Managing Congestion and Infection Externalities in a Road and Rail Network: Pricing versus Permits

Kexin Geng[1], Zhiyuan Liang*[2], Erik T. Verhoef[3], Yacan Wang[4]

[1] PhD, Departments of Economics, Beijing Jiaotong University, China; Department of Spatial Economics, Vrije Universiteit Amsterdam, the Netherlands

[2] PhD, Departments of Economics, Beijing Jiaotong University, China

[3] Professor, Department of Spatial Economics, Vrije Universiteit Amsterdam, the Netherlands

[4] Professor, Departments of Economics, Beijing Jiaotong University, China

SHORT SUMMARY

Peak-hour crowding of mass transit not only leads to uncomfortable passenger experiences but may also give rise to severe health risks. This paper analyzes the allocative efficiency of prices and permits before and after COVID-19 based on a crowding road and rail network where the two modes are imperfect substitutes, and mainly focuses on comparative results for uncertainty on social (outside the train system) and private (in the train system) infection cost parameters. By considering the uncertainty during COVID-19, we find that uncertainty of the private infection cost parameter will change the relative efficiency and welfare effect of these two instruments, but not uncertainty on social infection costs. Moreover, the numerical results indicate that pricing regulation performs better than the tradable permit scheme when private infection cost is uncertain. The results provide theoretical support for policymakers to choose the optimal instruments to internalize the multiple external costs when uncertainties exist.

Keywords: COVID-19, crowding costs, infection costs, multiple externalities, uncertainty

1. INTRODUCTION

Peak-hour crowding of mass transit is a severe problem in metropolitan areas all over the world. This excessive congestion not only leads to uncomfortable passenger experiences but may also give rise to severe health risks, especially during the COVID-19 pandemic (Oum & Wang, 2020). Because subway service as an enclosed environment has high risk of infection. As a result, passengers are more concerned about public transport hygiene than pre-COVID (Beck & Hensher, 2020). Passengers' perception of the additional health cost caused by crowding will then impact their travel behaviors, especially the travel modal choice (Jenelius and Cebecauer, 2020; Zhang et al., 2021). More seriously, rail passengers who choose to depart in busy hours impose negative externalities, notably by increasing the health cost for the other passengers and also, indirectly, non-passengers (Seidlein et al., 2021). Hence, the infection risk produced by each passenger is not only confined inside the carriage they take, but also brought to the whole city, or even a larger area.

The comparison between pricing-based and quantity-based tools on managing various kinds of externalities has a long history in the economic literature (e.g., Weitzman, 1974; Yohe, 1978; Stavins, 1997). Although quantity controls are generally less efficient than pricing, efficiency can be improved if usage rights can be traded among agents (de Palma & Lindsey, 2020). Previous studies found that when there is uncertainty about the marginal cost of abatement, and the policy cannot be adapted to the variations, tradable permits and price are not always equivalent (Weitzman, 1974; Czerny, 2010; de Palma et al., 2018; de Palma & Lindsey, 2020).

It is important to include uncertainty when comparing congestion charge and tradable mobility permits in the COVID-19 context. Since the epidemic as an unexpected exogenous shock is new and unfamiliar for everybody, individuals' infection costs are uncertain for policymakers in transportation system. Ignoring these uncertainties will affect the relative merits of different policies. What's more, the COVID-19 context brings new challenges for the comparison of price and permits. Unlike previous studies which only focus on the congestion externalities inside the traffic system, the infection externalities caused by COVID-19 emerge both inside and outside the traffic system, since the epidemic spreads among all people - not only passengers.

Hence, this study aims to extend previous studies by comparing the efficiency of prices and permits for controlling both crowding costs and infection costs under different types of uncertainty in public transport. The infection costs are composed by two parts. First is what we call the private infection cost, which is directly incurred by rail passengers. Note that also this private cost entails an external cost between rail passengers. The other is the social infection cost, which occurs when an infected passenger subsequently infects non-passengers. We perform a welfare comparison of prices and permits under the uncertainties of both private infection cost and social infection cost.

We address the following research questions: 1) How will the unregulated and first-best user equilibriums change after the COVID-19 pandemic? 2) How does allocative efficiency for a tradable permit scheme versus a congestion charge compare when considering the private infection cost uncertainty under the COVID-19 pandemic? 3) How does allocative efficiency for a tradable permit scheme versus a congestion charge compare when considering the social infection cost uncertainty under the COVID-19 pandemic?

2. METHODOLOGY

2.1 Problem Settings

We consider a simple network, with a parallel road and rail line that connects a single origin and destination, where the two modes are imperfect substitutes. Commuters can choose to use auto or metro for commuting based on the trade-off of travel cost by modes. The costs of usage by each mode are show below.

$$C_A = a_A + b_A \cdot n_A \tag{1}$$

$$C_M = a_M + b_M \cdot n_M \tag{2}$$

where C_A and C_M are costs of the trip by auto and metro separately (A denotes auto and M denotes metro hereafter). Parameter a_A and a_M are the intercepts of the marginal private cost curve, e.g., a_M includes a fixed ticket price for the rail. Parameter b_A and b_M govern the rate at which the facility becomes congested. Parameter n_A and n_M are the number of users choosing auto and metro.

The total travel cost (TC) for all travelers is the sum of the travel cost from both auto users and rail passengers, which is expressed as follows:

$$TC = C_A \cdot n_A + C_M \cdot n_M \tag{3}$$

where $C_A \cdot n_A$ is the total travel cost for auto users, and $C_M \cdot n_M$ is the total travel cost for rail passengers.

We assume that the two modes are imperfect substitutes. The inverse demand for mode j, which gives the marginal willingness to pay to travel of the n^{j}th user is:

$$D_A = F_A + B_A n_A + H_A n_M \tag{4}$$

$$D_M = F_M + B_M n_M + H_M n_A \tag{5}$$

where D_A and D_M are the inverse demand of auto and metro users separately, which give the marginal willingness to pay to travel of the n_Ath user and n_Mth user. F_A and F_M is the maximum willingness-to-pay. Coefficients B_A and H_A respectively measure how much the inverse demand decreases when there are more users on modes auto and metro. For metro users, coefficients B_M and H_M respectively measure how much D_M decreases when there are more users on modes metro and auto.

Gross consumer benefit (G) is the line integral of the two inverse demands and it is independent of the path used for integration:

$$\begin{aligned} G &= \int_{(0,0)}^{(n_A,n_M)} (D_A[x_A, x_M]\,dx_A + D_M[x_A, x_M]\,dx_M) \\ &= n_A\big(F_A + (B_A \cdot n_A/2)\big) + n_M\big(F_M + (B_M \cdot n_M/2)\big) + H n_A n_M \end{aligned} \tag{6}$$

Then, welfare (W) is the gross consumer benefit (G) minus total cost for all users (TC):

$$W = \int_{(0,0)}^{(n_A,n_M)} (D_A[x_A, x_M]\,dx_A + D_M[x_A, x_M]\,dx_M) - C_A \cdot n_A + C_M \cdot n_M \tag{7}$$

2.2 User equilibrium before COVID-19

We start from the normal context before the COVID-19 outbreak, for which we assume that on the road there is bottleneck congestion while in each train there is crowding congestion. Three policies are considered for rail: the no incentive case, the optimal toll scheme and the optimal tradable permit schemes; while there is a third-best toll implemented on the road.

2.3User equilibrium after COVID-19

Then, we discuss the context after the COVID-19 outbreak. The COVID-19 pandemic spreads through person-to-person contact. Since the auto vehicle separates each user into an enclosed small unit, we assume that the cost of usage for auto users will not be affected by the COVID-19. On the contrary, the in-carriage infection cost becomes an important part for train passengers, and increase the cost of usage for rail users. The cost of train after the COVID-19 outbreak (denoted by superscript V) is:

$${C_M}^V = a_M + b_M \cdot n_M + \eta \cdot n_M \tag{8}$$

where $\eta \cdot n_M$ expresses the private infection cost of train travelers, which is linear with the number of passengers. η is the private infection cost parameter, including both the medical cost paid for the treatment and the health cost capturing suffering of illness and residual effect of COVID-19 on health caused by an additional passenger (Oum & Wang, 2020).

The social infection cost is also considered in our model after COVID-19, hence, the social welfare function is expressed as:

$$W = \int_{(0,0)}^{(n_A,n_M)} (D_A[x_A, x_M]\,dx_A + D_M[x_A, x_M]\,dx_M) - C_A \cdot n_A - C_M \cdot n_M - A \cdot n_M \tag{9}$$

where A is the social infection cost parameter that relates the number of metro travellers to the social infection cost.

Similarly, the no incentive case, the optimal toll scheme and the optimal tradable permit scheme, which cover both the crowding cost and social infection cost for rail, are solved and compared.

2.4 Price versus Permits under uncertainty

The uncertainty of private infection cost and social infection cost are further discussed in this paper, separately.

In the private infection cost case, we assume that the regulator views η as a random variable with strictly positive density, $f(\eta)$, on the interval $[\underline{\eta}, \overline{\eta}]$, and associated distribution function $F(\eta)$.

In the social infection cost case, we assume that the regulator views A as a random variable with strictly positive density, $k(A)$, on the interval $[\underline{A}, \overline{A}]$, and associated distribution function $K(A)$.

The optimal toll scheme and tradable permit scheme are designed and compared in the above uncertain cases.

2.5 Numerical analyses

Finally, numerical examples are used to further illustrate the model.

Table 1 Parameters used in the numerical analysis

Parameter	Value
F_A	10000
F_M	10000
B_A	-0.5
B_M	-0.5
H	-0.3
a_A	10
a_M	2
b_A	0.01
b_M	0.01
A	2
η	0.1

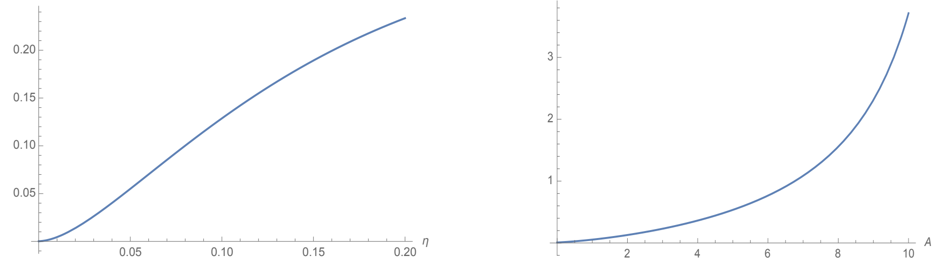
Based on the ratio of travel mode change before and after COVID in Beijing, we set the value of each parameter in our model. Specifically, the intercept or the maximum willingness-to-pay for auto (F_A) and for metro (F_M) are same, 10000. We assume that the demand elasticity for each mode is the same, and the parameters B_A equals B_M which is -0.5. And the cross-substitution effects parameter H is -0.3. Given the fixed cost for auto is larger than metro, the intercepts of the general price curve for auto is set to 10 while for metro is 2. Parameter b_A and b_M are 0.01. Finally, the social infection cost parameter A is 2 and the private infection cost parameter η is 0.1.

No incentive case, first-best, optimal toll scheme and optimal tradable permit scheme with uncertainties caused by COVID-19 are compared with the dynamic private infection cost parameter. The sensitivity analysis of different cases with uncertainties is conducted, which allows the change of parameters in demand function and cost function while the number of travelers in each mode fixed in no incentive case.

3. RESULTS AND DISCUSSION

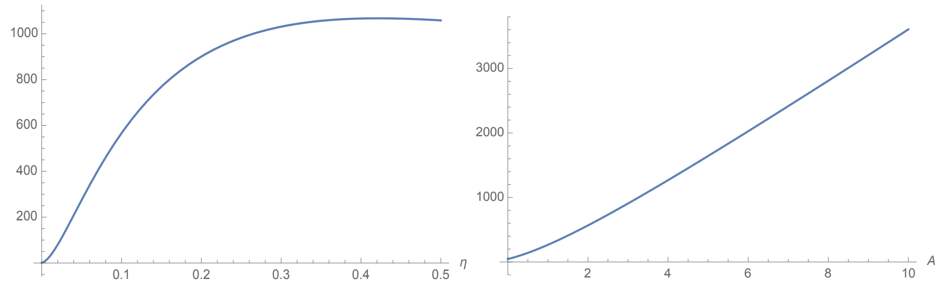
The analytical results show: (1) Rail travelers do not internalize the external cost of infection risks they impose on other commuters and citizens. (2) If no uncertainty exists in the demand and cost functions, both permits and prices can be used to reach the FBO with or without COVID-19 effects. (3) Uncertainty of private infection cost leads to the different equilibrium under optimal congestion and infection toll and tradable permits. Uncertainty of the social infection cost has no effect on the relative efficiency and welfare comparison between optimal toll and tradable permits.

The numerical analyses further find:
(1) The increase of the social infection cost parameter and the private infection cost parameter will enlarge the welfare improvement from prices or permits after COVID-19.



(a) Fixed value of social infection cost parameter A (b) Fixed value of private infection cost parameter η

Figure 3 Welfare change between the first-best equilibrium and the unregulated equilibrium after COVID-19 ($(W^{AC\_FBO} - W^{AC\_NI})/W^{AC\_NI}$)



(a) Fixed value of social infection cost parameter A (b) Fixed value of private infection cost parameter η

Figure 4 Welfare change between the first-best equilibrium and the unregulated equilibrium before and after COVID-19 ($(W^{AC\_FBO} - W^{AC\_NI})/(W^{BC\_FBO} - W^{BC\_NI})$)

(2) When considering the uncertainty of private infection cost, the fixed toll always performs better than fixed permits. When the distribution of social infection cost gets even larger, the differences between the fixed toll, fixed permits and the first-best case become more significant.

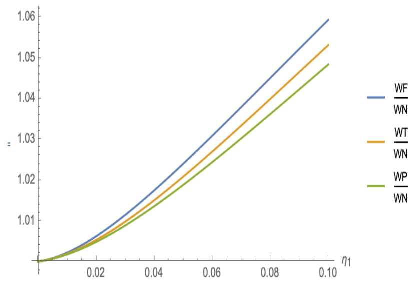


Figure 5a Welfare comparison with dynamic η_1(η_2=0)

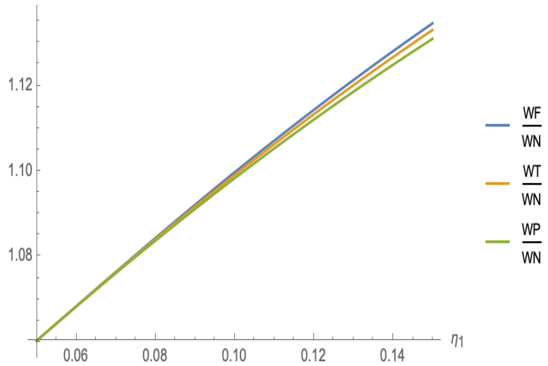


Figure 5b Welfare comparison with dynamic η_1(η_2=0.05)

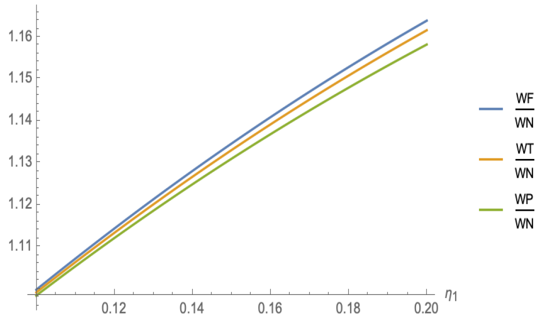


Figure 5c Welfare comparison with dynamic η_1(η_2=0.1)

Moreover, both the change of parameters in demand and cost functions have no effect on the order of the four cases (no incentive, fixed toll, fixed permits and first-best case) based on the social welfare. The fixed toll always performs better than the fixed permits no matter how the parameters in demand functions or cost functions change.

Table 2 Parameters in demand functions change

b_M	b_A	a_M	a_A	WN	WT	WP	WF
0.014	0.014	-39.120	-96.247	$9.831*10^{7}$	$1.081*10^{8}$	$1.080*10^{8}$	$1.081*10^{8}$
0.013	0.013	-28.840	-69.685	$9.813*10^{7}$	$1.079*10^{8}$	$1.078*10^{8}$	$1.079*10^{8}$
0.012	0.012	-18.560	-43.123	$9.796*10^{7}$	$1.077*10^{8}$	$1.076*10^{8}$	$1.077*10^{8}$
0.011	0.011	-8.280	-16.562	$9.778*10^{7}$	$1.075*10^{8}$	$1.074*10^{8}$	$1.075*10^{8}$
0.01	**0.01**	**2**	**10**	**$9.760*10^{7}$**	**$1.073*10^{8}$**	**$1.072*10^{8}$**	**$1.074*10^{8}$**
0.009	0.009	12.280	36.562	$9.743*10^{7}$	$1.071*10^{8}$	$1.070*10^{8}$	$1.072*10^{8}$
0.008	0.008	22.560	63.123	$9.725*10^{7}$	$1.069*10^{8}$	$1.068*10^{8}$	$1.070*10^{8}$
0.007	0.007	32.840	89.685	$9.708*10^{7}$	$1.067*10^{8}$	$1.066*10^{8}$	$1.068*10^{8}$
0.006	0.006	43.120	116.246	$9.690*10^{7}$	$1.065*10^{8}$	$1.064*10^{8}$	$1.066*10^{8}$

Table 3 Parameters in cost functions change

B_A	B_M	F_A	F_M	WN	WT	WP	WF
-0.3	-0.3	7343.84	7944.01	$6.917*10^{7}$	$8.524*10^{7}$	$8.520*10^{7}$	$8.524*10^{7}$
-0.4	-0.4	8671.92	8972.01	$8.356*10^{7}$	$9.529*10^{7}$	$9.523*10^{7}$	$9.533*10^{7}$

-0.5	**-0.5**	**10000**	**10000**	**$9.760*10^7$**	**$1.073*10^8$**	**$1.072*10^8$**	**$1.074*10^8$**
-0.6	-0.6	11328.1	11028	$1.117*10^8$	$1.200*10^8$	$1.200*10^8$	$1.201*10^8$
-0.7	-0.7	12656.2	12056	$1.257*10^8$	$1.332*10^8$	$1.331*10^8$	$1.332*10^8$
-0.8	-0.8	13984.2	13084	$1.398*10^8$	$1.465*10^8$	$1.464*10^8$	$1.466*10^8$
-0.9	-0.9	15312.3	14112	$1.539*10^8$	$1.600*10^8$	$1.600*10^8$	$1.601*10^8$

4. CONCLUSIONS

This paper analyzed prices and permits managing public transport in a road and rail network with crowding and infection cost, where the auto and metro are imperfect substitutes. We start from the normal context before the COVID-19 outbreak, which means that on the road there is bottleneck congestion while in each train there is crowding congestion. We assume that the road congestion is managed by an optimal congestion fee. An economic model was used to solve the socially optimal congestion price scheme and tradable permit schemes for rail. Then, we discuss the context after the COVID-19 outbreak. To that end, the private infection cost is added in the cost of usage for rail, which depends on the number of passengers. We acknowledge that because of the further spreading of pandemic, the social infection cost is higher than the private infection cost. This creates another externality in this research, and affects the equilibrium and the optimum of the transportation system. The socially optimal congestion price scheme and tradable permit scheme, covering both the crowding and infection cost, are solved and compared. Furthermore, we separately study the uncertainties of the private infection costs and social infection costs, and their effects on the welfare comparison between prices and permits are discussed.

The preliminary results show that, in a stationary context, prices and permits have equivalent efficiency on inducing travelers to internalize this external cost. The existence of external cost of infection risks implies that the optimal toll and the optimal permit price under the COVID-19 context should be higher than the marginal crowding externality and also include the marginal infection cost inside and outside the traffic system. But this condition will change when we consider the uncertainty of infection costs. We assume that the congestion charge scheme cannot be day-to-day adaptive and the supply of permits is fixed for all possible states. Then, in the private infection cost uncertain context, the pricing regulation performs better than the tradable permit scheme. Especially when the distribution of the parameter becomes wide, and the difference between marginal private infection cost and the marginal crowding cost is at a relatively low level, the welfare gain obtained by prices is slightly larger than it obtained by tradable permits. For the next step, we will gradually compare the welfare gains of prices and permits from the basic case without uncertainties and social externalities to more complex cases, and under different demand and supply cases.

This study contributes to the existing literature in the following ways. First, we provide an approach for analyzing congestion and infection externalities in a joint framework. Future research can expand the current study by considering more complex contexts capturing, for example, heterogeneity of travelers. Second, our modeling analysis sheds light on the efficiency of tradable permits in managing mass transit crowding with unexpected demand and cost shocks, which in our model represented by the COVID-19. It can help governments and public transport operators to design and adjust their instruments for managing passenger flows in mass transit.

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REFERENCES

Beck M. J., Hensher D.A. 2020. Insights into the impact of COVID-19 on household travel and activities in Australia – The early days of easing restrictions. *Transport Policy*, Vol.96, pp.94-100.

Czerny A.I. 2010. Airport congestion management under uncertainty. *Transp. Res. Part B Methodol*. Vol.44, pp.371–380.

de Palma A., Proost S., Seshadri R., Ben-Akiva M. 2018. Congestion tolling-dollars versus tokens: A comparative analysis. *Transportation Research Part B: Methodological*, Vol.108, pp.261–280.

de Palma, A., Lindsey R. 2020. Tradable permit schemes for congestible facilities with uncertain supply and demand. *Economics of Transportation*, Vol.21, pp.100149.

Jenelius, E., Cebecauer M. 2020. Impacts of COVID-19 on public transport ridership in Sweden: analysis of ticket validations, sales and passenger counts. *Transp. Res. Interdiscip. Perspect*. Vol.8, pp.100242.

Oum T. H., Wang K. 2020. Socially optimal lockdown and travel restrictions for fighting communicable virus including COVID-19. *Transport Policy*, Vol.96, pp.94-100.

Seidlein L., Alabaseter G. Deen G., Jakobal K. 2021. Crowding has consequences: Prevention and management of COVID-19 in informal urban settlements. *Building and Environment,* Vol.188, pp.107472.

Stavins R.N. 1997. Correlated uncertainty and policy instrument choice. *J. Environ. Econ. Manag.* Vol.30, pp.218–232.

Weitzman M.L. 1974. Prices vs. quantities. *Rev. Econ. Stud.* Vol.41, No.4, pp.477–491.

Yohe G.W. 1978. Towards a general comparison of price controls and quantity controls under uncertainty. *Rev. Econ. Stud.* Vol.45, pp.229–238.

Zhang J., Hayashi Y., Frank L.D. 2021. COVID-19 and transport: findings from a world-wide expert survey. *Transport Policy*, Vol.103, pp.68–85.