

Preferences for using the London Underground during the COVID-19 pandemic

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Preferences for using the London Underground during the COVID-19 pandemic

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ABSTRACT

The COVID-19 pandemic has drastically impacted people's travel behaviour and introduced uncertainty in the demand for public transport. To investigate user preferences for travel by London Underground during the pandemic, we conducted a stated choice experiment among its pre-pandemic users ($N = 961$). We analysed the collected data using multinomial and latent class logit models. Our discrete choice analysis provides two sets of results. First, we derive the crowding multiplier estimate of travel time valuation (i.e., the ratio of the value of travel time in uncrowded and crowded situations) for London underground users. The results indicate that travel time valuation of Underground users increases by 73% when it operates at technical capacity. Second, we estimate the sensitivity of the preference for the London Underground relative to the epidemic situation (confirmed new COVID-19 cases) and interventions (vaccination rates and mandatory face masks). The sensitivity analysis suggests that making face masks mandatory is a main driver for recovering the demand for the London underground. The latent class model reveals substantial preference heterogeneity. For instance, while the average effect of mandatory face masks is positive, the preferences of 30% of pre-pandemic users for travel by the Underground are negatively affected. The positive effect of mandatory face masks on the likelihood of taking the Underground is less pronounced among males with age below 40 years, and a monthly income below 10,000 GBP. The estimated preference sensitivities and crowding multipliers are relevant for supply–demand management in transit systems and the calibration of advanced epidemiological models.

1. Introduction

The COVID-19 pandemic has severely affected the demand for public transport in many parts of the world (Tirachini & Cats, 2020; Transport Strategy Centre, 2020; Vickerman, 2021). Initial lockdown measures resulted in a sharp drop in ridership (Transport Strategy Centre, 2020). Demand for public transport has increased since the early stages of the pandemic but remains below pre-COVID levels, possibly due to decreased out-of-home activity participation and a perceived risk of infection in enclosed public spaces (Tirachini & Cats, 2020; Transport Strategy Centre, 2020; Vickerman, 2021). Despite increasing vaccination rates and the gradual easing of restrictions, the trajectory of future public transport demand is uncertain.

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SARS-CoV-2, the virus that causes COVID-19, spreads via droplets and aerosols (Anderson et al., 2020; Asadi et al., 2020; Morawska & Cao, 2020). As a consequence, COVID-19 transmissions are more likely to occur in enclosed spaces such as public transport (Morawska & Milton, 2020; Prather et al., 2020). To counteract the spread of COVID-19, authorities have mandated various non-pharmaceutical interventions, such as closures of schools and non-essential businesses, work-from-home, and restrictions to out-of-home activities. Interventions such as physical distancing requirements, mandatory face masks and stricter hygiene protocols aim at reducing the risk of contagion in public spaces, including public transport. Besides, information campaigns of public health authorities have emphasised that such measures can effectively prevent COVID-19 transmissions. However, at the same time, such measures have affected the demand for public transport. In some jurisdictions, authorities even discouraged the use of public transport (see Tirachini & Cats, 2020, and the literature referenced therein).

To this date, there is no conclusive evidence about the likelihood of COVID-19 infections on public transport compared to other places (Hörcher et al., 2021). However, it is well established that face masks effectively reduce the risk of contagion when adequate physical distancing cannot be maintained (Cheng et al., 2021). In addition, COVID-19 vaccines provide effective protection against symptomatic and asymptomatic infections with the virus (Dagan et al., 2021; Hall et al., 2021). Regardless of the objective effectiveness of these measures, travellers may still perceive that travelling by public transport presents a significant infection risk, especially in crowded conditions. Thus, perceived infection risks and the absence or presence of countermeasures are likely to affect the demand for public transport, both during and after the COVID-19 pandemic.

Knowledge of public transport users' sensitivities to crowding, the epidemic situation and non-pharmaceutical interventions is essential both in the short run and in the long run in a post-pandemic world. First, insights into demand characteristics may inform the design and implementation of demand management strategies aimed at reducing crowding levels in public transport (Hörcher et al., 2021; Tirachini & Cats, 2020). Second, advanced person-centric epidemic modelling and simulation frameworks (e.g. Aleta et al., 2020; Müller et al., 2021), which account for time- and place-specific infection risks as well as various aspects of activity-travel behaviour, depend on detailed information about demand characteristics in order to accurately forecast the progression of the epidemic situation. Finally, insights into demand characteristics are crucial for supply-side planning and management, project appraisal and welfare analysis.

A substantial body of literature investigated crowding sensitivities of subway demand before the COVID-19 pandemic (Bansal et al., 2019, 2022a; Li & Hensher, 2011; Tirachini et al., 2017; Wardman & Whelan, 2011). Crowding is typically measured in terms of passenger densities, vehicle occupancy rates and the availability of empty seats or standing room. In general, higher levels of crowding are found to increase the disutility of travel time. The effect of crowding on travel time valuation of public transport users is quantified using the crowding multiplier, i.e. the ratio of the value of travel time under crowded and uncrowded situations.

To this date, only a few studies have investigated crowding sensitivities in the context of the COVID-19 pandemic. Using data from two stated choice surveys conducted before and after the outbreak of the COVID-19 pandemic among users of the public transport system in Seoul, Korea, Cho and Park (2021) find that crowding multipliers after the outbreak of the pandemic are between 1.04 and 1.23 higher than the one before the pandemic. Similarly, Aghabay et al. (2021) conducted two stated choice surveys before and after the outbreak of the COVID-19 pandemic among public transportation users in Tehran, Iran. The authors find that relative to before the pandemic, sitting crowding multipliers increases between 0% and 27% and that standing crowding multipliers increased between 5% and 44%. Finally, Shelat et al. (2021) conducted a stated choice survey among public transit users in the Netherlands in May 2020. Using a latent class logit model, the authors identify two segments in the sample. The first segment is labelled “COVID conscious”. Its members are comparatively sensitive to crowding and infection rates. The second segment is labelled “infection indifferent”. Its members are insensitive to the prevalent infection rate and exhibit an only marginally higher sensitivity to crowding compared to pre-pandemic estimates.

To the best of our knowledge, no study to this date has jointly investigated the effect of crowding, the epidemic situation and the presence or absence of (non-)pharmaceutical interventions such as face masks and vaccination on the preference for public transport. The discrete choice experiments analysed in the before-and-after studies by Cho and Park (2021) and Aghabay et al. (2021) consider standard crowding and travel attributes—in the same way as many other studies conducted prior to the COVID-19 pandemic—but do not include attributes pertaining to the severity of the epidemic situation and (non-)pharmaceutical interventions. Thus, the two studies are helpful in identifying changes in crowding multipliers in response to the outbreak of the COVID-19 pandemic. However, they do not provide insights into public transit users' sensitivities to the epidemic situation and (non-)pharmaceutical interventions. The discrete choice experiment administered by Shelat et al. (2021) include the current infection rate as an attribute, but masks are assumed to be mandatory in all presented experimental scenarios and vaccination rate is ignored. Consequently, the study does not offer insights into public transit users' sensitivities to the non-pharmaceutical interventions and pharmaceutical measures.

To address this gap in the literature, we conducted a stated preference experiment among the pre-COVID users of the London Underground and analysed the collected data using multinomial and latent class logit models. Our analysis contributes to the literature with two main results. First, a post-pandemic crowding multiplier for travel time valuation is estimated for the London Underground. Second, the results provide insights into the sensitivity of the preferences for the London Underground with respect to the epidemic situation (confirmed new COVID-19 cases), non-pharmaceutical interventions (whether masks are mandatory or not), and pharmaceutical measures (vaccination rates). To illustrate the practical significance of the considered attributes, we analyse their effects on the probability of using the Underground by its pre-pandemic users. Variations in these probabilities across users with different demographic characteristics and opinions about countermeasures are also presented.

We organise the remainder of this paper as follows. In Section 2, we describe the survey design, data collection, and modelling approach of the study. In Section 3, we present the estimation results and analyse the practical significance of attributes and preference heterogeneity. Finally, we conclude in Section 4.

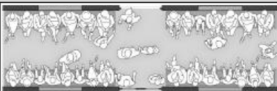
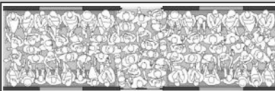
Attributes	Travel profile 1	Travel profile 2
Crowding levels		
	1 person / square metre	6 persons / square metre
Standing in the tube?	No	No
In-vehicle (on-board) travel time (minutes)	21 minutes	30 minutes
Daily new COVID-19 cases in the UK (per 100 thousand inhabitants)	50	10
Mask compulsory?	Yes	Yes
Vaccinated population in the UK	50%	80%

Fig. 1. An example of a choice scenario presented to respondents.

Table 1

Attribute levels of the discrete choice experiment design.

Attributes	Travel profile 1	Travel profile 2
Crowding density (persons per square meter)	[0,1,2,4,6]	[0,1,2,4,6]
Standing in the Underground?	[Yes, No]	[Yes, No]
Travel time (minutes)	[-30%, current,15%,30%]	[-30%, current,15%,30%]
Daily new COVID-19 cases (per 10 ⁵)	[10,30,50,70,90]	[10,30,50,70,90]
Mask compulsory?	[Yes, No]	[Yes, No]
Vaccine adoption in the UK	[5%,20%,35%,50%,65%,80%]	[5%,20%,35%,50%,65%,80%]

2. Methodology

2.1. Survey and experimental design

We conducted a stated preference survey among pre-pandemic users of the London Underground between March and May 2021. The survey included questions regarding respondents' current travel behaviour, exposure to COVID-19, vaccination status, socio-demographic characteristics as well as regarding perceptions about COVID-19 vaccination, face masks and the UK government's approach to handle the pandemic. The main part of the survey consisted of a discrete choice experiment (DCE) to understand the preferences of users of the London Underground during the pandemic. In the DCE, respondents were provided with choice scenarios based on crowding levels in the London Underground, travel time, daily new confirmed COVID-19 cases (7-day rolling average), the COVID-19 vaccinated population, and mask norms. In each scenario, respondents were asked to choose their preferred travel profile among two options involving travel by London Underground. An example of a choice scenario is presented in Fig. 1.

For the DCE, we adopted a partial profile design with three blocks and eight choice situations per block (Kessels et al., 2011; Kessels et al., 2015). One of three blocks was randomly chosen and presented to a respondent. All blocks were distributed uniformly over the respondents. The levels of the considered attributes in the DCE are presented in Table 1. The maximum crowding density level is six persons per square meter, which is the technical capacity of the London Underground. Travel time is pivoted on a respondent's travel time in the most frequent trip by the Underground. The highest level of daily new confirmed cases (7-day rolling average) is 90 per 100,000 inhabitants, which is the maximum observed number of daily new cases in the UK, which occurred in January 2021. We chose the remaining attribute levels based on design judgement. Technical details of the partial profile design are presented in the Appendix.

2.2. Data collection

To ensure that the respondents were familiar with the London Underground and hypothetical bias in the DCE remained minimal,

Table 2

London population and sample proportions across different demographic groups.

	2011 United Kingdom census (London population)	Sample proportions (N = 961)
Gender		
Male	49.5%	48.3% (464)
Female	50.5%	51.7% (497)
Age		
19 to 39 years	47.4%	41.7% (401)
40 to 59 years	32.0%	36.3% (349)
60 + years	21.7%	22.0% (211)
Asian or Asian British?	18.5%	14.7%
Married?	39.9%	37.5%
Unemployed or retired?	25.3%	16.9%

Table 3

Travel mode preferences of workers before and during the COVID-19 pandemic (N = 798).

Travel mode	All workers			Workers who commuted		
	Nov-19	Jun-20	Jan-21	Nov-19	Jun-20	Jan-21
Bus/tram	74	54	62	9%	13%	14%
Underground	542	168	190	69%	39%	42%
Car	39	69	67	5%	16%	15%
Taxi/ridesharing/carpool	4	14	16	1%	3%	4%
Bicycle/walk	32	84	73	4%	20%	16%
Rail	93	38	41	12%	9%	9%
I did not travel to work	14	371	349			

Table 4

Attitudes regarding COVID-19 vaccines and masks.

	Agree	Somewhat agree	Somewhat disagree	Disagree
Vaccine-related statements				
I trust COVID-19 vaccine technology.	53%	34%	7%	5%
I am worried about the side-effects of the COVID-19 vaccine.	22%	29%	27%	22%
I think the vaccine will not be powerful in the long term.	16%	37%	33%	13%
The information provided by the government regarding COVID-19 vaccines is credible.	33%	48%	14%	5%
Mask-related statements				
Any kind of mask helps in controlling COVID-19 spread.	40%	39%	14%	8%
I always wear a mask at public spaces.	77%	17%	4%	3%
Wearing a mask can cause respiratory issues.	11%	27%	33%	30%

we set strict eligibility criteria for the survey participation. Londoners older than 18 years, who had used the London Underground for three or more round trips per week in 2019, had spent more than nine months in London during 2020, and intended to stay more than nine months in London during 2021 were eligible for the survey. The study was reviewed and approved by the Research Governance and Integrity Team at Imperial College London on March 11, 2021 (SETREC number: 21IC6629) under the Science Engineering Technology Research Ethics Committee (SETREC) process.

In total, 1080 responses were collected. To maintain data quality, we performed several checks. After excluding fast responses (i.e., with a response time below forty percent of the median response time), straight-liners (i.e., chose the same travel profile number across all eight choice situations in the DCE), and inconsistent responses (i.e., reported household size lower than the sum of the number of children and workers), 961 responses remained for further analysis. [Table 2](#) shows that the sample is representative of the London population across gender, age groups, ethnicity, and marital status, but slightly underrepresents the unemployed or retired group.

2.3. Summary statistics

Travel mode preferences of commuters before and during the pandemic are presented in [Table 3](#). The table shows that around 45% of workers did not commute during the pandemic, whereas this proportion was below 2% before the pandemic. Among workers who commuted, the share of the London Underground has dropped by around 25–30% during the pandemic. At the same time, shares of sustainable travel modes and cars have increased by 10–15%. These statistics suggest that understanding the factors that can help regain the demand for the London Underground is the need of this hour.

[Table 4](#) presents a summary of attitudes regarding COVID-19 vaccines and masks. 87% and 81% of respondents trust vaccine technology and the information provided by the UK government regarding vaccines, respectively. However, 51–53% of respondents

Table 5

Trust in COVID-19 vaccine technology and satisfaction with government's approach among respondents with different vaccination levels.

	First dose (N = 435)	Both doses (N = 98)	No dose (N = 428)
<i>I trust COVID-19 vaccine technology</i>			
Agree	96%	98%	76%
Disagree	4%	2%	24%
<i>Satisfaction with government's approach to the COVID-19 pandemic</i>			
Satisfied	57%	63%	45%
Dissatisfied	43%	37%	55%

are worried about the vaccines' side effects and do not find vaccines powerful in the long term. Despite that 38% of respondents believe in possibilities of respiratory issues due to mask usage, 94% of respondents wear masks in public spaces. 79% of respondents believe in the abilities of a mask to control the COVID-19 spread. The summary statistics also show that only 52% of respondents are satisfied with the UK government's approach to handling the pandemic, 9% of respondents tested COVID positive, and 55% of respondents have taken at least one dose of the vaccine.

We also explore heterogeneity in respondents' opinions across their vaccination status in Table 5. The results indicate that only 2–4% of those respondents who have taken at least one dose of a vaccine do not trust vaccine technology, but this proportion is much higher (24%) for unvaccinated respondents. This statistic shows that around one-fourth of unvaccinated respondents might be reluctant to be vaccinated. Similarly, the proportion of respondents satisfied with the UK government's approach towards the COVID-19 pandemic increases with the vaccination status. More specifically, while only 45% of the unvaccinated respondents are satisfied with the government's approach, 57% of the respondents who have taken the first dose of a vaccine and 63% of the fully vaccinated respondents are satisfied.

2.4. Modelling approach

The multinomial logit (MNL) model is the base model in analysis of the stated choice data. The model defines the utility that respondent n ($n = 1, \dots, N$) attaches to travel profile j ($j = 1, 2$) in choice situation s ($s = 1, \dots, 8$) as the sum of a systematic and a stochastic component:

$$U_{njs} = V_{njs} + \varepsilon_{njs} = \mathbf{x}_{njs}\beta + \varepsilon_{njs}.$$

The stochastic component ε_{njs} is the idiosyncratic error term, which is assumed to be independent and identically distributed across n, j, s according to a standard Gumbel distribution.

In our analysis, we specify the systematic component of the utility to investigate the main effects of alternative-specific attributes and possible two-way interactions. The main focus behind the interaction analysis is to investigate how the effect of COVID-related attributes and travel time on the preference for the Underground changes with crowding density. To quantify the extent of this heterogeneity, we compute *crowding multipliers* that capture the ratio of marginal utility of attributes in crowded and uncrowded Underground. In another utility specification, interactions between alternative-specific attributes and individual-level covariates (i.e., demographic characteristics and opinions) are included to capture systematic heterogeneity in the effects of the attributes.

The MNL probability that respondent n chooses travel profile j in choice situation s is obtained using the following closed-form expression:

$$p_{njs} = \frac{\exp(V_{njs})}{\sum_j \exp(V_{nj's})}.$$

To explore the unobserved preference heterogeneity in the effects of attributes, the more flexible latent class MNL (LC-MNL) model is adopted. In the LC-MNL model, the marginal utility of an attribute (β_n) is considered to follow a discrete distribution across the population (Greene and Hensher, 2003). Specifically, LC-MNL assumes that the population has Q distinct and unobserved classes of individuals with different values for the preference parameters across the classes, but preferences remain the same within each class.

$$g(\beta_n|\gamma) = \begin{cases} \beta_1 & \text{with probability } w_{n1}(\gamma) \\ \vdots & \\ \beta_Q & \text{with probability } w_{nQ}(\gamma) \end{cases},$$

where a respondent n belongs to class q with probability $w_{nq}(\gamma)$, such that $\sum_q w_{nq}(\gamma) = 1$ and $w_{nq}(\gamma) > 0$. Note that $\gamma = (\gamma_1, \dots, \gamma_Q)$ is a vector of parameters that are used to specify the class-specific probabilities:

$$w_{nq}(\gamma) = \frac{\exp(\mathbf{h}_n \gamma_q)}{\sum_q \exp(\mathbf{h}_n \gamma_q)},$$

where \mathbf{h}_n is a vector of demographics and opinion-based indicators and γ_1 is set to zero for identification. Thus, the unconditional probability of the series of choices made by respondent n is:

Table 6
Practical relevance of alternative-specific attributes.

Explanatory variables	Loglikelihood
Alternative-specific constant (alternative 2)	−5318.0
Alternative-specific variables (main effects)	
Crowding density (persons/ meter ²)	−5255.2
Standing in the Underground?	−5317.7
Travel time (minutes/100)	−5291.5
Daily new COVID cases (per 10 ⁷)	−5307.5
Mask compulsory?	−4871.2
Vaccine adoption (%)	−5195.4

Table 7
Parameter estimates of MNL and LC-MNL models.

Explanatory variables	MNL		LC-MNL		Class 2	
	Estimate	z-value	Class 1 Estimate	z-value	Estimate	z-value
Alternative-specific constant (alternative 2)	−0.127	−4.3	−0.099	−1.6	−0.181	−3.7
Travel time (minutes/100)	−0.900	−3.3	−2.053	−3.6	−0.886	−2.1
Daily new COVID cases (per 10 ⁷)	−0.750	−5.5	−1.434	−4.5	−0.759	−3.7
Mask compulsory?	1.029	15.2	−0.302	−2.0	1.771	15.6
Vaccine adoption (%)	1.488	15.1	1.229	5.9	2.120	12.5
Travel time × Crowding density	−0.109	−2.6	−0.082	−0.9	−0.108	−1.8
Mask compulsory × Crowding density	0.032	1.7	0.064	1.5	0.064	2.1
Daily new COVID cases × Crowding Density	−0.169	−4.1	0.052	0.6	−0.377	−5.9
Vaccine adoption × Crowding Density	−0.108	−2.8	−0.228	−2.7	−0.158	−2.5
Travel time × Mask compulsory?	−0.669	−5.2	−0.709	−2.5	−0.634	−3.0
Class proportion			0.297		0.703	
Loglikelihood	−4664.2		−4508.9			
McFadden R-square	0.123		0.152			

$$f(y_n | \mathbf{x}, \mathbf{h}; \boldsymbol{\beta}, \boldsymbol{\gamma}) = \sum_q w_{nq}(\boldsymbol{\gamma}) \prod_s \left[\frac{\exp(V_{nj_s})}{\sum_j \exp(V_{nj_s})} \right],$$

where $\mathbf{y}_n = (y_{n1}, \dots, y_{nS})$ is a vector of choices made by respondent n and j_s is the alternative chosen at choice occasion s . The above probability expression is used to compute the loglikelihood of the sample, which is maximised using the `gmnl` package in R (Sarrias and Daziano, 2017) to estimate model parameters.

3. Results

In this section, we present the estimation results of the MNL and LC-MNL models. The parameter estimates provide insights into the statistical significance of the predictors and the extent of preference heterogeneity. We also illustrate the practical significance of the predictors by providing crowding multiplier estimates and plotting the effect of attributes on the probability to use the Underground during the pandemic. We first focus on the effect of alternative-specific attributes, followed by the investigation of systematic preference heterogeneity across socio-demographic groups.

To obtain an initial understanding of the explanatory power of each attribute, we estimate multiple MNL models while keeping one attribute at a time along with the alternative-specific constant. Table 6 presents the results of this exercise. The increase in the model fit over the constant-only model shows the empirical relevance of the attribute. The results indicate that mandatory face masks and higher rates of vaccination are the top two drivers in loglikelihood improvement (from −5318.0 to −4871.2 and −5195.4), whereas the addition of the standing attribute leads to virtually no gain in the loglikelihood (from −5318.0 to −5317.7). The likelihood ratio test suggests that the constant-only model is superior to the one with the constant and standing attribute (Chi-square statistic: 0.49, DOF: 1, p-value: 0.48).

The results of the MNL and LC-MNL models are presented in Table 7. We include ASCs in both models¹. The MNL results indicate that travel time and daily new COVID-19 cases negatively affect the respondents' likelihood to choose the Underground. However, the effects of mandatory face masks and higher rates of vaccination are positive. The interaction effect estimates show that the negative

¹ There is abundant literature on ASC exclusion in the case of unlabelled alternatives (Hensher et al., 2005). However, a parallel strand of the literature argues that ASCs in the case of unlabelled alternatives capture status quo bias, and their exclusion might bias the remaining utility parameters as they would try to capture the effect of ASCs (Morrison et al., 2002). The other potential bias in the context of this study can be related to attention on a specific part of the display screen. Therefore, we prefer to stick with ASCs in our utility specification.

Table 8
Crowding multipliers for all alternative-specific attributes.

Explanatory variables	Crowding density (persons/ meter ²)					
	1	2	3	4	5	6
	MNL					
Travel time	1.12	1.24	1.36	1.48	1.61	1.73
Daily new COVID cases	1.23	1.45	1.68	1.90	2.13	2.35
Mask compulsory?	1.03	1.06	1.09	1.12	1.16	1.19
Vaccine adoption (%)	0.93	0.85	0.78	0.71	0.64	0.56
	LC-MNL (Class 1)					
Vaccine adoption (%)	0.81	0.63	0.44	0.26	0.07	−0.11
	LC-MNL (Class 2)					
Travel time	1.12	1.24	1.37	1.49	1.61	1.73
Daily new COVID cases	1.50	1.99	2.49	2.98	3.48	3.97
Mask compulsory?	1.04	1.07	1.11	1.14	1.18	1.22
Vaccine adoption (%)	0.93	0.85	0.78	0.70	0.63	0.55

Table 9
Travel time multipliers of the mandatory face mask.

Travel time (in minutes)	MNL	LC-MNL	
		Class 1	Class 2
20	0.87	1.47	0.93
40	0.74	1.94	0.86
60	0.61	2.41	0.79
80	0.48	2.88	0.71
100	0.35	3.35	0.64

effect of travel time and new COVID-19 cases, and the positive effect of mandatory face masks are enlarged with the increase in crowding density. However, the positive effect of vaccination rates attenuates with increasing crowding levels. The positive effect of mandatory face masks on the preference to take the Underground decreases with the travel time, most probably because the discomfort due to wearing a mask increases with the travel duration. All the main and interaction effects are statistically significant at a 0.1 level.

We could identify two classes with distinct preferences in the LC-MNL model². The Bayesian information criterion (BIC) shows that the LC-MNL model outperforms the MNL model (MNL: 9417.9 vs. LC-MNL: 9205.7). The direction of the effects and their statistical significance in class 2 of the LC-MNL model are similar to those of the MNL model. However, class 1, with a share of 29.7%, has several differences. For instance, the effect of mandatory face masks on preference to use the Underground is negative in class 1 (as opposed to being positive for class 2). Moreover, unlike class 2, the effect of travel time, mandatory face mask, and daily new COVID-19 cases do not vary with crowding density.

3.1. Crowding multipliers

To understand the heterogeneity in the effect of travel time and COVID-related attributes at different crowding levels, we present crowding multipliers in Table 8. The MNL results indicate that the crowding multiplier for travel time at the technical capacity of the Underground is 1.73. This result implies that the travel time valuation of underground users when travelling in the most crowded situation increases by 73% relative to the uncrowded condition. While there is substantial heterogeneity in the reported crowding multipliers for the UK (see Wardman and Whelan, 2011 for a detailed review), we benchmark our results against the Whelan and Crockett (2009), whose study design closely corresponds to ours. They report a seated crowding multiplier of 1.63 at the technical capacity that is close to our estimates. Given the substantial variability in the pre-pandemic crowding multipliers for the UK, an exact comparison of pre- and post-pandemic crowding valuations is challenging. Nevertheless, the results provide preliminary evidence that the pandemic does not have a considerable effect on the seated crowding valuation³.

Similarly, we also compute crowding multipliers for new COVID-19 cases, mandatory face masks, and vaccine adoption, which are 2.35, 1.19, and 0.56 for MNL. The crowding multipliers of travel time, mandatory face mask, and vaccine adoption are similar for class 2 of LC-MNL and MNL, but the former has a much higher multiplier for new COVID-19 incidences (3.97 vs. 2.35). Since the interaction of crowding density is only statistically significant with vaccine adoption in class 1 of LC-MNL, we only compute the crowding multiplier for it. Class 1 is relatively less sensitive to crowding, but the positive effect of vaccine adoption drops to zero in highly crowded Underground.

² We also estimated an LC-MNL specification with three latent classes but encountered empirical identification and convergence issues.

³ We could not compute standing multipliers because the interaction of crowding density and travel time with the attribute characterising whether a passenger is standing or not does not turn out to be statistically significant.

Table 10

Results of LC-MNL (class membership as a function of demographics and perceptions).

Explanatory variables	Class 1		Class 2	
	Estimate	z-value	Estimate	z-value
Utility equation				
Alternative-specific constant (alternative 2)	−0.109	−2.0	−0.199	−4.0
Travel time (minutes/100)	−1.777	−4.0	−1.420	−3.1
Daily new COVID cases (per 10 ⁷)	−1.179	−4.3	−0.772	−3.7
Mask compulsory?	−0.398	−4.4	1.604	20.2
Vaccine adoption (%)	1.005	5.6	2.370	13.6
Travel time × Crowding density	−0.003	0.0	−0.199	−3.0
Mask compulsory × Crowding density	0.056	1.6	0.056	1.8
Daily new COVID cases × Crowding Density	−0.011	−0.1	−0.340	−5.4
Vaccine adoption × Crowding Density	−0.249	−3.4	−0.130	−2.0
Class membership link function				
Constant			−1.195	−4.5
Age below 40 years?			−1.323	−12.8
Monthly household income > 10,000 lb?			−0.586	−6.4
Unemployed or retired?			0.538	3.8
Asian or Asian British?			0.744	5.9
Have at least a bachelor's degree?			0.477	5.0
Married?			−0.423	−4.6
Male?			−0.562	−6.1
Mask helps in controlling COVID spread?			0.727	7.5
Always wear a mask at public spaces?			2.614	11.1
Wearing a mask can cause respiratory issues?			−1.521	−17.3
Received a dose of COVID-19 vaccine?			0.590	6.3
Tested positive for COVID?			−0.462	−3.0
Loglikelihood	−4431.4			
McFadden R-square	0.167			

Similar to the crowding multiplier, we present the travel time multiplier for mandatory face masks in Table 9. The MNL results indicate that the positive marginal utility of mandatory face masks decreases by 65% for a 100-minute long trip. For the same trip length, the positive marginality of mandatory face masks reduces by 36% for class 2, and the magnitude of negative marginal utility rapidly increases by 235% for class 1 of LC-MNL. Essentially, individuals from class 1 (around 29.7%) dislike the mandatory mask policy.

3.2. Systematic preference heterogeneity

To further investigate the preference heterogeneity, we parameterise the class-membership probability in LC-MNL with socio-demographic characteristics and individuals' opinions about mask usage and the COVID-19 vaccine. Such parameterisation is insightful in terms of identifying the association of consumer profiles with the identified classes. To delve deeper into attribute-level preference heterogeneity, we estimate the MNL model with the interaction of alternative-specific and individual-level attributes. Tables 10 and 11 summarize the parameter estimates of LC-MNL and MNL, respectively. The individual-level attributes in the MNL specification turn out to have substantial overlap with the attributes in the class-membership function of LC-MNL. Note that the specifications presented in the last subsection are more suitable for forecasting because they do not involve opinion-based covariates. However, new specifications are beneficial from an exploratory perspective as they offer more insights into preference heterogeneity. The new specification of the LC-MNL model is superior to the earlier LC-MNL specification in terms of BIC (earlier LC-MNL: 9205.7 vs. new LC-MNL: 9140.1). The new LC-MNL specification also outperforms the new MNL specification in terms of BIC (new MNL: 9174.5 vs. new LC-MNL: 9140.1), but we discuss how analysing results of both specifications in tandem offers consistent insights.

The LC-MNL results indicate that an unmarried bachelor's degree holder who is older than 40 years has a higher probability of being in class 2. The MNL results show that preference for the Underground of this demographic group is more negatively affected than their counterparts as the London Underground transitions from no-crowding to its technical capacity. This demographic group will be most benefited by the real-time crowding information system. The higher chance of this demographic group being in class 2 of LC-MNL is consistent with the MNL results because class 2 is more sensitive to crowding density (indicated by statistical significance of all crowding density interactions in class 2). The existing literature corroborates these findings. Older and more educated riders are less inclined to travel in crowded Underground, perhaps because perceive higher risk of COVID transmission in crowded conditions. For instance, Rosi et al. (2021) find that older people perceive higher severity of COVID-19 infection. Moreover, highly educated individuals realise higher chances of getting infected by COVID-19 (Rattay et al., 2021; Reed-Thryselius et al., 2022), and are more likely to get vaccinated against COVID-19 than those with low education levels (Bansal et al., 2022b).

Those who have tested COVID-19 positive and have a monthly income above 10,000 lb are more likely to belong to class 1 in LC-MNL, suggesting that class 1 is more sensitive to new COVID-19 cases than class 2. Consistently, MNL results indicate that the negative effect of new COVID-19 cases on the likelihood of choosing underground is more severe for this demographic group. This result is consistent with the finding of Reed-Thryselius et al. (2022) that people with higher risk perceptions of COVID-19 have higher income

Table 11
Results of MNL (interaction effects of demographics and perceptions).

Explanatory variables	Estimate	z-value
Alternative-specific constant (alternative 2)	−0.145	−4.8
Travel time (minutes/100)	−1.239	−4.4
Daily new COVID cases (per 10 ⁷)	−0.644	−4.2
Mask compulsory?	0.326	2.2
Vaccine adoption (%)	0.840	3.6
Travel time × Crowding density	−0.136	−3.0
Mask compulsory × Crowding density	0.033	1.7
Daily new COVID cases × Crowding Density	−0.154	−3.6
Vaccine adoption × Crowding Density	−0.080	−1.8
Travel time × Mask compulsory?	−0.354	−2.6
Interaction with demographics		
Crowding density × Age below 40 years?	0.069	2.9
Crowding density × Have at least a bachelor's degree?	−0.111	−4.8
Crowding density × Married?	0.051	2.2
Daily new COVID cases × Tested positive for COVID?	−0.696	−2.1
Daily new COVID cases × Monthly household income > 10,000 lb?	−0.474	−2.3
Mask compulsory? × Age below 40 years?	−0.410	−5.9
Mask compulsory? × Male?	−0.239	−3.7
Mask compulsory? × Unemployed or retired?	0.283	3.1
Mask compulsory? × Mask helps in controlling COVID spread?	0.299	3.9
Mask compulsory? × Always wear a mask at public spaces?	0.945	7.5
Mask compulsory? × Wearing a mask can cause respiratory issues?	−0.554	−8.5
Mask compulsory? × Monthly household income > 10,000 lb?	−0.138	−1.9
Vaccine adoption × Worried about side-effects of COVID vaccine?	−0.460	−2.6
Vaccine adoption × Vaccines won't be powerful in long term?	−0.444	−2.6
Vaccine adoption × Mask helps in controlling COVID spread?	1.182	6.5
Vaccine adoption × Asian or Asian British?	0.675	3.0
Vaccine adoption × Received a dose of COVID-19 vaccine?	0.427	2.5
Loglikelihood	−4466.5	
McFadden R-square	0.1601	

than their counterparts.

Male respondents who are younger than 40 years and are employed have higher chances of being in class 1 of LC-MNL. Note that the mandatory face mask negatively affects class 1's preferences to use the Underground during the pandemic. These results are aligned with the findings from the literature. For instance, [Barber and Kim \(2021\)](#) find that the elder people perceive a higher risk of COVID-19, and [Bronfman et al. \(2021\)](#) observe that females are more inclined to wear masks as a preventive measure because of a higher fear of infection. MNL results are consistent with those of LC-MNL as the positive effect of mandatory face masks on the preference for the Underground attenuates for young employed male respondents. These results indicate that this demographic group should be disproportionately targeted for information campaigns about the importance of masks in public transport. Similarly, face mask supporters (i.e., those who always wear a mask in public spaces, agree that masks help in controlling COVID-19 spread and do not cause respiratory issues) have a higher probability of being in class 2 of LC-MNL, which has a positive effect of the mandatory face mask on the Underground preference. Consistently, MNL results also indicate that face mask supporters have a much higher positive effect of mandatory face masks on the preference for the Underground.

LC-MNL results show that Asian or Asian British pre-pandemic users who have received a COVID-19 vaccine dose and have positive opinions about masks have a higher chance to belong to class 2, which has a higher positive effect of vaccine adoption. Similarly, MNL results indicate that this group has a much higher propensity to use the Underground as the vaccine adoption increases. MNL results also show that respondents with a positive opinion about vaccines (i.e., vaccines will be powerful in the long term and does not have side effects) have a higher inclination to use the Underground as vaccine adoption increases. However, we do not find these perception-related attributes statistically significant in LC-MNL's class probability.

This section has highlighted substantial heterogeneity in the effects of crowding density, new COVID-19 cases, mandatory face masks, and vaccination rates across segments of pre-pandemic users with differing demographics and opinions about countermeasures. The next section evaluates the extent of these effects while focusing on the COVID related factors.

3.3. Sensitivity analysis

To illustrate the practical significance of the attributes and the extent of preference heterogeneity, we create predicted probability plots using the parameter estimates of the final MNL specification. The calculation of the predicted probabilities is based on the incremental logit model that capitalises on the linear-in-parameter utility specification (Chapter 5, [Ben-Akiva and Lerman 2018](#)). We assign the attributes of alternative 1 as the average of the difference in attributes of alternatives 1 and 2 across the sample, and attributes of alternative 2 are set to zero. To find the effect of a specific attribute on the propensity to travel by Underground with MNL, we only vary this attribute for alternative 1 and predict the probability to choose alternative 1. These probability plots show the change in propensity to use the Underground due to variation in a specific attribute.

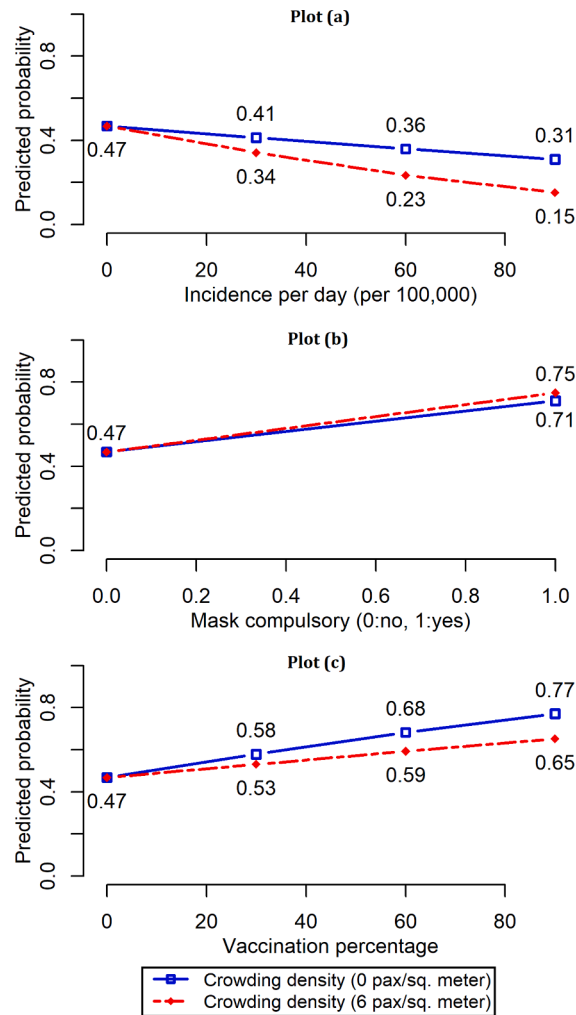


Fig. 2. Heterogeneity in the effect of COVID-related factors on the probability of choosing the London Underground across crowding levels.

Fig. 2 uses MNL results presented in Table 7 to show the variation in the main effects of the attributes related to COVID-19 at different crowding levels. In an uncrowded scenario, an increase in daily new COVID-19 cases from zero to maximum reduces the probability to choose the Underground by 0.16 (from 0.47 to 0.31 in Fig. 2a). However, at the technical capacity, the negative effect of new COVID-19 cases become twice (i.e., the reduction in probability increases from 0.16 to 0.32), perhaps due to the much higher perceived risk of infection in the crowded Underground. Similarly, mandatory face masks and an increase in vaccine adoption from 0% to 90% lead to an increase in probability to take the Underground by 0.24 and 0.30 in an uncrowded scenario (see Fig. 2b and 2c). These numbers change to 0.28 and 0.18 when the Underground operates at its technical capacity. This result implies that the crowding density marginally increases the importance of mandatory face mask norms but substantially reduces the benefits associated with the vaccine adoption.

Fig. 3 highlights the heterogeneity in the effect of factors related to COVID-19 across different demographics, vaccination status, and COVID-19 infection. The results indicate that high-income pre-pandemic users who have tested COVID positive are much negatively affected by new COVID-19 cases than their counterparts. Fig. 3a shows that an increase in COVID-19 cases from zero to maximum reduces the probability to choose the Underground by 0.33 for the indicated socio-demographic group, while the reduction in probability is 0.13 for its counterpart. The positive effect of mandatory face masks on the likelihood of taking the Underground is more pronounced among unemployed/retired females with age above 40 years and a monthly income below 10,000 lb relative to their counterparts (probability increment: 0.35 vs. 0.11, Fig. 3b). The positive effect of vaccination rates on the likelihood of using the London Underground is higher for respondents who identify as Asian or Asian-British and have taken a vaccine dose. The increase in probability to use the Underground for this group due to an increase in vaccination from zero to 90% is 0.40, but the increment reduces to 0.26 for their counterparts (Fig. 3c).

Fig. 4 focuses on preference heterogeneity across individuals with different opinions about face masks and the COVID-19 vaccine. The most noticeable heterogeneity in the effect of mandatory face masks is across respondents segmented based on their opinions

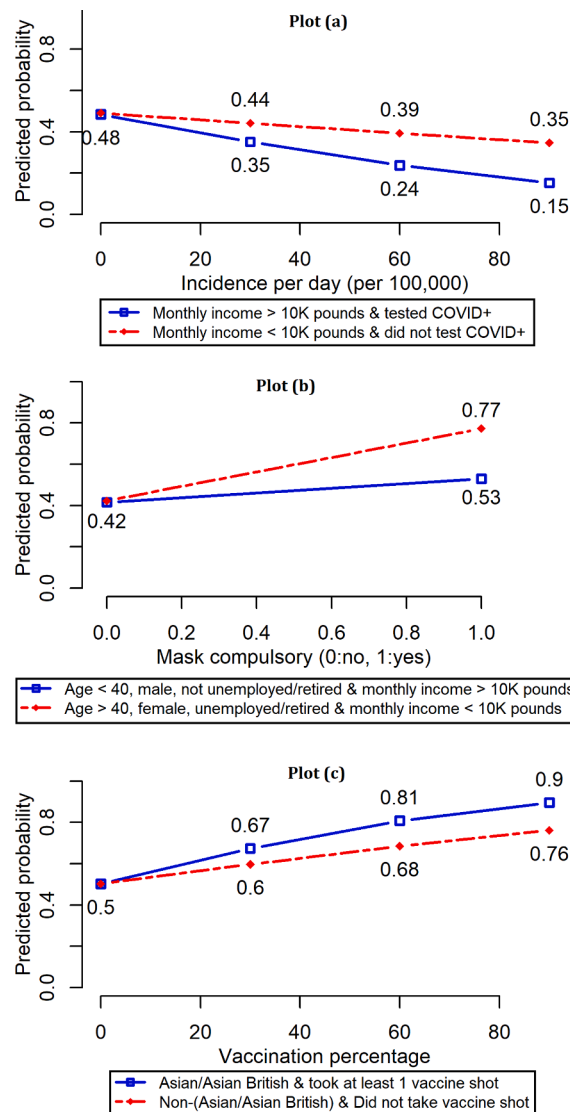


Fig. 3. Heterogeneity in the effect of COVID-related factors on the probability of choosing the London Underground across groups with different socio-demographic characteristics.

about mask usage. Mandatory face masks lead to an increase in the probability of choosing the Underground by 0.31 for mask supporters, but a decrease in probability to 0.10 for counterparts (Fig. 4a). As the UK moves towards a full-vaccination scenario, respondents with the opinion that masks help in controlling the spread of COVID-19 have a more striking increase in the likelihood to use the Underground than their counterparts (probability increment: 0.36 vs. 0.19, Fig. 4b). A similar observation is made for pre-pandemic users with positive opinions about vaccination and their counterparts (probability increment: 0.37 vs. 0.25, Fig. 4c). These results illustrate the importance of improving perceptions about face masks and vaccines in increasing the effectiveness of the countermeasures to increase the Underground demand.

4. Conclusions

The COVID-19 pandemic has severely impacted the demand for public transport in many parts of the world. Notwithstanding the gradual easing of restrictions and increasing rates of vaccination, future demand for public transport remains uncertain. This study investigated the factors that influence the preferences of pre-pandemic users for the London Underground during the pandemic. To that end, we conducted a stated choice experiment among pre-pandemic users of the London Underground and analysed the collected data using discrete choice models. Our study offers insights into the sensitivities of pre-pandemic users to travel by London Underground during the pandemic relative to travel attributes (crowding density, travel time), the epidemic situation (new confirmed COVID-19 cases), non-pharmaceutical interventions (whether masks are mandatory or not) and pharmaceutical interventions

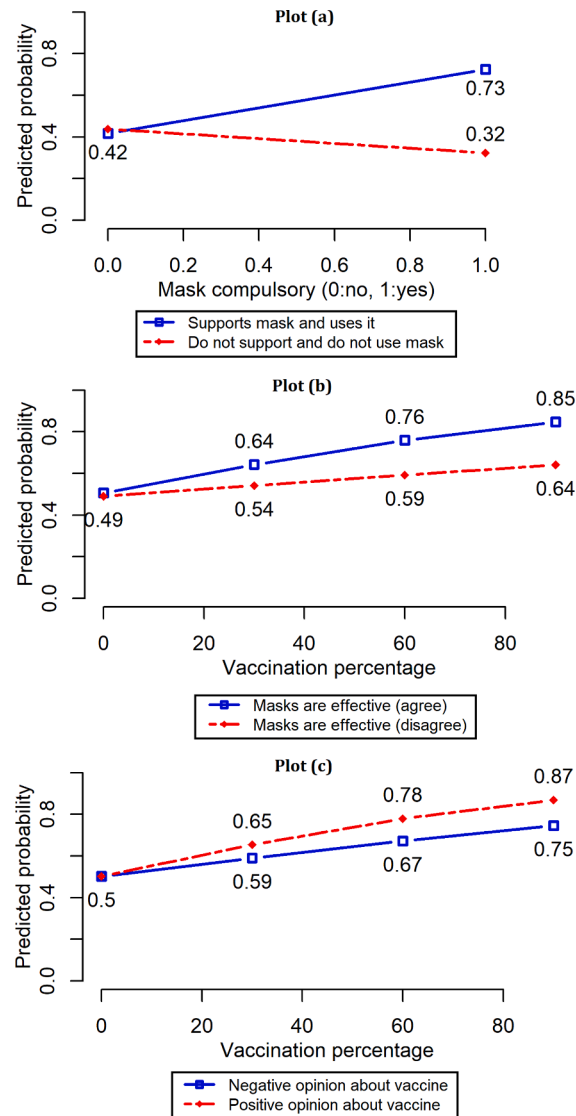


Fig. 4. Heterogeneity in the effect of COVID-related factors on the probability of choosing the London Underground across groups with different opinions.

(vaccination rates). The derived implications for policy and practice are discussed below in detail.

First, we present the post-pandemic crowding multiplier estimate of travel time valuation (the ratio of the value of travel time in uncrowded and crowded situations) for the London underground. The result indicates that the travel time valuation of the London Underground users increases by 73% when the Underground operates at its technical capacity. After combining crowding multipliers with the value of travel time estimates⁴, welfare gains due to reducing crowding levels can be estimated. These estimates are critical because countries like the UK provide guideline to include them in public transport project appraisals (Wardman, 2014). Optimality of several supply-side decisions such as service frequency, vehicle size, and the fare is also governed by crowding valuation estimates. Similarly, we also present the first estimates of crowding multipliers for attributes related to COVID-19 for a subway system. These estimates also provide an impact of crowding on reducing or improving the effectiveness of interventions in recovering the Underground demand during the pandemic. For instance, on average, the positive effect of mandatory face masks is relatively less affected by crowding, but the positive effect of vaccine adoption reduces substantially with increasing crowding levels.

Second, our discrete choice analysis results suggest that over 70% of the respondents favour mandatory face masks. On average, the improvement in preference for the Underground due to 100% vaccine adoption is equivalent to the one obtained by making the face mask mandatory. Therefore, face masks should be made mandatory to encourage the use of public transport during the pandemic. Our

⁴ Hess et al. (2017) provide the value of travel time estimates for different travel modes and trip purposes for the UK.

Table A1

Partial profile design with three surveys (blocks).

Survey	Choice situation	Crowding density	Standing in Underground?	Travel time ratio	New COVID-19 cases	Mask compulsory?	Vaccine adoption
1	1	0	No	1.15	70	No	35%
1	1	0	No	0.7	90	Yes	20%
1	2	0	Yes	0.7	30	Yes	80%
1	2	1	Yes	1	30	No	20%
1	3	6	Yes	0.7	10	No	50%
1	3	4	No	0.7	50	Yes	50%
1	4	4	No	1.3	10	Yes	50%
1	4	2	Yes	1.15	10	Yes	5%
1	5	1	Yes	1.15	50	No	5%
1	5	1	No	0.7	70	Yes	5%
1	6	0	No	1.3	70	No	20%
1	6	4	Yes	1.3	30	No	65%
1	7	2	Yes	1.15	50	No	80%
1	7	2	No	1.15	90	Yes	35%
1	8	0	Yes	1.3	30	No	20%
1	8	1	Yes	0.7	50	Yes	20%
2	9	2	Yes	1	10	Yes	50%
2	9	2	No	1.3	10	No	5%
2	10	1	No	0.7	50	Yes	50%
2	10	6	No	1	10	Yes	80%
2	11	2	Yes	1.3	50	No	65%
2	11	6	No	1.15	50	Yes	65%
2	12	2	Yes	1.3	90	No	35%
2	12	0	Yes	1.3	50	Yes	5%
2	13	2	No	0.7	30	Yes	65%
2	13	1	Yes	0.7	30	No	5%
2	14	1	No	1.15	10	Yes	5%
2	14	1	Yes	1.3	50	Yes	80%
2	15	4	Yes	1.15	50	No	80%
2	15	6	No	1.3	30	No	80%
2	16	0	Yes	1.15	10	Yes	20%
2	16	0	Yes	1	70	No	35%
3	17	4	Yes	1.3	10	No	50%
3	17	1	No	1.3	30	Yes	50%
3	18	1	No	1	50	No	80%
3	18	1	Yes	0.7	30	No	65%
3	19	0	Yes	1	70	No	5%
3	19	2	No	1.3	70	Yes	5%
3	20	0	No	1	50	Yes	5%
3	20	0	Yes	1.15	50	No	35%
3	21	1	No	1.15	30	No	80%
3	21	0	No	1.15	50	Yes	50%
3	22	4	Yes	1.3	10	Yes	65%
3	22	4	No	1.15	50	No	65%
3	23	6	No	0.7	30	No	50%
3	23	0	Yes	0.7	30	Yes	65%
3	24	1	Yes	1.3	50	Yes	65%
3	24	2	Yes	0.7	90	Yes	20%

results also indicate that the positive effect of face masks on the Londoners' preferences for the London underground sharply decreases with travel time, perhaps due to discomfort arising from wearing face masks for a longer duration. The discomfort caused by mandatory face masks on long-distance trips can be offset by providing other amenities, such as free last-mile connectivity with bike-sharing system.

Third, our results show that travellers are sensitive to crowding levels, especially when COVID-19 cases are high. For instance, the effect of COVID-19 cases on preference for the Underground in overcrowded conditions becomes almost twice as negative as the one in uncrowded conditions. Therefore, advanced traveller information systems which provide updates on expected crowding levels may effectively reduce the risk of contagion on public transport and encourage travellers to take the Underground in off-peak periods.

Fourth, our findings reveal that the perception of users about masks and vaccines determines the extent to which countermeasures affect their propensity to use public transport. The effect of countermeasures also varies across socio-demographic characteristics. For instance, the effect of mandatory face masks on the likelihood of taking the Underground is less pronounced among males with age below 40 years and a monthly income below 10,000 lb. Thus, designing targeted information campaigns about the importance of masks, safety and efficacy of vaccines is critical to recovering the demand for public transport.

There are multiple ways in which future research can build upon the work presented in this paper. First, the data for this study were collected between March and May 2021. Thus, the data only capture a snapshot of people's preferences and perceptions in a

dynamically evolving environment. As respondents provided their answers under the impression of recent events, namely the gradual easing of lockdown restrictions and the ramp-up of vaccination campaigns, it would be instructive to repeat the analysis with data collected at a future point in time. Likewise, the study could be replicated in a different geographical context to evaluate the transferability of the results to other public transport systems. Second, at a more general level, our study underlines the importance of accounting for epidemic factors and non-pharmaceutical interventions in mathematical models of activity-travel behaviour. To plan for the “new normal” and possible future pandemics, the analysis presented in this paper may be extended to other components of travel behaviour (e.g., destination and detailed travel mode choices). Third, there are several avenues of improvement in the considered experiment design and data collection methods, namely i) consideration of uncertainty in crowding and travel time attributes (Gao et al., 2021; Harrison et al., 2014; Li et al. 2010), ii) conducting virtual-reality-based experiments to represent variations in crowding levels during the trip (Sadeghi et al., 2021), iii) using alternative indicators of the severity of the epidemic situation such as a score that aggregates various metrics including new cases, hospitalisation, deaths and hospital capacity, and iv) collecting panel data to capture changes in pre- and post-pandemic travel behaviour over time.

CRediT authorship contribution statement

Prateek Bansal: Conceptualization, Methodology, Data curation, Software, Writing – original draft. **Roselinde Kessels:** Conceptualization, Methodology, Software, Writing – original draft. **Rico Krueger:** Conceptualization, Methodology, Writing – original draft. **Daniel J. Graham:** Writing – review & editing, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. – Partial profile design of the discrete choice experiment (DCE)

The design of the DCE involved three blocks and eight choice situations per block. Each choice situation had two possible travel profiles of the London Underground. One of three blocks was randomly chosen and presented to the respondent. The design appears in Table A.1. The design accounted for the independent estimation of all main effects of the six attributes and all two-way interaction effects between them. The following restrictions were incorporated in the design: first, the two highest levels of daily new COVID-19 cases (70 and 90 per 10⁵) are incompatible with the three highest vaccination rates (50%, 65%, and 80%), and second, the two highest crowding levels (4 and 6) are not aligned with the three lowest vaccination rates (5%, 20%, and 35%) and the two highest levels of daily new COVID-19 cases (70 and 90 per 10⁵).

The choice situations contained partial profiles that were described by four varying attributes and two attributes with constant levels. For illustrative purposes, Table A.1 shows the varying attributes in grey. The constant attributes enable the estimation of the attribute interaction effects. In a block, each attribute is held constant in two or three choice sets and varied in five or six choice sets. The design was created using the partial profile design algorithm of Kessels et al. (2015) in the JMP Pro 16 software (SAS Institute Inc, Cary, NC, USA).

The design is Bayesian D-optimal, meaning that it incorporates all available knowledge about respondents' preferences in optimizing the D-criterion value to obtain the design that guarantees the most precise preference estimates. Defining priors was straightforward for the continuous attributes. That is, lower levels of crowding, in-vehicle (on-board) travel time, and daily new COVID-19 cases in the UK are generally preferred for travelling by the London Underground than higher levels for these attributes. The opposite is the case for the vaccinated population in the UK. We did not provide any prior preference regarding the standing and mask attributes as both preference directions on these attributes could be possible in COVID-19 times. Also, we allowed for quite some uncertainty or variability regarding all prior beliefs in the design optimization.

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