Flexible reservation scheme for urban transportation network management in a multimodal context

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1. INTRODUCTION

INTRODUCTION

How to alleviate urban traffic congestion?

- **Traffic congestion, a persistent and critical challenge in the global urbanization process, leading to tremendous economic losses and environmental pollution**
  - A typical US driver wasted **42 hours** due to congestion in 2023, while the average UK driver endured even more, spending **61 hours** in traffic jams. The economic loss of congestion was estimated **at $70.4 billion** in the U.S. and **£7.5 billion** in the U.K.
- Rapid increase in the number of private cars is a primary contributor to traffic congestion
  - **Private car (PC):** convenience and privacy
  - **Public transit (PT):** lower travel cost, more environmentally friendly

Promote public transit and implement effective management strategies for PC

Reservation-based TDM

- Reservation-based TDM schemes have shown promise in **balancing the capacity of transportation infrastructure and the travel demand of commuters**
  - **Reduction of the cost** of implementing reservation-based strategies due to advances in technology (Monitoring the traffic flow & Collecting the travel demand and preferences)
  - **Absence of direct monetary payment** makes it less likely to be perceived as disguised tax (More welcomed by the public)
- **However**
  - Administrative enforcement required for implementing such strategy
  - Absence of flexibility impedes public acceptance **(inherent)**
- **Critical challenge in the implementation: Noncompliance**

Motivations

- **Road capacity partition for two modes** (to serve PT and PC commuters, respectively) would introduce more flexibility into the scheme -> **Multimodal context**
- The combination of the **reservation scheme** and **auction mechanism** represents a hybrid TDM scheme that integrates the pricing and quantity instruments (Liu et al., 2015; Su & Park, 2015) -> **Auction-based reservation**
  - Allowing commuters to **self-select according to their personal preferences**, thereby inducing a shift in demand from the central peak to the shoulder peaks, enhancing the effectiveness of TDM schemes
- Road resource is **scarce and perishable**, which imposes stringent requirements on the stability of demand and accuracy of information. Demand fluctuations **lead to underutilization of road capacity or scramble**. **Consider the underlying noncompliance** due to expected scheduling conflicts -> **Reallocation and penalty mechanisms**

Flexible reservation scheme for urban transportation network management in a multimodal context

Auction-based reservation **Congestion management & noncompliance management**

PART I

INTRODUCTION

This work focuses on

(1) Introducing a **reservation-based TDM strategy** for congestion management during the morning commute in a **multimodal transportation context**

(2) **Characterizing and analyzing the noncompliance** in the proposed reservation scheme

(3) Exploring an efficient approach to **mitigate the adverse effects of noncompliance**

Main contributions

(1) A **flexible reservation scheme is proposed** to reduce traffic congestion during the morning commute in a multimodal transportation context

(2) Noncompliance of commuters, **including cancellation and no show**, is characterized and analyzed

(3) The **reallocation mechanism** is introduced and incorporated into the reservation scheme to mitigate the negative influence of noncompliance

(4) The system cost under the implementation of the proposed reservation scheme is analyzed

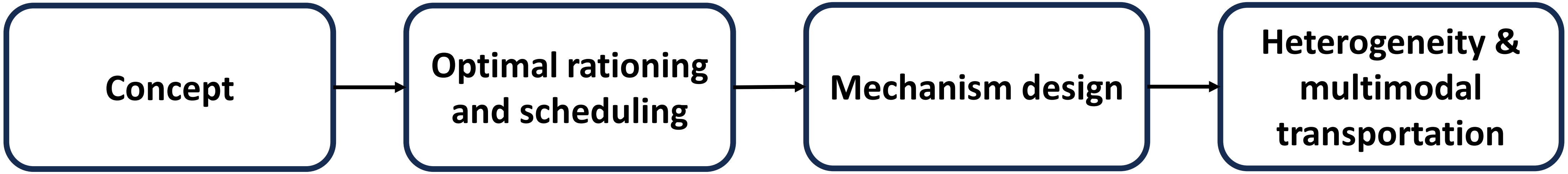
2. LITERATURE REVIEW

PART II

LITERATURE REVIEW

Highway reservation

- Concept of the highway use reservation system was **initially proposed by Wong (1997)**
- **Highway space inventory control system** (Teodorović et al., 2005; Edara & Teodorovic, 2008) and the **token-based transportation reservation system** (Liu et al., 2013) were developed
- Liu et al. (2015) examined the design and the efficiency of a highway use reservation system, and they **explored the auction-based reservation** to mitigate the efficiency loss caused by user heterogeneity
- Su and Park (2015) introduced an **auction-based traffic management scheme** and conducted an agent-based simulation to illustrate the application potential of this strategy.



LITERATURE REVIEW

Road capacity reservation

Auction theory

- Liu et al. (2015) examined the design and the efficiency of a highway use reservation system, and they explored the **auction-based reservation** to mitigate the efficiency loss caused by user heterogeneity
- Su and Park (2015) introduced an **auction-based traffic management scheme** and conducted an **agent-based simulation** to illustrate the application potential of this strategy

Autonomous vehicles

- Lamotte et al. (2017) investigated capacity allocation in a single bottleneck dynamic framework with a **booking mechanism for autonomous vehicles**
- Narayanan et al. (2022) formulated a bilevel game-theoretic model integrating Dynamic User Equilibrium with **SAV (Shared Autonomous Vehicles)** chain formation
- Xu et al. (2024) addressed the network design problem for **autonomous truck dedicated lanes**, optimizing the trade-off between safety-related network impacts and carbon emissions using a specialized two-stage algorithm

Transportation network analysis

- Li et al. (2023) introduced a **linear programming framework** for a combined **booking and rationing** strategy, aiming to secure efficient traffic flow patterns without compromising user equity and flexibility
- Ye et al. (2024) developed a **disaggregated spatiotemporal traffic assignment** method with a system-optimal orientation, employing a novel reverse feasible route searching algorithm to **ensure reliable reservation services** and analyze supply-demand matching.

Other reservation schemes in the transportation field

Parking services

- Shao et al. (2016) proposed a **reservation and allocation model of shared parking lots** that maximizes the use of private resources to benefit the community as a whole
- Shao et al. (2020) proposed an **auction-based parking reservation** scheme **considering demand disturbance**, which achieves incentive compatibility, and efficient allocation
- Cheng et al. (2023) proposed a **parking-sharing mechanism** that amends the Vickrey-Clarke-Groves auction with the notion of scale control, where IC and IR are guaranteed.

Public transit services

- Tang et al. (2024) developed an entry reservation strategy to **optimize the commuter flow during morning peak hours** on a metro line and constructed a **multi-objective passenger flow joint optimization model** to minimize the total trip cost at the reservation station.
- Zhang et al. (2024) **analyzed and optimized the reserved inbound services** of metro stations in Beijing and modeled the congestion and choices of travelers using the Vickrey bottleneck approach.

Charging services

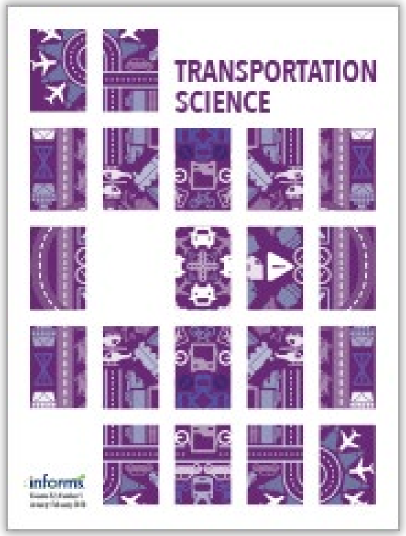
- Conway (2017) described **a simulation model on the charging infrastructure** deployed in Ireland, quantitatively revealing the advantages of a routing and charge point reservation system.
- Zhang et al. (2020) designed **an intelligent mobile charging system for electric vehicles by promoting charging reservations**. Results show superior performance gains by promoting the reservation-based mobile charger selection, especially for mobile chargers equipped with sufficient power capacity.

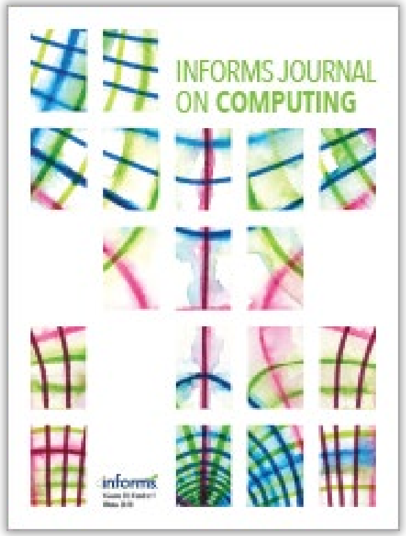
PART II

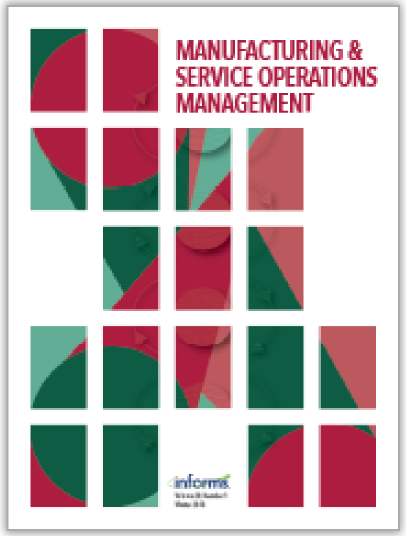
LITERATURE REVIEW

Noncompliance management

- Noncompliance is comprehensively investigated in airline industry and other operations management fields
- Management strategy can be classified into the following types
  - **Active – Overbooking**: Subramanian et al. (1999); Bertsimas and Popescu (2003); Alexandrov and Lariviere (2012)
  - **Passive – Penalty**: Huang and Matsubara (2007); Constantin et al. (2008); Alexandrov and Lariviere (2012)
  - **Hybrid – Two Stage Planning (First stage – Improving strategic slack; Second stage – Dynamic adjustment):** Cummings et al. (2025)





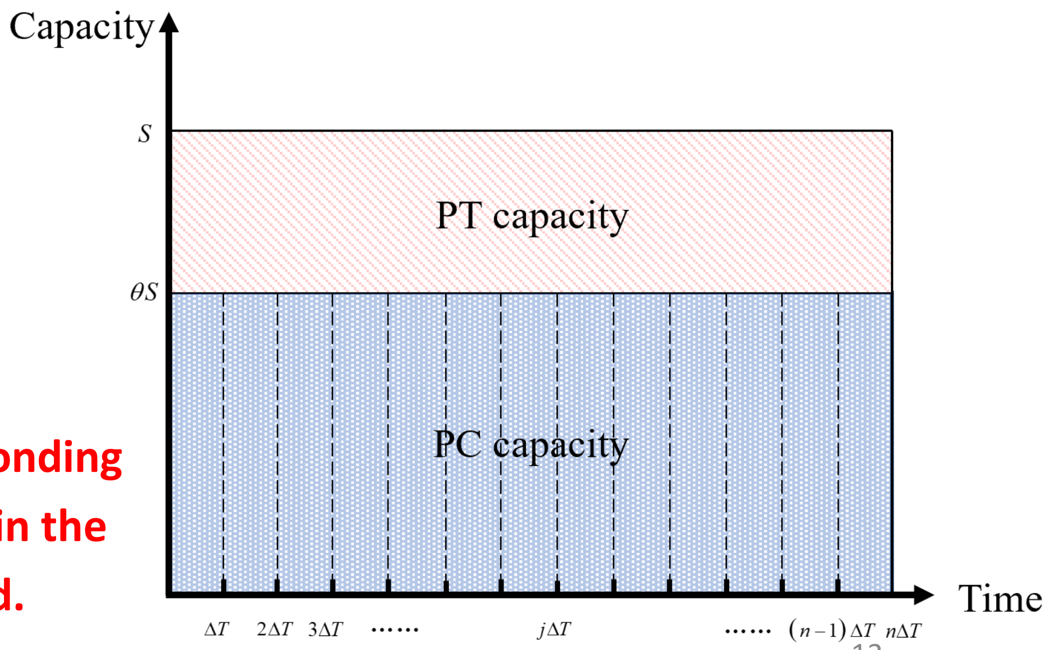


3. MODEL FORMULATION

MODEL FORMULATION

Initial allocation

- The bottleneck capacity S is divided into two parts: PC capacity θS and PT capacity $(1-\theta)S$
- The travel demand N is fixed and the set containing all N commuters is denoted by Ω
- The morning peak is discretized into finite n time intervals with identical length $\Delta T = \frac{N}{nS}$; The set contains all time intervals is $\mathcal{T}$
- Before the start of the morning peak, each commuter $i \in \Omega$ submits the bid prices $\mathbf{v}_i = \left(v_{i1}, v_{i2}, \ldots, v_{in}\right)^{\mathrm{T}}$
- The authority would allocate the PC travel right to commuters to maximize the social welfare $\sum_{i \in N} \sum_{j \in \mathcal{T}} v_{ij} x_{ij}$,



Commuters who want to utilize PC capacity must have corresponding travel right for a specific time interval; Those who do not obtain the PC travel right in any time interval can only take PT instead.

PART III

MODEL FORMULATION

Initial allocation

- x_{ij} indicate the allocation status of the PC trave right in time interval j to commuter i: $x_{ij}=1$ signifies that commuter i obtains the corresponding travel right and vice versa ($x_{ij}=0$)
- The efficient allocation that maximizes the total social welfare is formulated as

$$\max_{\mathbf{X}} \; V(\mathbf{X}) = \sum_{i\in\Omega}\sum_{j\in\mathcal{T}} v_{ij}x_{ij},$$ Social welfare maximization

$s.t.$

$$\sum_{j\in\mathcal{T}} x_{ij} \le 1, \text{ for } i\in\Omega,$$ Each commuter obtains at most one PC travel right

$$\sum_{i\in\Omega} x_{ij} \le \frac{\theta\,|N|}{n}, \text{ for } j\in\mathcal{T},$$ PC capacity of each interval is completely utilized without being wasted or overallocated

$$x_{ij}\in\{0,1\}, \text{ for } i\in\Omega, j\in\mathcal{T}.$$ Binary variable

The problem is solved by Scip solver via Python interface;

Scip: Non-commercial MIP and MINLP solvers

VCG payment

- After completing the initial allocation, payment of winners for PC travel right is determined based on **VCG payment rule**
- $W(\Omega)$ is the optimal value of the objective function and $W(\Omega \backslash i)$ is the optimal value where commuter i is excluded
- The VCG payment for commuter i is stated as

$$P_i^{VCG} = W(\Omega \backslash i) - \left(W(\Omega) - \sum_j v_{ij} x_{ij}^* \right), \ \forall i \in \Omega,$$

- x_{ij}^* is the component of the **optimal solution** $\mathbf{X}^*$
- Winners who obtain the PC travel right should pay **non-negative VCG payment**, as their participation bring negative externality to others

The VCG payment is zero for those who do not win in the initial allocation

- Such VCG payment rule guarantees **incentive compatibility and individual rationality** of the scheme (Vickrey, 1961; Clarke, 1971; Groves, 1973)

MODEL FORMULATION

Formulation of travel cost

- We treat commuters as homogeneous
- The travel cost of PC commuter departing in time interval j, denoted by c_j^{PC}, is formulated as

$$c_j^{PC}=\max\left\{\beta\left(t_j-t^*\right),\gamma\left(t^*-t_j\right)\right\},$$

- The travel cost of PT commuters, denoted by c^{PT}, is formulated as

$$c^{PT}=\pi g\left(N^{PT}\right)+f^{PT},$$

where π is the unit cost of body congestion and $g\left(N^{PT}\right)$ is an increasing function with respect to the total PT travel demand N^{PT} that describes the discomfort experienced by a PT commuter, and f^{PT} is the transit fare

- The travel time and the scheduling of bus departures are not included in this study
- The travel cost that a PT commuter incurred is mode-dependent, i.e., closely related to the mode choice of other commuters

Logit-based model

- We adopt the logit-based model to formulate the mode choice behavior, namely reservation behavior of commuters
- Let mode 1 and mode 2 represent PC and PT, respectively; and the generalized utility of mode $r = 1,2$, which is denoted by u_r, is formulated as

$$u_r = U - c_r + \xi_r, \qquad r = 1,2$$

- where U is the utility achieved by completing the trip on this day; ξ_r follows an independently and identically distributed Gumbel distribution with mean zero
- The modal split at the aggregate travel demand level is governed by a logit formula

$$N_r = N \frac{e^{-\omega c_r}}{e^{-\omega c_1} + e^{-\omega c_2}}, \; r = 1, 2,$$

- where ω is a positive parameter that correlates with the standard deviation of random variables; A larger value of indicates a smaller perception error in travel utility, and an individual is more likely to choose the mode with the minimum travel cost

MODEL FORMULATION

Willingness to pay of commuters

- Each commuter selects the mode with a higher utility between PC and PT. While for different time intervals, the willingness to pay (WTP) of commuters is the utility difference (or cost difference) between two distinct travel modes
- The WTP of commuter i for the PC travel right in interval j, which is denoted by v_{ij}, is formulated as

$$v_{ij} = u_{ij}^{PC} - u_{i}^{PT}$$

- Hence, the bid prices can be obtained accordingly
- Once the bid prices of all commuters are determined, the PC travel right is then allocated by completing the initial allocation process

$$\max_{\mathbf{X}} \ V(\mathbf{X}) = \sum_{i \in \Omega} \sum_{j \in \mathcal{T}} v_{ij} x_{ij},$$

$$s.t.$$

$$\sum_{j \in \mathcal{T}} x_{ij} \le 1, \ \text{for } i \in \Omega,$$

$$\sum_{i \in \Omega} x_{ij} \le \frac{\theta |N|}{n}, \ \text{for } j \in \mathcal{T},$$

$$x_{ij} \in \{0,1\}, \ \text{for } i \in \Omega, j \in \mathcal{T}.$$

MODEL FORMULATION

Considering noncompliance

- Considering real-world scenarios, commuters' travel **plans may be disrupted by unforeseen events**
- Commuters who obtained PC travel rights in the initial allocation may cancel the reservation for PC travel and shift to take PT; or they might cancel the trip plans on this day completely
- We consider **two types of noncompliance** in this study:
  - **Cancellation**: Commuters who obtained the PC travel rights cancel the reservation for PC travel before departure and shift to take PT on this day
  - **No show**: Commuters who obtained PC travel rights in the initial allocation cancel the reservation later than the start of the reserved time interval or do not show up for their reservations
- To mitigate **the adverse effect of noncompliance (cancellation),** this study introduces the **reallocation mechanism** into the reservation scheme, as **no show cannot be identified in advance and managed then**

Reallocation of PC travel right

- Before introducing and formulating the reallocation process, four sets are introduced as shown below

$C^r = \left\{ i \in N \mid \sum_j x_{ij} = 1 \right\}$: The set of commuters who have the PC travel rights.

$C^{nr} = \left\{ i \in N \mid \sum_j x_{ij} = 0 \right\} = C \setminus C^r$: The set of commuters who do not have PC travel rights.

C^d : The set of commuters who have departed from the residential district.

C^{nd} : The set of commuters who have not departed from the residential district.

- These four sets are **dynamically maintained** during the whole morning peak period
- For C^{nr}, there exist two disjoint subsets: C^l and C^w ,
  - C^l contains all commuters who do not get the PC travel right **from the beginning till now**
  - C^w contains commuters who **once had** the PC travel right **but are noncompliant**

Reallocation of PC travel right

- **Assumptions regarding the reallocation**
  - No intentional noncompliance Implicit assumption in most TDM studies
  - Commuters in C^l will be retained as standby candidates in the reallocation process; The released PC travel right of noncompliant commuters will be released and reallocated to **commuter in $\boldsymbol{C^l} \cap \boldsymbol{C^{nd}}$**
  - Reallocation is conducted **in sequence rather than in batches**
- For commuter c who has the PC travel right and become noncompliant then, his/her travel right will be released and reallocated
- The reallocation is determined by solving the problem below

$$\max_{\left(x_{ij},\, i \in C^l \cap C^{nd}\right)} \sum_{i \in C^l \cap C^{nd}} v_{ij} x_{ij} ,$$

Achieve the max social welfare by reallocating the released PC travel right

$$s.t.$$

$$\sum_i x_{ij} = 1, \text{ for } i \in C^l \cap C^{nd}.$$

Only one commuter can win in a reallocation process

Reallocation of PC travel right

Algorithm 1	Reallocation for cancellations	Note
Inputs	Sets of commuters: C^r, C^l, C^w, C^{nd} Time interval j of the cancellation request Noncompliant commuter c Bid prices b_{ij} for all $i \in C^l \cap C^{nd}$ Current allocation matrix $\mathbf{X}_c$	
Outputs	Updated sets C^r, C^l, C^w Updated allocation matrix $\mathbf{X}'_c$	
	Move commuter c from C^r to C^w	// Update C^r and C^w
	Generate the optimal solution $x_{ij}, i \in C^l \cap C^{nd}$ by solving problem (13) to (14); $k \leftarrow \{i \in C^l \cap C^{nd} \mid x_{ij} = 1\}$	// Winner determination
	Move commuter k from C^l to C^r	// Update C^r and C^l
	Set $x_{cj} \leftarrow 0$;	// Update allocation matrix

- The value of total social welfare before and after reallocation is denoted by $V(\mathbf{X_c})$ and $V(\mathbf{X'_c})$, respectively
- It holds
$$V(\mathbf{X}'_c) \le V(\mathbf{X}_c) \le V(\mathbf{X}^*) = W(\Omega),$$
- Reallocation process is accompanied by the **noncompliance of commuters with higher utilities**.
- Hence, it can be easily verified that the noncompliance of commuter i would pose negative influence on social welfare.

Identification of no show

- Some commuters may not show up for their reservations without cancelling the reservation in advance
- Such absences of commuters **ultimately lead to the waste of the initially PC capacity**, which **cannot be reallocated** as the authority is not able to know their failure in attending the reservations before the end of the corresponding time interval
- **Identification:**
  - At the end of the time interval j, commuter c who has the PC travel right for this time interval and fails to attend the reservation, will be identified as no show

The reallocation process is not suitable for managing no show

The VCG payment of these no show commuters will not be refunded, which can be treated as penalty

MODEL FORMULATION

Determination of penalty for noncompliant commuters

- The loss in social welfare in the reallocation due to the noncompliance of commuter c is $V(\mathbf{X_c}) - V(\mathbf{X'_c})$
- Once commuter c cancels his/her reservation**, the VCG payment $\boldsymbol{P_c^{VCG}}$ will be refunded**
- However, this noncompliant commuter c has to **endure the penalty for the cancellation**
- The penalty fee z_c is governed by

$$z_c = P_c^{VCG} - P_k^{VCG},$$

- where $\boldsymbol{k}$ **is the winning standby candidate** in the reallocation process; Such a setting of penalty **fee achieves the consistency of total payment** before and after the reallocation
- The VCG payment of the new winner k holds $P_k^{VCG} = v_{pj},$
  - p is the commuter with the **second-highest bid price** for interval j in the set of available standby candidates
  - The VCG **auction reduces to a second-price auction**, where k pays the second-highest submitted bid v_{pj}

MODEL FORMULATION

Analytical results of the flexible partial reservation scheme

- For the reservation scheme incorporated with the reallocation and penalty mechanisms, we have the following propositions

Proposition 1. *The penalty fee z_c for a noncompliant commuter c is non-negative and it is not higher than the VCG payment P_c^{VCG}, i.e., $P_c^{VCG} \geq z_c \geq 0$.*

Proposition 2. *(Incentive compatibility) For any bid prices $\mathbf{b}_{-i}$ of the other commuters and any true values $\mathbf{v}_i$, reporting $\mathbf{b}_i = \mathbf{v}_i$ weakly maximizes the expected utility U_i over all possible misreports $\mathbf{b}'_i \ (\neq \mathbf{v}_i)$.*

Proposition 3. *(Individual rationality), under truthful bidding $\mathbf{b}_i = \mathbf{v}_i$, the expected utility of commuter i is non-negative, i.e., $U_i \geq 0$, ensuring that every commuter will participate in the scheme.*

Proposition 4. *(Early reporting of noncompliance) For a noncompliant commuter i who is rational, he/she will cancel the reservation as early as possible once the unforeseen disruption occurs to increase his/her expected utility.*

MODEL FORMULATION

Analytical results of the flexible partial reservation scheme

Proposition 1. *The penalty fee z_c for a noncompliant commuter c is non-negative and it is not higher than the VCG payment P_c^{VCG}, i.e., $P_c^{VCG} \geq z_c \geq 0$.*

- The max penalty for any noncompliant commuter c is **non-negative and not greater than his/her VCG payment P_c^{VCG}**
- For no show commuter c, the penalty z_c equals the VCG payment P_c^{VCG}
- For cancellation commuter c, the penalty z_c depends on P_k^{VCG} (the payment of new winning commuter k in the reallocation process)

Proposition 4. *(Early reporting of noncompliance) For a noncompliant commuter i who is rational, he/she will cancel the reservation as early as possible once the unforeseen disruption occurs to increase his/her expected utility.*

- The number of potential standby candidates for reallocation decreases over time
- Noncompliant commuter then has a strong incentive to cancel the reservation at the earliest possible time to reduce the penalty induced

4. NUMERICAL ANALYSES

NUMERICAL ANALYSES

Basic setting

- The values of schedule delay early and schedule delay late are denoted β and γ, and it holds $\gamma > \beta$

Table 1: Parameter settings in the model.

Parameter	N	n	S	t^*	γ
Value	1000	20	500	8.6	8
Parameter	θ	ω	π	f^{PT}	β
Value	0.6	0.5	0.01	2	2

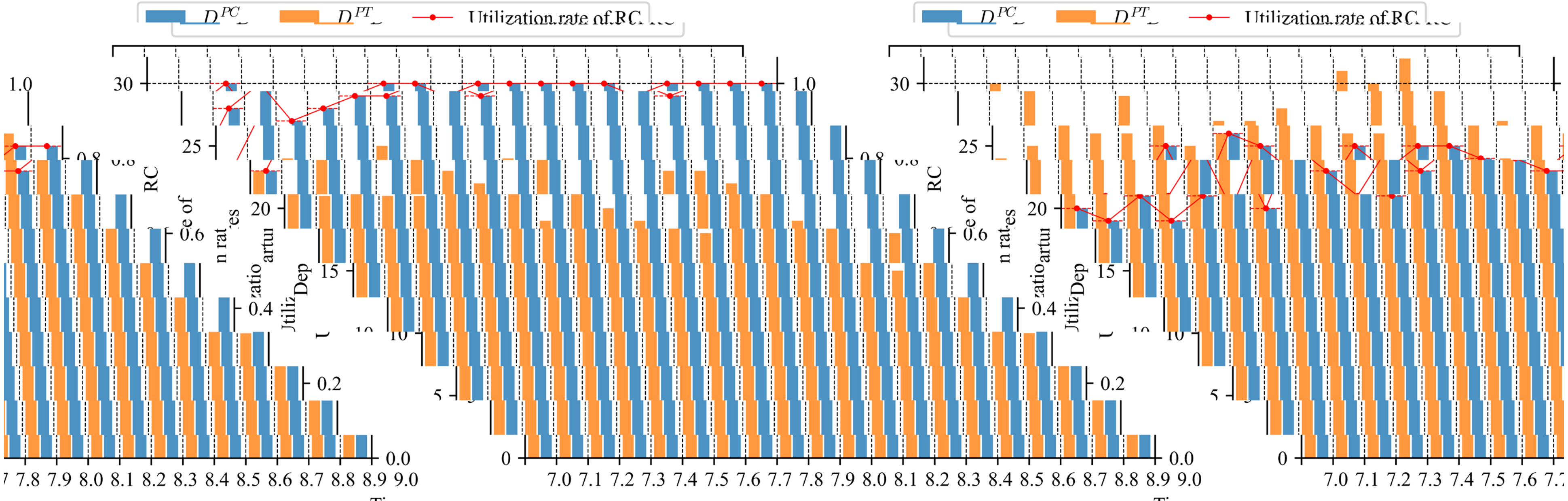
Note: $N / S = 2$ indicates the duration of the morning peak is 2 hours. γ / β is set to 4, approximates the setting suggested by Arnott et al. (1990b) where $\beta = 3.9$, $\gamma = 15.21$, and $\gamma / \beta \approx 4$. The specification of in-vehicle congestion function is adopted from Huang (2002). Under such parameter settings, the preferred arrival time t^* is exactly at the boundary between 16th and 17th time intervals.

For computational convenience, we adopt the parameter settings in Table 1

NUMERICAL ANALYSES

Departures in each time interval

- The utilization rate of PC capacity (denoted by red dashed lines in subplots (a) and (b)), is significantly higher when incorporating the reallocation mechanism in the proposed reservation scheme
- The departures of PC commuters are not sufficient (a proportion of the PC capacity is wasted) in the intervals at the beginning of the morning peak.



...es in each interval (No reallocation)

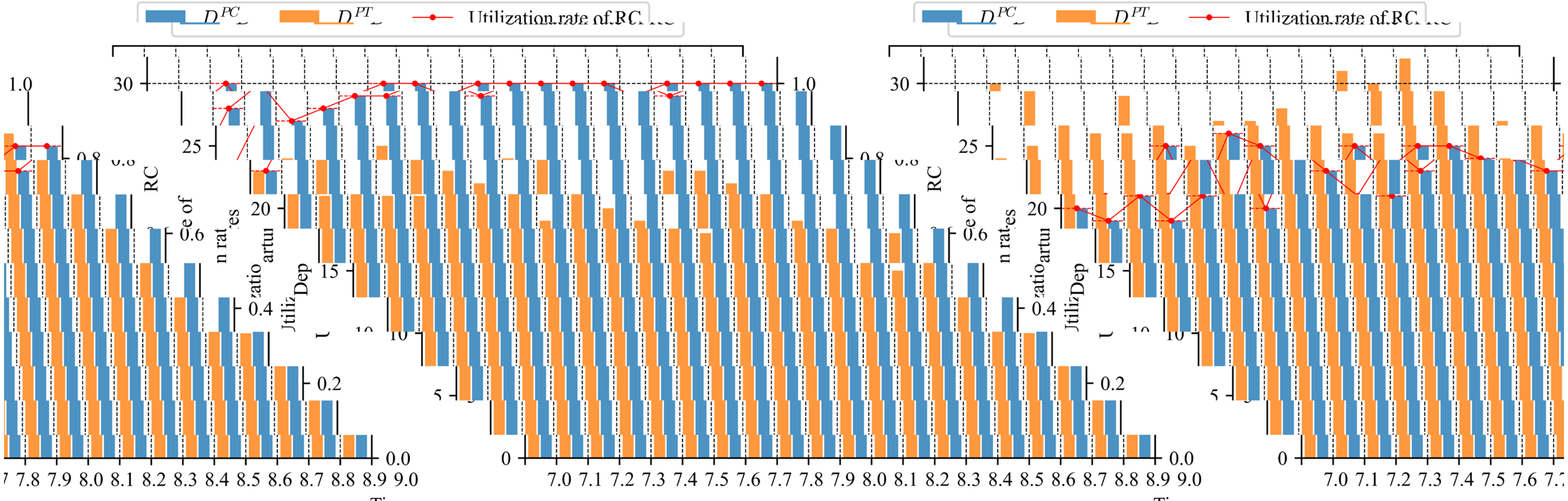
(a) Departures in each interval (Reallocation)

(b) Departu...

NUMERICAL ANALYSES

Departures in each time interval

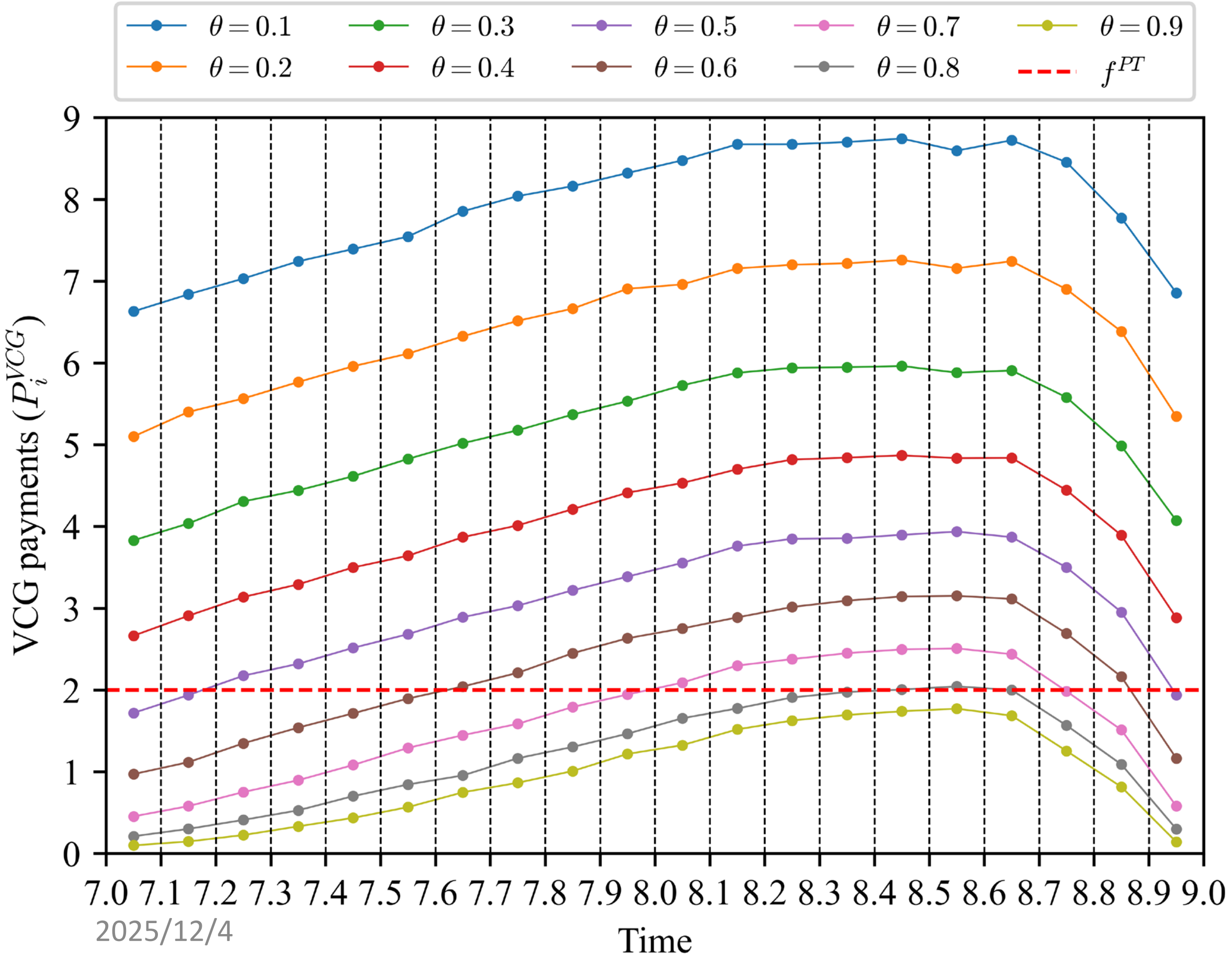
- Although early cancellations provide more standby candidates, the limited buffer period of the other standby candidates leads to a relatively lower reallocation success rate
- The orange bar in subplot (b) signifies that the average commuter load of PT is higher, leading to a further decline in travel experience. The introduction of the reallocation mechanism **improves the utilization rate of PC capacity by 25%** under the given parameter settings.



(a) Departures in each interval (Reallocation)

(b) Departu

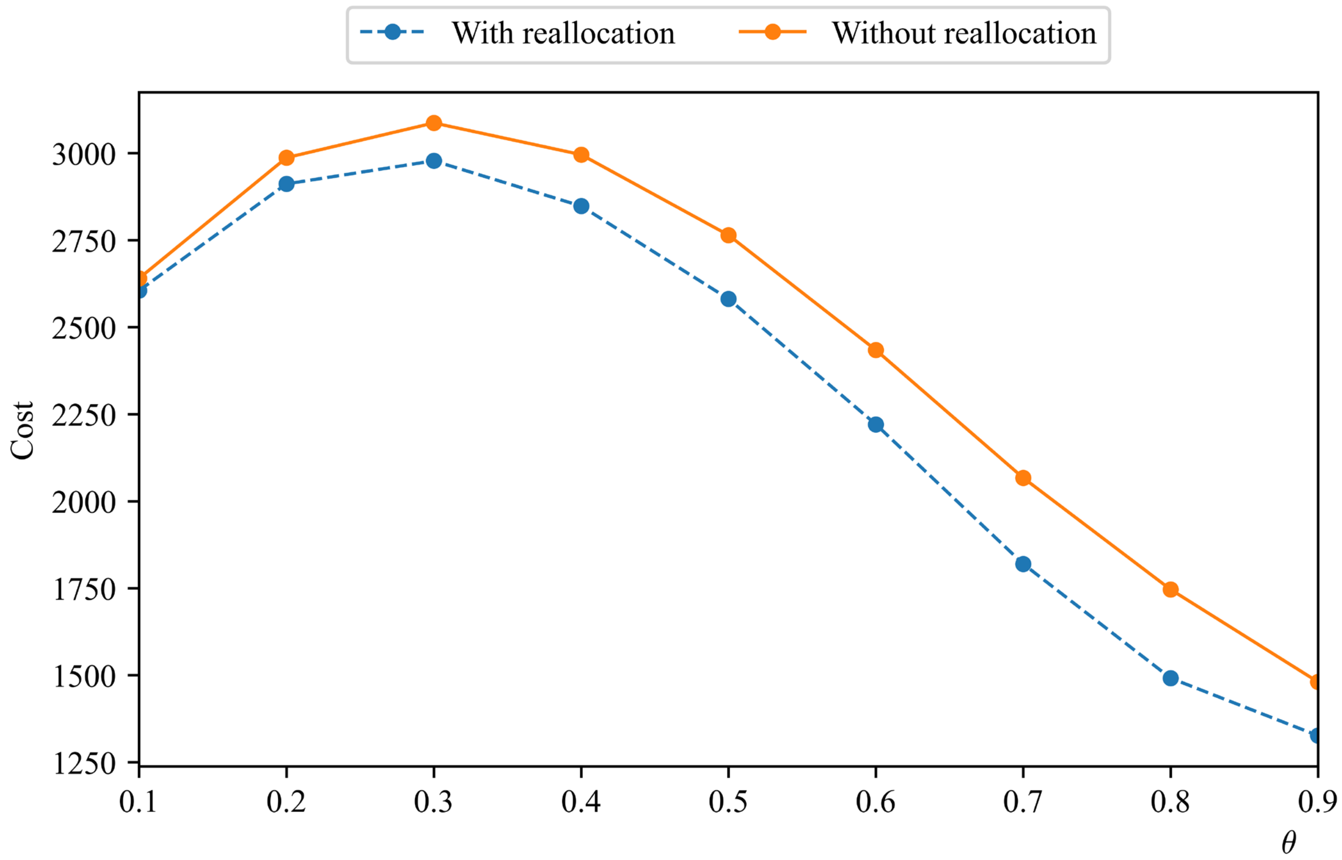
Average VCG payment for PC travel rights



- The average VCG payment for PC travel is higher for time intervals closer to t^*, and the trend generally shows an increase first, followed by a decrease across time dimension
- When $\boldsymbol{\theta}$ **is greater than 0.8**, the average payment for PC travel for any time interval **is lower than the transit fare** $\boldsymbol{f^{PT}}$

NUMERICAL ANALYSES

Total revenue of the system

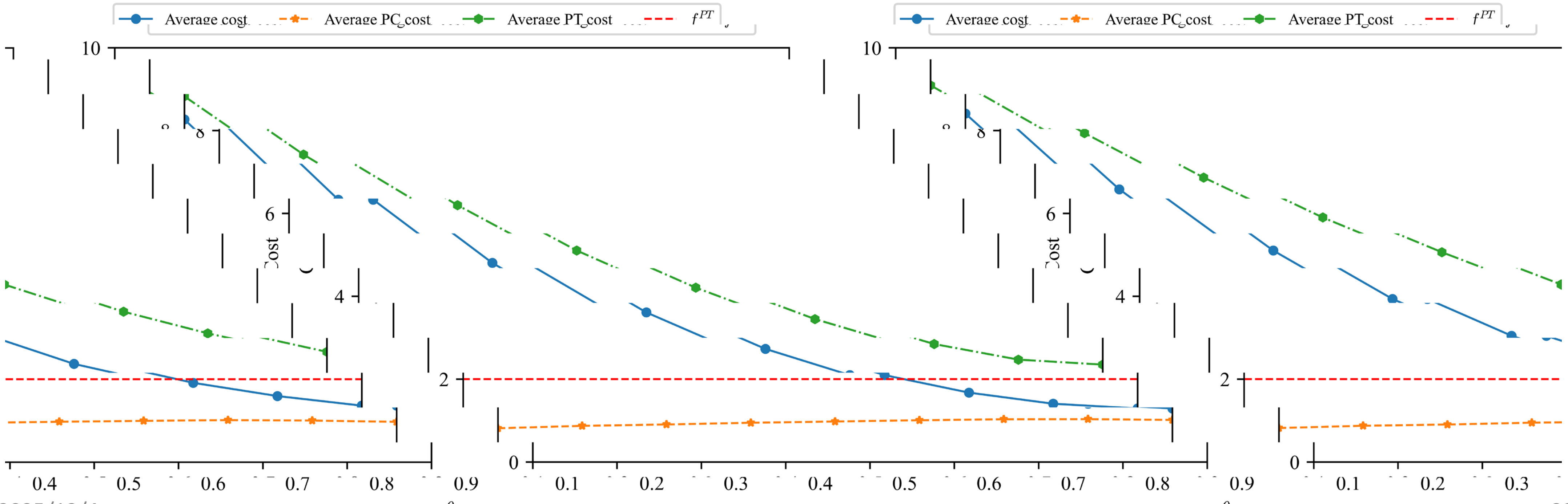


- The total revenue equals the sum of all VCG payments, penalties and public transit fares collected, minus the refund of the VCG payments for noncompliant commuters.
- The introduction of reallocation mechanism leads to a reduction in the authority's total revenue under the implementation of the reservation scheme. From the perspective of revenue maximization, the reasonable range for θ should be between 0.2 - 0.4.

NUMERICAL ANALYSES

Average system cost, average PC cost, and average PT cost

- As θ increases, the average system cost significantly decreases
- The average cost of PT is reduced accordingly as body discomfort is mitigated as well
- The average cost of PC commuters does not exhibit substantial variation and consistently remains below the public transit fare



(b) Without reallocation

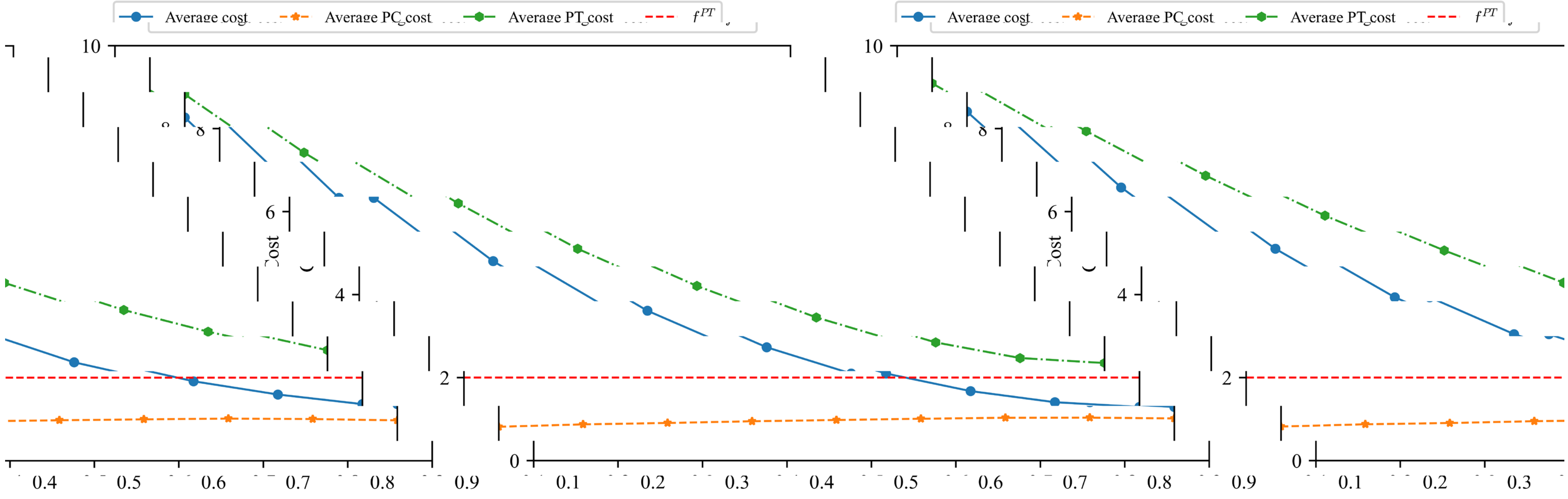
(a) With reallocation

PART IV

NUMERICAL ANALYSES

Average system cost, average PC cost, and average PT cost

- When there is no reallocation mechanism, the average system cost, the average travel cost of PT and PC commuters are all higher than the corresponding cases with the reallocation mechanism
- Although increasing θ reduces the average system cost, it lowers the total revenue when considering the authority’s perspective alone



(b) Without reallocation

(a) With reallocation

5. CONCLUSION & DISCUSSION

CONCLUSION & DISCUSSION

Concluding remarks

- The findings in this study demonstrated that **noncompliance has significant influence on the implementation and efficiency of the proposed reservation scheme**; hence incorporating potential noncompliance behavior into such schemes is essential
  - Noncompliance leads to the underutilization of the PC capacity to be reserved, **especially for the time intervals close to the start of rush hour, exacerbating the in-vehicle congestion for PT as well**
  - The average VCG payment made by PC commuters for each time **interval decreases as $\boldsymbol{\theta}$ increases**
  - When θ exceeds 0.8, the average payment drops even below the public transit fare f^{PT}; as θ decreases, the revenue exhibits a trend of **increasing first and then decreasing** (reaches the maximum when θ between 0.2 and 0.4), while the average system cost and the average travel cost of PT commuters are **monotonically decreasing**
  - The introduction of the reallocation mechanism **improves the utilization rate of PC capacity by 25%** under the given parameter settings.

CONCLUSION & DISCUSSION

Future research

- Heterogeneous scenarios (Values of time, preferred arrival time……)
- Active noncompliance management: overbooking…… (instead of the passive penalty mechanism)
- Reservation priority based on trip length, values of time, or historical noncompliance records……

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