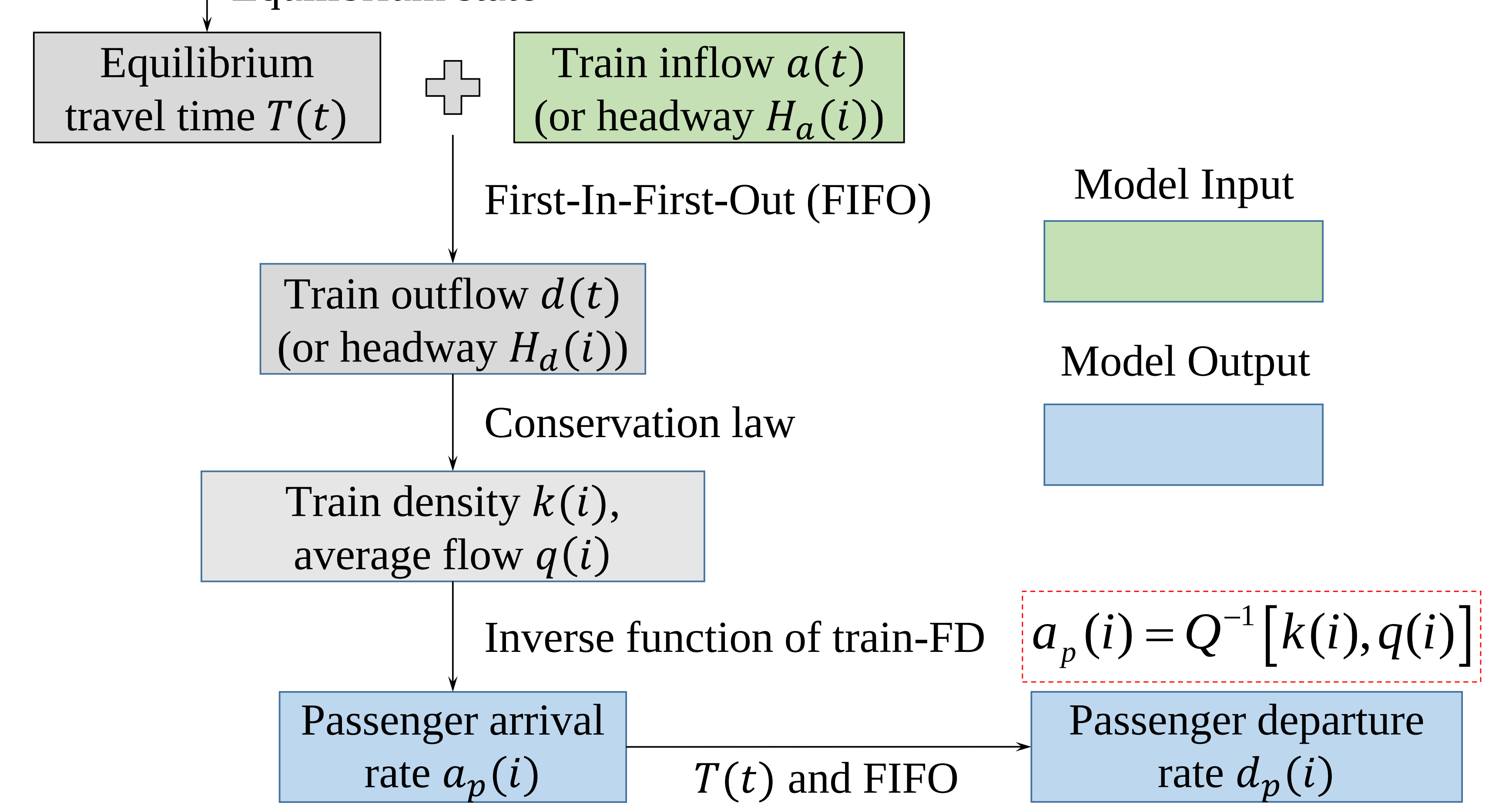
- Dynamic model conceptual structure

Travel costs under equilibrium state



Travel cost assumption

Equilibrium state



Equilibrium travel time $T(t)$

Train inflow $a(t)$ (or headway $H_a(i)$)

First-In-First-Out (FIFO)

Train outflow $d(t)$ (or headway $H_d(i)$)

Conservation law

Train density $k(i)$, average flow $q(i)$

Inverse function of train-FD

$a_p(i)=Q^{-1}\left[k(i),q(i)\right]$

Passenger arrival rate $a_p(i)$

$T(t)$ and FIFO

Passenger departure rate $d_p(i)$

Model Input

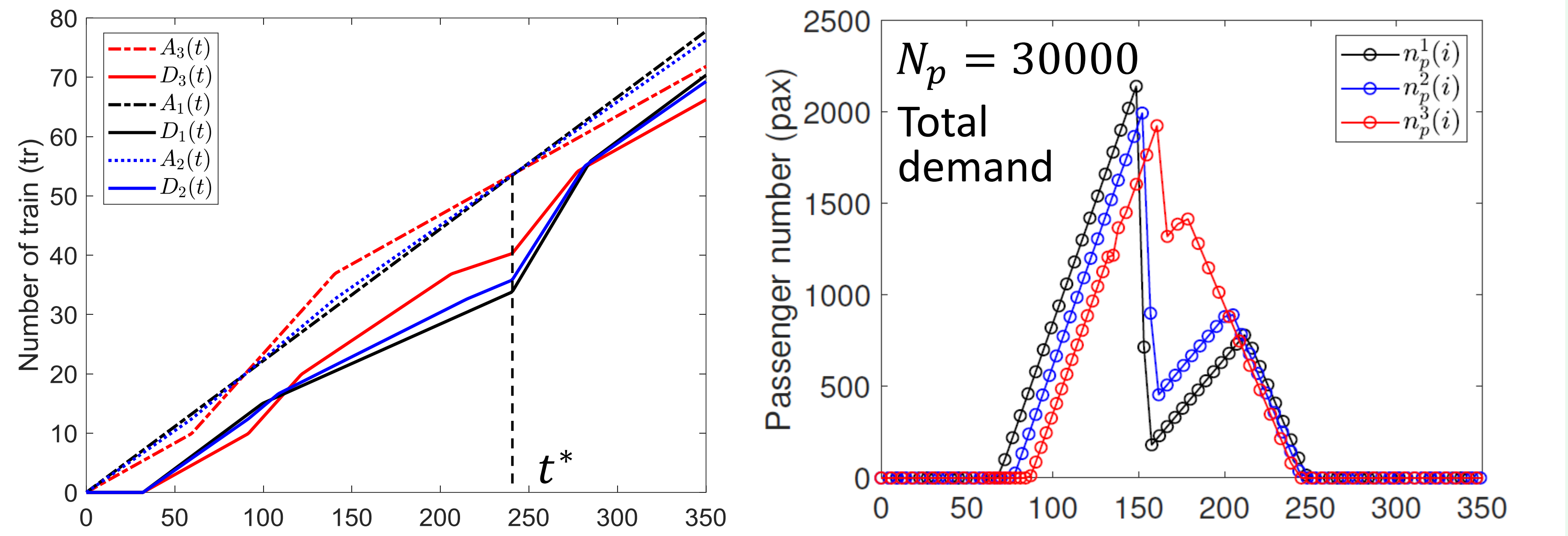
Model Output

5. Conclusions

- Rightness of conventional peak/off-peak timetable can be well-interpreted by the proposed model.
- Effectiveness of coarse pricing evaluated and found to strongly depend on temporal settings.
- Pareto improvement found to exist if properly applying both surcharge and reward during commute period

3. Application: peak/off-peak timetable

- Comparison of constant & peak/off-peak timetable



Cumulative curves of trains

Riding passenger on each train

$$n_p(i)=a_p(i)\cdot\frac{H_a(i)+H_d(i)}{2}$$

- From operator view, larger/smaller $a(t)$ before/after $t^* - T(t^*)$ raised/reduced $d(t)$. As a result, system performance $q(t)$ variation due to passenger influence alleviated
- From passenger view, higher frequency led to fewer passengers on each train before t^*, thus less dwell time needed. As a result, travel time decreased compared to constant case

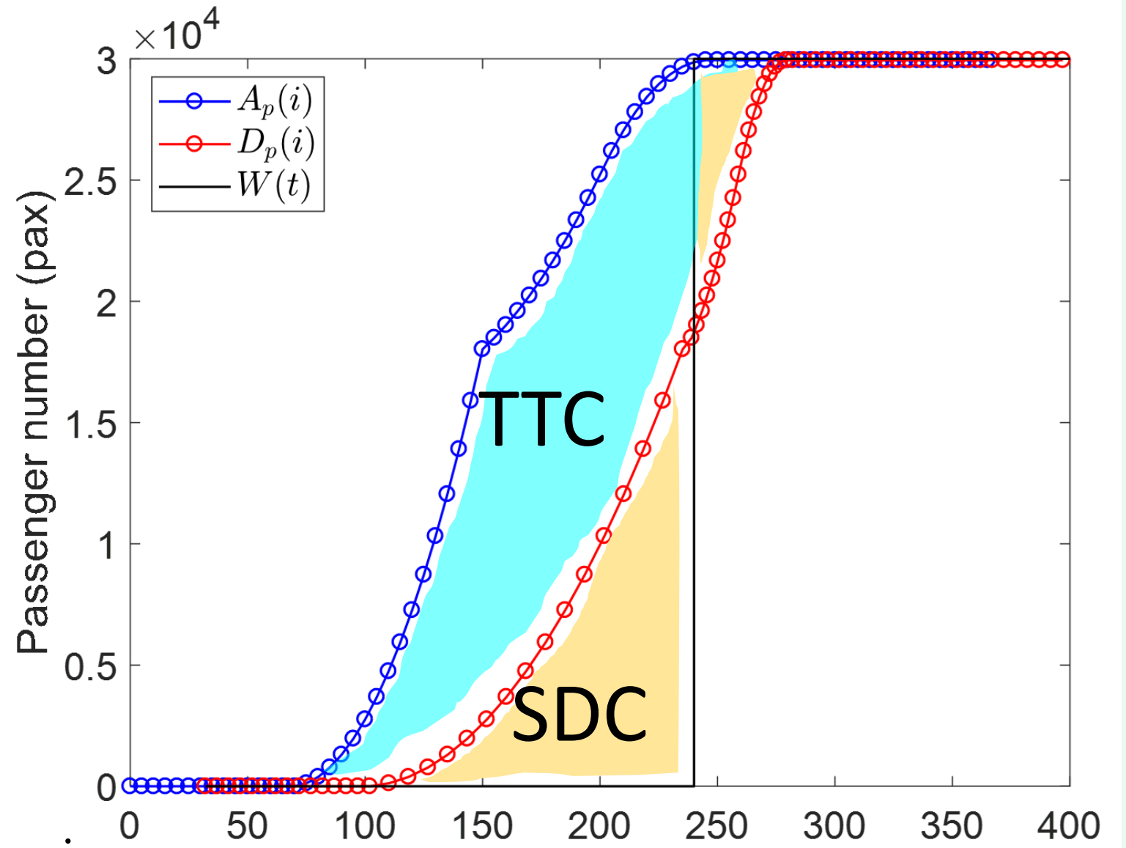
4. Application: coarse pricing

- Coarse pricing: surcharge or reward
  - Coarse pricing leads to sudden change of travel time at the start and end time of pricing period (i.e., t^+ and t^-)
  - To guarantee FIFO and a feasible equilibrium, $p/\alpha \le H_d - \tau$
  - Effectiveness of coarse pricing evaluated based on its end time ($t^- - t^*$) and duration ($t^+ - t^-$) by:
    1. User cost (UC) change (%)
    2. Social cost (SC) change (%)
    3. In-vehicle crowding (%) top-5

$$UC = TTC + SDC \pm p = SC \pm p$$

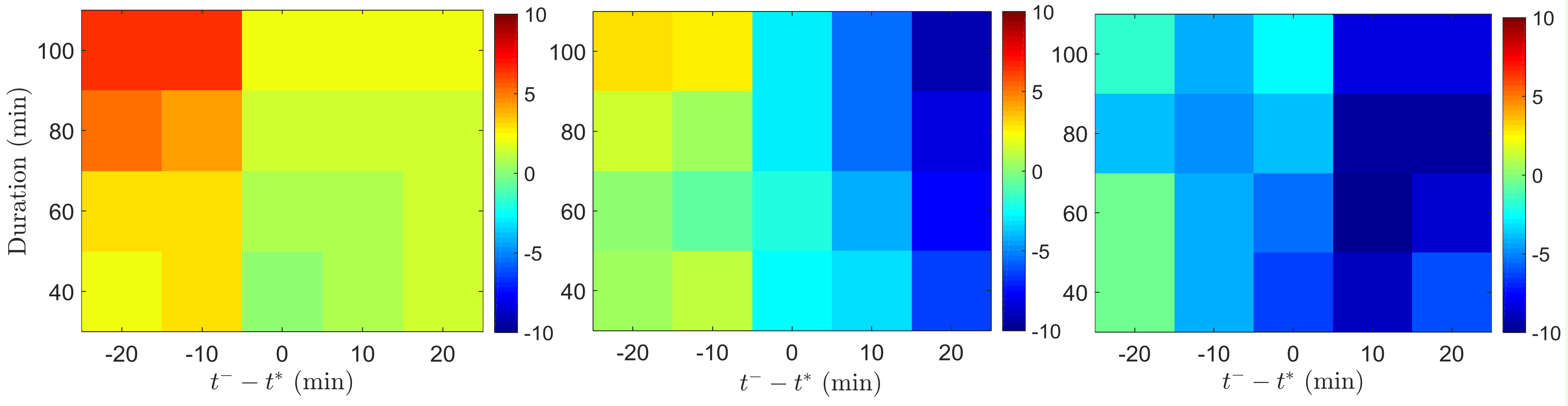
$$TTC=\sum_{i=1}^{I}\alpha\left(T(t)-T_0\right)n_p^i$$

$$SDC=\sum_{i=1}^{I_1}\beta\left(t^*-t\right)n_p^i+\sum_{i=I_1+1}^{I}\gamma\left(t-t^*\right)n_p^i$$

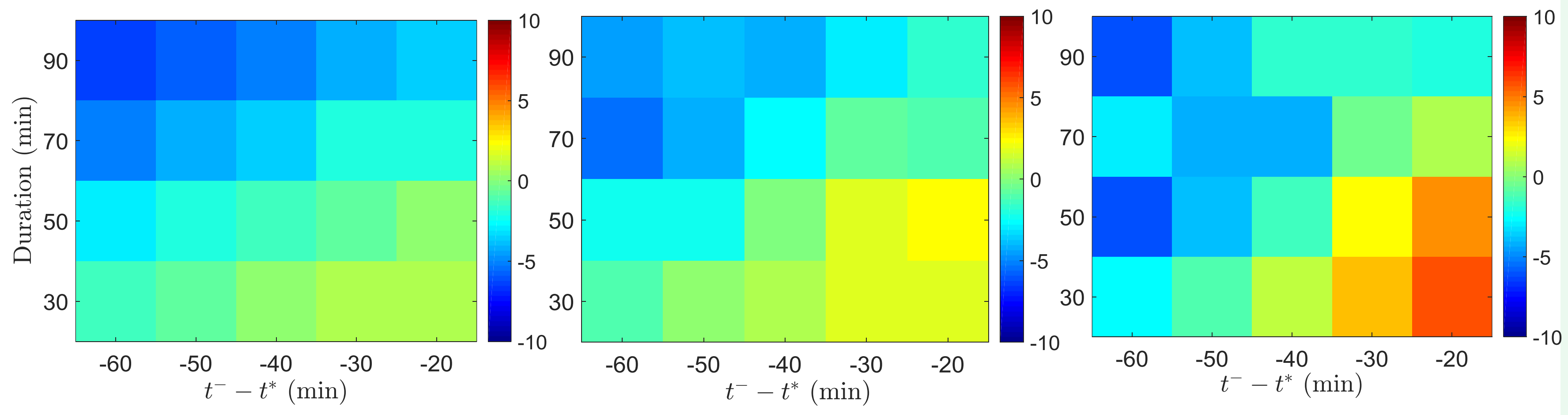


Cumulative curves of passengers

- Surcharge $p = 2\$$ UC generally increase, longer, earlier, higher



- Reward $p = 2\$$ UC generally decrease, longer, earlier, lower



UC change (%)

SC change (%)

$\sum n_p$: top5 change (%)

- SC increase or decrease strongly depends on when pricing ends
- In-vehicle crowding decrease for surcharge case, depends for reward