北京航空航天大學 BEIHANG UNIVERSITY | 经济管理学院 SCHOOL OF ECONOMICS AND MANAGEMENT

Morning Peak Reservation Scheme Incorporating Noncompliance Behaviors: Modeling and Analysis

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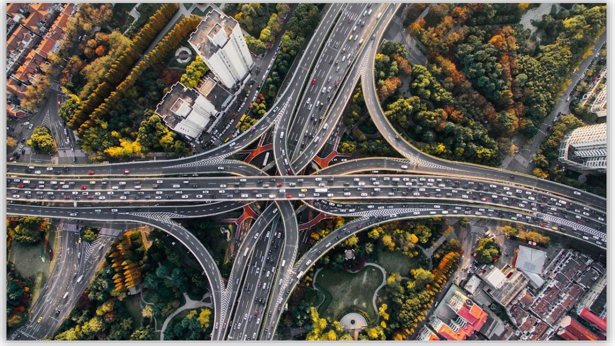
PART I

INTRODUCTION

How to alleviate traffic congestion?

- Simply increasing road capacity may lead to an unexpectedly worse situation: ***Braess Paradox***
- Travel demand management (TDM): internalizing the negative externalities
  - Pricing instrument: Congestion Pricing
  - Quantity instrument: Car use restriction, **Reservation**
  - Hybrid instrument: Tradable credit, Karma (Self-contained economy, non-tradable)



Ideal travel demand management scheme

Effectiveness	**Relief traffic congestion** and the resulting deadweight loss	**Trade-Off**
Fairness	Reduce speculation and ensure **fair use of road commodity**	
Flexibility	**Avoid compulsive**, rigid administrative order	
Practicality	Simple mechanism design and **reasonable investment**	

MOTIVATION & CONTRIBUTION

Survey on acceptability of reservation strategy (Xi’an Shaanxi, 2024)

Critical concerns about the reservation scheme

- Inconvenience travel
- Equity issues
- **Limited flexibility**

Some unexpected event changes the driver’s schedule and he has to depart earlier or later than the reserved time slot, and the reservation system **provides no alternatives**,

then noncompliance occurs

Noncompliance behavior

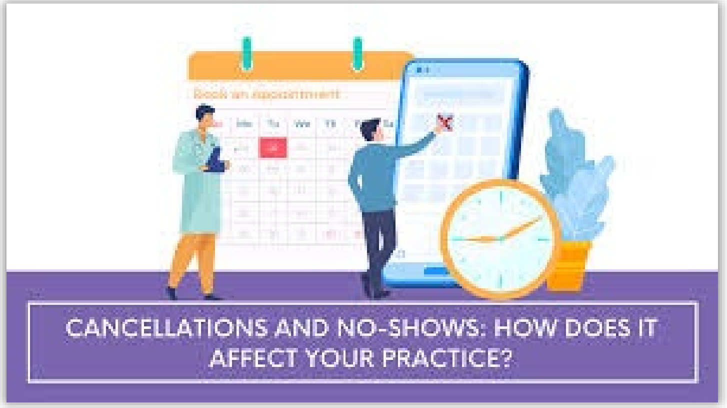
Known as ***no show*** *or* ***last-minute cancellations*** in the service industries

- Medical appointments
- Airline ticketing & Hotel booking

Lead to the **underutilization of resources**, impacting the efficiency of the reservation system

Mainly caused by:

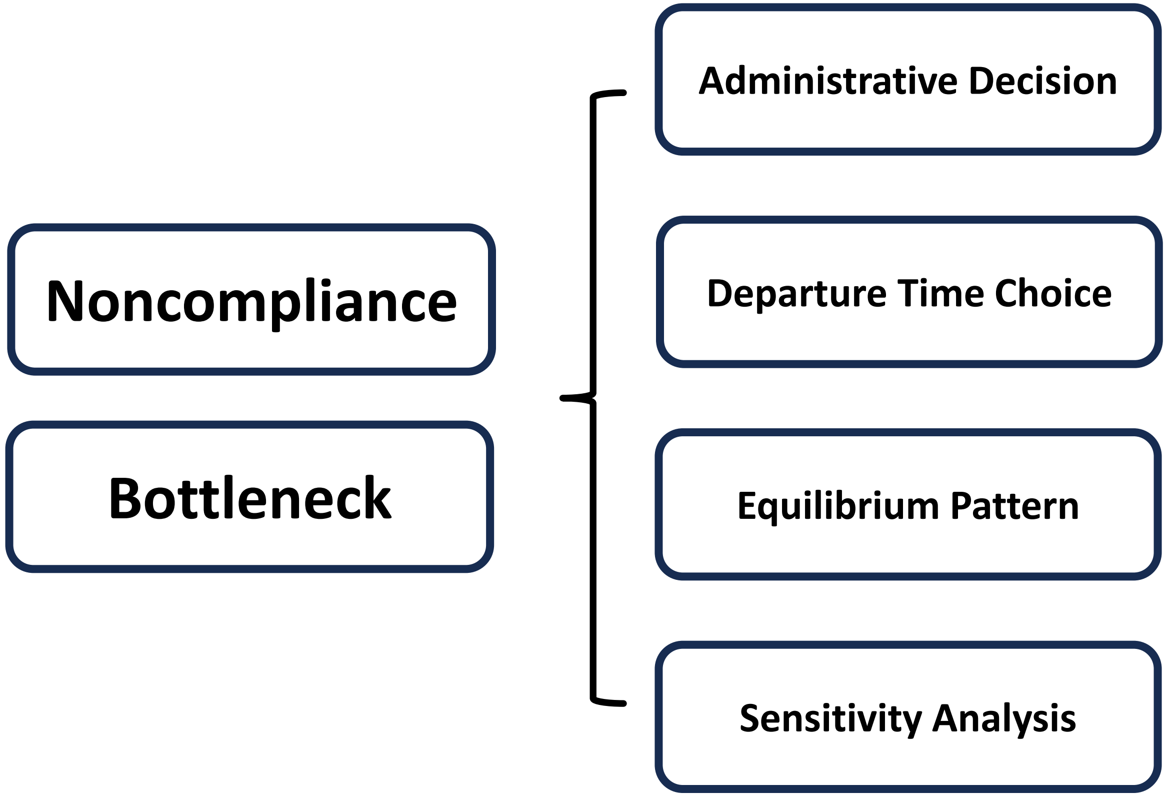
- Forgetfulness
- Change in plans
- Communication Issues
- **Unforeseen circumstances**



MOTIVATION & CONTRIBUTION

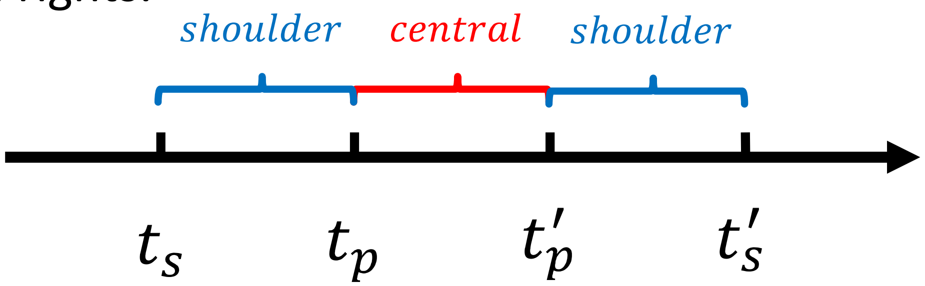
Reservation scheme incorporating noncompliance

- A reservation scheme is designed to alleviate traffic congestion during morning commute
- Optimal time window division and initial reservation rights distribution are determined
- **Noncompliance is conceptualized and incorporated into the reservation scheme**
- Reservation and departure time choice are investigated under equilibrium condition
- Efficiency of the reservation scheme and the travel cost of individual travelers are analyzed.



Reservation scheme

- Consider N **homogeneous commuters** who travel from home to workplace every day along a highway with a single bottleneck.
- Authority first divides the morning peak period into three discrete time windows:
  - The first shoulder peak period $T_s^1 = [t_s, t_p)$
  - The central peak period $T_p = [t_p. t_p')$
  - The second should peak period $T_s^2 = \left[t_p', t_s'\right)$
- Within M days of a policy implementation cycle, every traveler should book a time window one day in advance. Every commuter is allocated with M_2 central peak reservation rights and $M_1 = M - M_2$ shoulder peak reservation rights.



Noncompliance in the reservation scheme

In practice, commuters may have noncompliance behaviors, i.e., **unpunctuality arrival at the bottleneck** before the start of the booking period or after the end of it, due to:

- **Work rescheduling** $t^* \rightarrow t^*_{new}$
- Travel time uncertainty $T_f \rightarrow T_f'$
- Emergency needs $N \rightarrow N'$

Assumptions of noncompliance

- A small proportion of the commuters will experience unpredictable disturbances and the preferred arrival time to the destination will shift from t^* to t^*_{new}, and then change departure time based on rational principle and other commuters who have not will travel as they booked
- After the work rescheduling, the new preferred arrival time of an individual at the workplace is a random variable, uniformly distributed between t_s and t_s', that is to say, $t^*_{new} \sim U(t_s, t_s')$

PART IV

MODEL PROPERTIES

Optimal time window division $\{t_s^*, t_p^*, {t'_p}^*, {t'_s}^*\}$

- For administration, the first thing when designing a reservation scheme is to **specify time windows during the morning peak period**
- An optimal time window division scheme is introduced, based on the principle of maximizing social welfare
- On the theoretical basis of Liu et al. (2015), *mass departure* can be observed in the **time window that starts later than t^* when the equilibrium state is reached**

W. Liu et al./Transportation Research Part C 56 (2015) 293–308

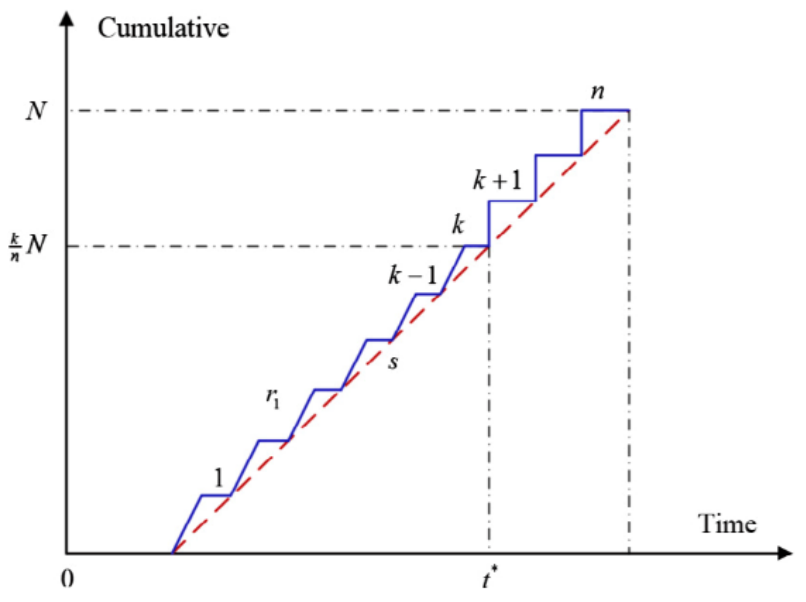


Fig. 4. Commuting equilibrium under the n-step reservation scheme.

MODEL PROPERTIES

Optimal time window division $\left\{t_s^*, t_p^*, {t_p'}^*, {t_s'}^*\right\}$

$$Min\ TC_s^1 + TC_s^2 + TC_p$$

Minimize total cost

$$s.t.\begin{cases}(t^* - t_s)\beta = \frac{1}{2}(t_s' - t_p')\alpha + \left(\frac{1}{2}(t_s' + t_p') - t^*\right)\gamma \\ t_s' = t_s + \frac{N}{S} \\ \frac{t_p' - t^*}{t^* - t_p} = \frac{\beta}{\gamma}\end{cases}$$

Fairness constraint

Full utilization of capacity(1)

Queue length constraint

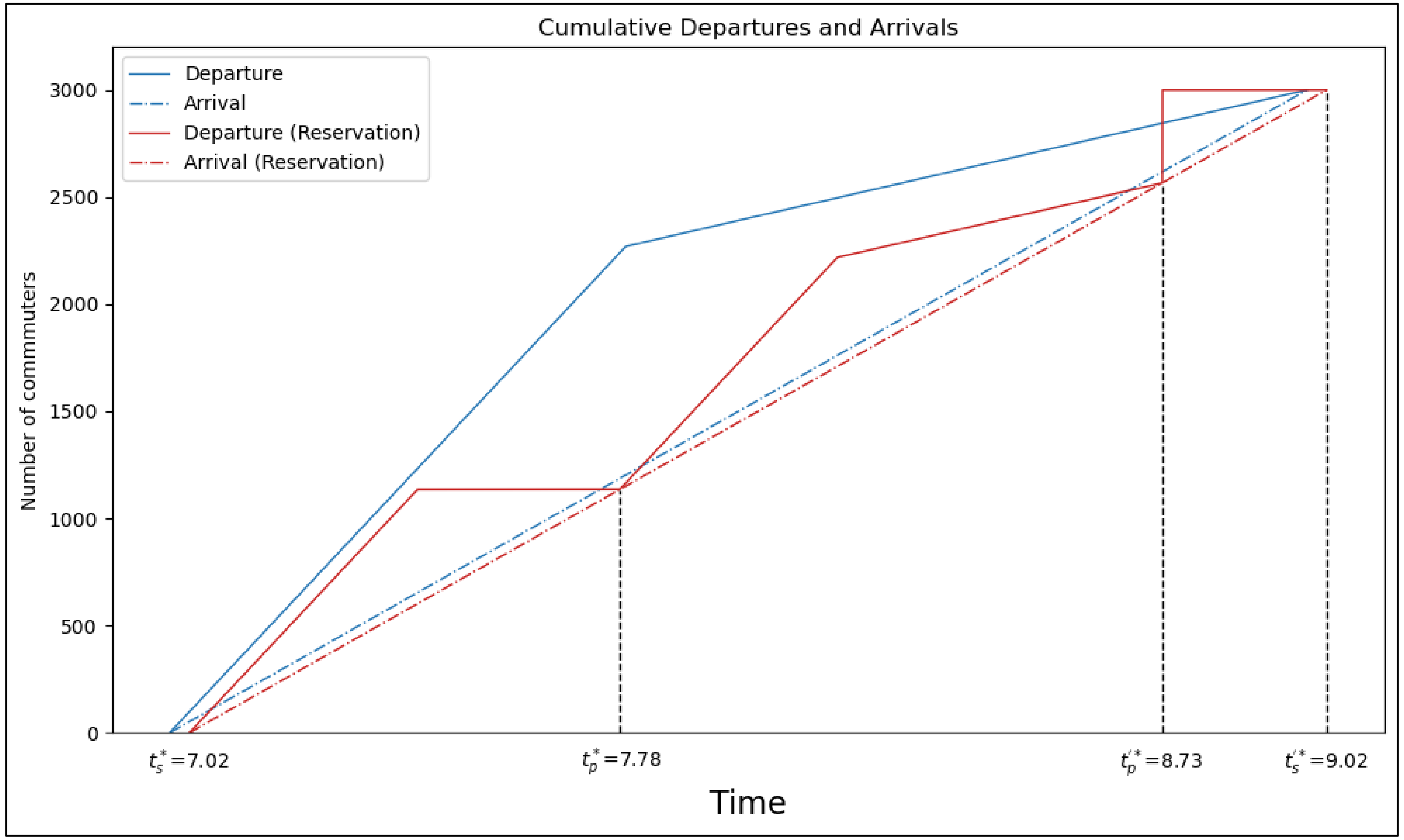
$$\begin{cases}t_s^* = t^* - \left(\frac{N}{S}\right)\left(\frac{\gamma\left(\gamma(\beta + 2\gamma) + \alpha(3\beta + 2\gamma)\right)}{2(\alpha + \gamma)(\beta + \gamma)^2}\right) \\ t_p^* = t^* - \left(\frac{N}{S}\right)\left(\frac{\gamma\left(\gamma^2 + \alpha(2\beta + \gamma)\right)}{2(\alpha + \gamma)(\beta + \gamma)^2}\right) \\ {t_p'}^* = t^* + \left(\frac{N}{S}\right)\left(\frac{\beta\left(\gamma^2 + \alpha(2\beta + \gamma)\right)}{2(\alpha + \gamma)(\beta + \gamma)^2}\right) \\ {t_s'}^* = t^* + \left(\frac{N}{S}\right)\left(\frac{\beta\left(\alpha(2\beta + \gamma) + \gamma(2\beta + 3\gamma)\right)}{2(\alpha + \gamma)(\beta + \gamma)^2}\right)\end{cases}$$

F.O.C. & S.O.C. are applied to solve the problem and verify the uniqueness of the optimal solution

PART IV

MODEL PROPERTIES

Optimal time window division $\{t_s^*, t_p^*, t_p'^*, t_s'^*\}$



Parameter	Value
N	3000
S	1500 $\left(\frac{N}{S}=2\right)$ implies the duration of morning peak is 2 hours
α	9.91
β	4.66
γ	14.48
t^*	8.5

Ideal departure and arrival pattern under optimal time window division

MODEL PROPERTIES

Initial central peak reservation rights distribution M_2

Considering that all commuters are rational, they will certainly try to utilize all central peak reservation rights by the end of the policy implementation cycle.

Under the user equilibrium state, a fair initial central reservation rights distribution to every commuter M_2 is given by:

$$\frac{M_2}{M} = \frac{T_p}{T_s^1 + T_p + T_s^2}$$

It is trivial that the average travel cost during T_p is smaller than that during T_s^1 and T_s^2. By applying the Karush-Kuhn-Tucker (KKT) conditions to solve a constrained optimization problem, the above conclusion can be easily derived.

MODEL PROPERTIES

Departure time choice after work rescheduling

Since all commuters have grasped the departure and arrival patterns of the user equilibrium state under the reservation scheme, once a commuter has undergone work rescheduling, he will rationally decide their departure time based on the principle of minimizing individual travel cost

For various extents of work rescheduling (different t_{new}^*) , an individual commuter's new departure time decision scheme is as follows:

$$t' = \begin{cases} t_s, & t_s < t_{new}^* \leq t_1 \\ t_p, & t_1 < t_{new}^* \leq t^* \\ t'_p, & t^* < t_{new}^* \leq t_2 \\ t'_s, & t_2 < t_{new}^* \leq t'_s \end{cases}$$

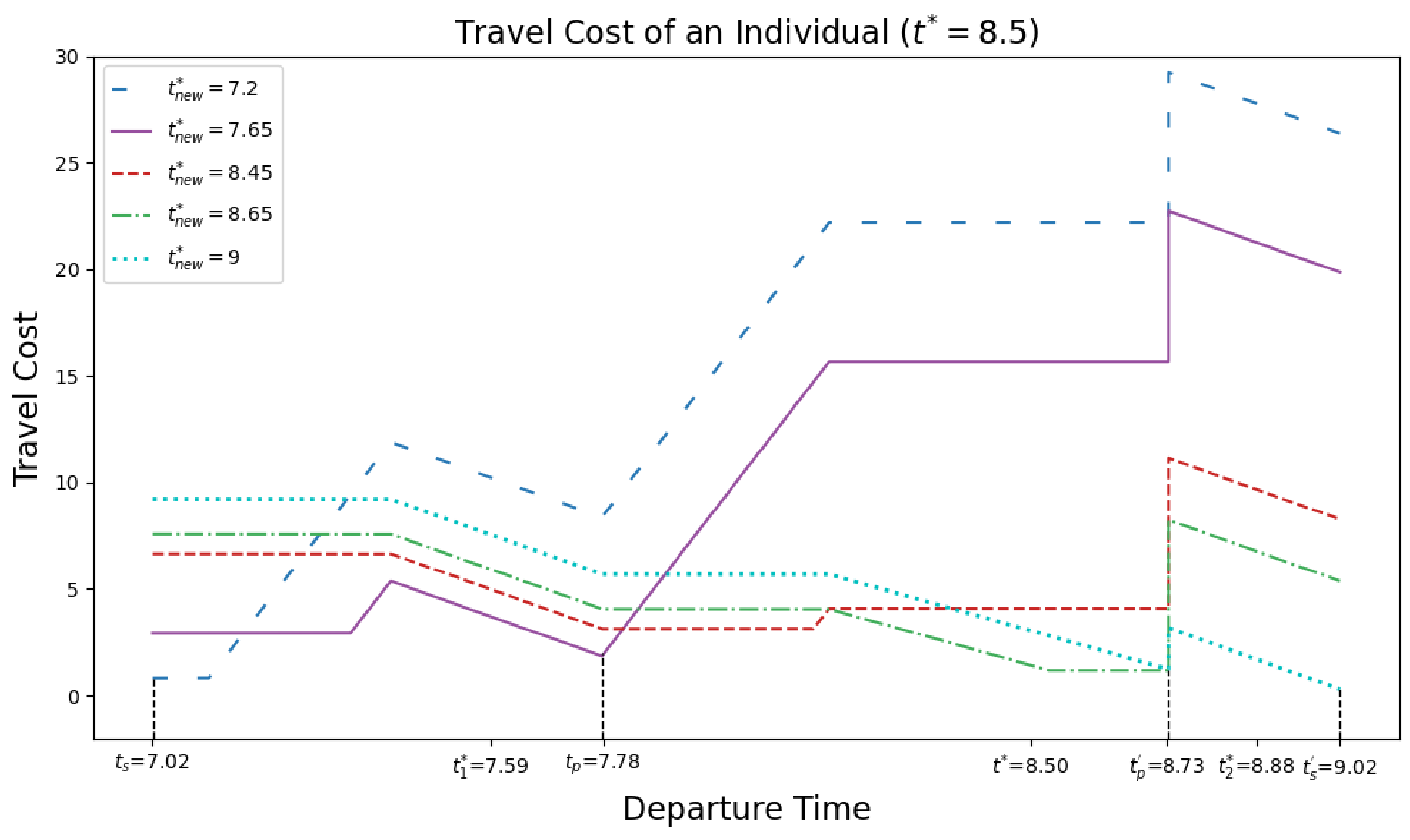
where $t_1 = \frac{\gamma t_p + \beta t_s}{\beta + \gamma}$ and $t_2 = \frac{\frac{1}{2}\beta(t'_s + t'_p) + \gamma t'_s - \frac{1}{2}\alpha(t'_s - t'_p)}{\beta + \gamma}$

MODEL PROPERTIES

Departure time choice after work rescheduling

For an individual traveler who has undergone work rescheduling, he can certainly find a departure time from $\{t_s^*, t_p^*, {t_p'}^*, {t_s'}^*\}$ to minimize travel cost

$$t' = \begin{cases} t_s, & t_s < t_{new}^* \le t_1 \\ t_p, & t_1 < t_{new}^* \le t^* \\ t_p', & t^* < t_{new}^* \le t_2 \\ t_s', & t_2 < t_{new}^* \le t_s' \end{cases}$$



Collective departure and arrival pattern with noncompliance

- p_v denotes the probability of the work rescheduling for an individual commuter. Whether a commuter will experience the work rescheduling can be represented by a random variable V following Bernoulli distribution, i.e., $V \sim Ber(p_v)$.
- Considering that there is a fixed number of N commuters would travel during every morning peak and the assumption that potential work rescheduling of each commuter is independent, the total number of the travelers who experience work rescheduling, denoted as R, can also be represented by a random variable following a binomial distribution, i.e., $R \sim B(N, p_v)$.
- Therefore, for a given morning peak scenario on any day, the expected number of travelers experiencing work rescheduling is $E[R] = Np_v$.

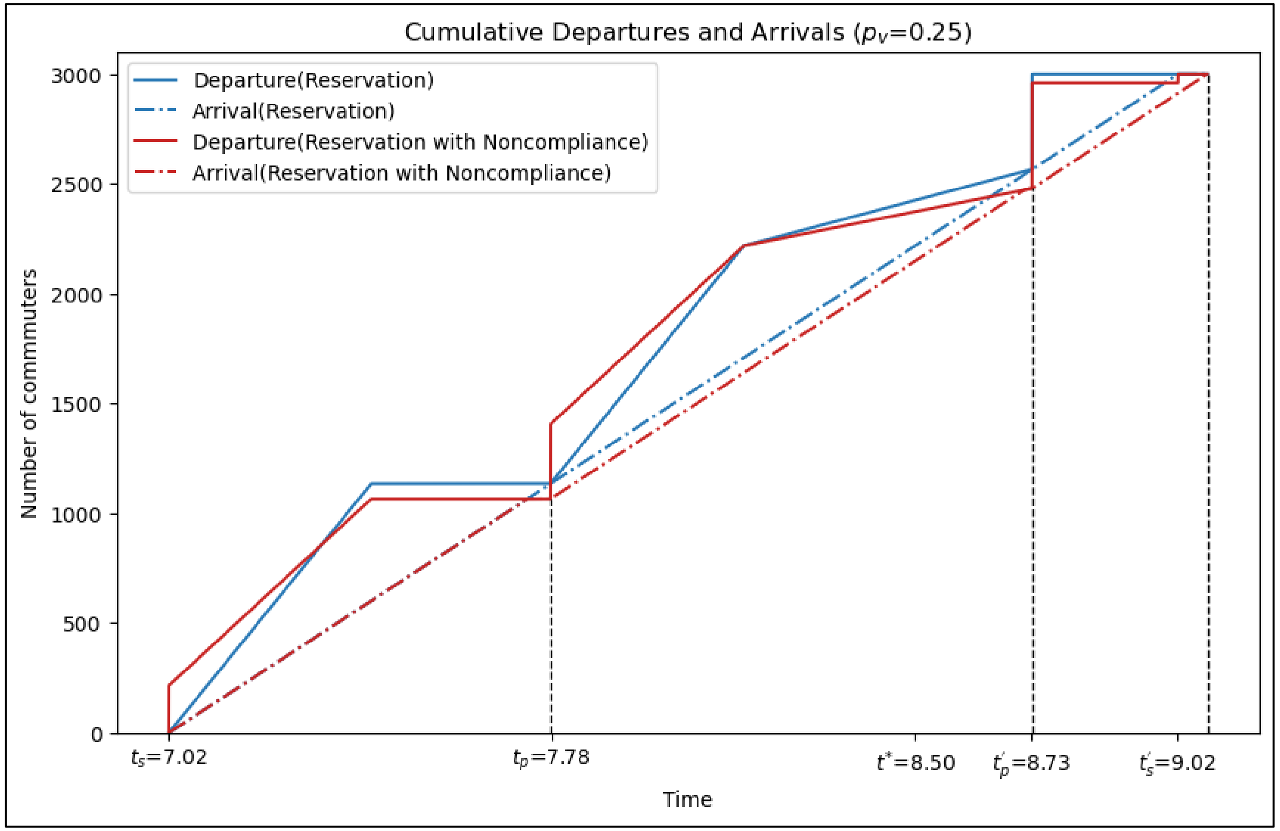
Collective departure and arrival pattern with noncompliance

- Based on the departure time decision rule, the new departure and arrival pattern can be obtained

The number of commuters in each time period under user equilibrium state caused by work rescheduling are denoted by N_1, N_2 and N_3. And N_0, N_4 denote the number of commuters who depart earlier than t_s or later than t_s'

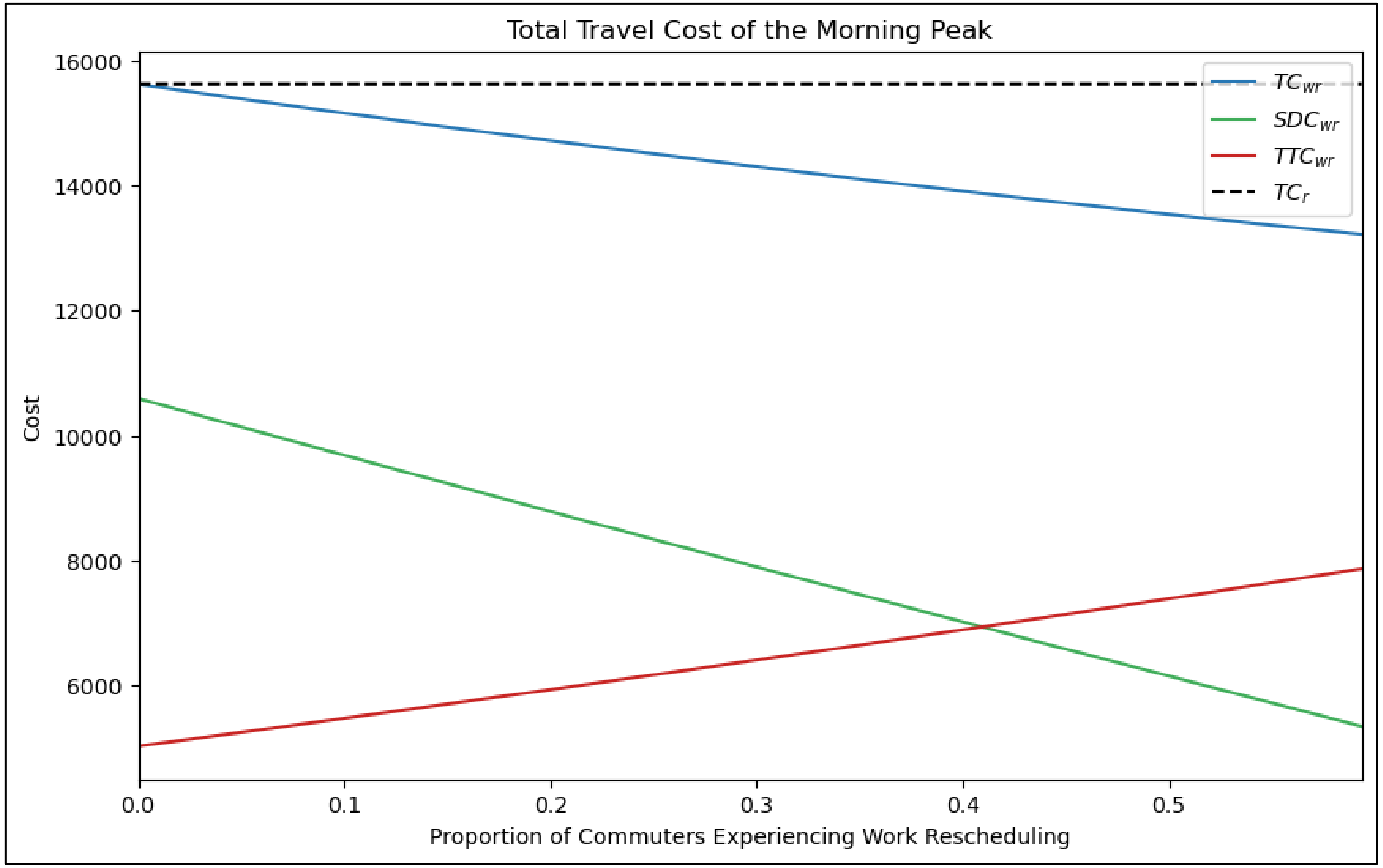
$$\begin{cases} N_0 = 0 \\ N_1 = \dfrac{N\gamma}{2(\beta+\gamma)} \\ N_2 = \dfrac{N\left(\gamma^2 + \alpha(2\beta+\gamma)\right)}{2(\alpha+\gamma)(\beta+\gamma)} \\ N_3 = \dfrac{N\beta\gamma}{(\alpha+\gamma)(\beta+\gamma)} \\ N_4 = 0 \end{cases}$$

$$\begin{cases} N_0' = N_0 = 0 \\ N_1' = N_1(1-p_v) + Np_vp_1 = \dfrac{N\gamma(\beta(1-p_v)+\gamma)}{2(\beta+\gamma)^2} < N_1 = \dfrac{N\gamma}{2(\beta+\gamma)} \\ N_2' = N_2(1-p_v) + Np_vp_2 = \dfrac{N(2(1-p_v)\alpha\beta^2 + 3\alpha\beta\gamma + (\alpha+\beta)\gamma^2 + \gamma^3)}{2(\alpha+\gamma)(\beta+\gamma)^2} < N_2 = \dfrac{N\left(\gamma^2 + \alpha(2\beta+\gamma)\right)}{2(\alpha+\gamma)(\beta+\gamma)} \\ N_3' = N_3(1-p_v) + Np_vp_3 = \dfrac{N\beta\left(2p_v\alpha\beta + p_v\gamma(\gamma-\beta) + 2\gamma(\beta+\gamma)\right)}{2(\alpha+\gamma)(\beta+\gamma)^2} > N_3 = \dfrac{N\beta\gamma}{(\alpha+\gamma)(\beta+\gamma)} \\ N_4' = Np_vp_4 = \dfrac{Np_v\beta\gamma(\alpha+\beta)}{2(\alpha+\gamma)(\beta+\gamma)^2} > N_4 = 0 \end{cases}$$



SENSITIVITY ANALYSIS

Total travel cost during the morning peak

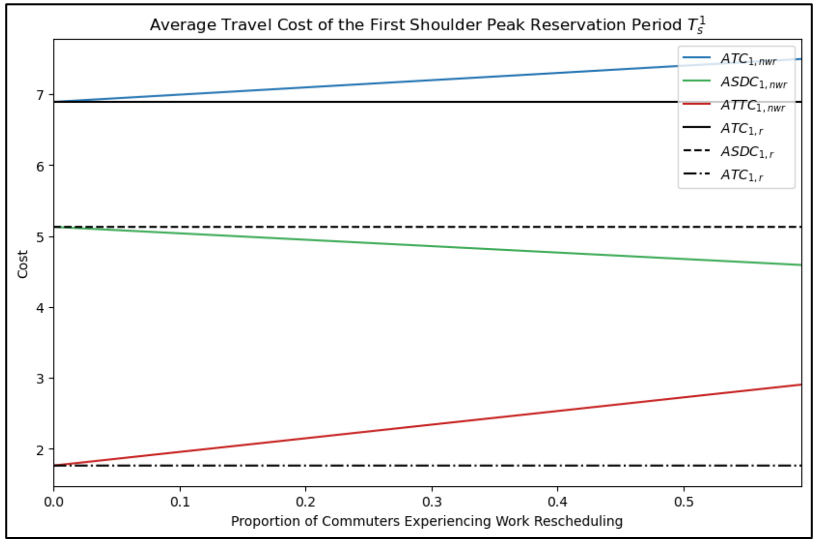


- Total travel cost TC_{wr} (corresponding to the blue curve) have declined slightly
- Upward trend of red line indicates that total queuing cost TTC_{wr} at the bottleneck has increased, resulting growth in deadweight loss for the society as a whole.
- The decline in TC_{wr} is only due to the fact that total schedule delay cost SDC_{wr}
- Congestion has become even aggravated eventually due to noncompliance

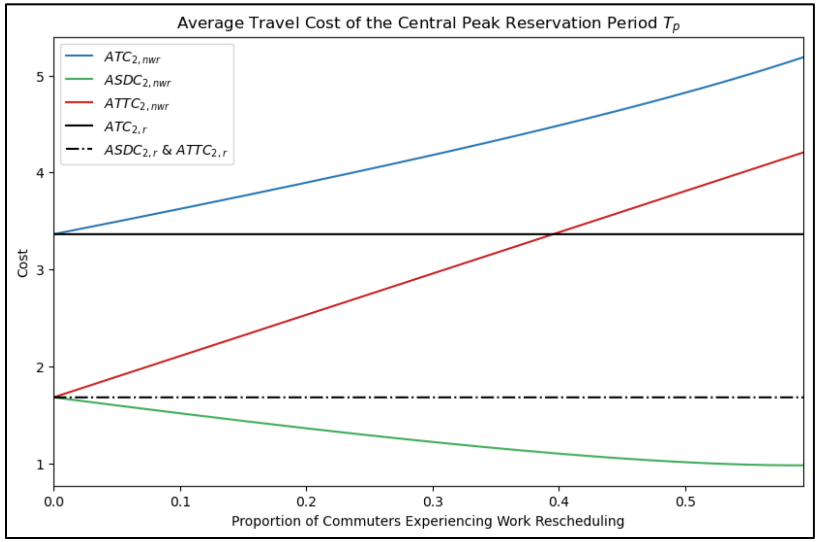
PART V

SENSITIVITY ANALYSIS

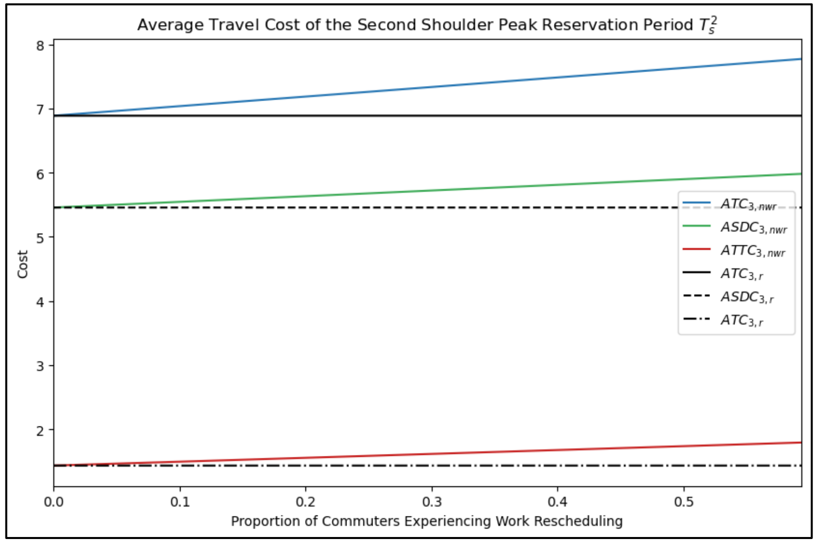
Individual travel cost during the morning peak



T_s^1



T_p



T_s^2

- Travel time cost of T_p increase rapidly with the growth of p_v, indicating that noncompliance would seriously aggravate the traffic congestion during the central peak period

DISCUSSION

CONCLUSION

- Proposed reservation scheme with optimal time window division and initial central peak reservation rights distribution would improve the efficiency of the bottleneck by 52.3% in the ideal circumstance
- As the proportion of commuters that undergo unexpected work rescheduling increases, the total travel cost has dropped but the total travel time cost, i.e., queuing time cost has increased, which signifies an even more severe congestion than it used to.

FUTURE WORK

- The uncertainty of free-flow travel time may lead to noncompliance
- Elaborate punishment and compensation mechanisms, which means that reservation rights for different time windows and noncompliance have potential value indeed
- Day-to-day evolution process of the reservation time window and departure time adjustment

Thank you for listening!

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