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ORIGINAL RESEARCH

To increase or to decrease the price? Managing public transport queues during COVID-19 in the presence of strategic commuters

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Abstract
The impact of COVID-19 on urban travel behavior has been unprecedented. It has significantly influenced the travel mode choices of different urban commuters in various countries across the globe. Given that the public transport providers need to tradeoff between minimizing the spread of COVID-19 and providing an affordable travel choice in this environment, we develop a strategic queueing model to analyze the effect of different pricing strategies on the commuter behavior. In particular, we consider a Markovian queue in front of a public transport ticket counter wherein strategic commuters arrive at the service facility and make joining or balking decisions based on their derived utilities. In contrast to conventional wisdom, we suggest that the public transport provider needs to decrease the price to filter out the wealthy commuters who possess feasible alternative travel options from using public transport and promote the commuters with no alternatives in using public transport.

Keywords Public transport · COVID-19 · Strategic behavior · Queueing game · Pricing

JEL classification L91 · R48

1 Introduction

COVID-19 has significantly influenced the travel mode choice behavior of urban commuters across the globe (Bhaduri et al. 2020, Mützel and Scheiner 2022). In particular, public transport ridership has been significantly impacted by COVID-19 due to the risk of infection spread (Gkiotsalitis and Cats 2021a). This decline in public transport ridership has been reported in different countries such as Hungary

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(Bucsky 2020), Sweden (Jenelius and Cebecauer 2020), India (Bhaduri et al. 2020), Poland (Wielechowski et al. 2020) and Finland (Tiikkaja and Viri 2021) among others. While the demand for public transport dropped drastically during the early stages of COVID-19 when lockdowns were imposed, the public transport ridership started to increase with lockdown relaxations. In fact, reports suggest that the metro ridership returned to 70% of its normal level in Asia, 50% of its normal level in Europe and 20–30% of its normal level in the Americas by July 2020 (Transport Strategy Centre 2020; Vickerman 2021). With the increase in demand for public transport post-lockdown relaxations, the public transport provider faces a dilemma on how to best provide the public transport services such that the crowds are maintained at manageable levels to prevent the spread of COVID-19 and at the same time, ensure that the services are accessible to the commuters who are required to travel and are left with no other alternative. It is important to note that the public transport provider needs to filter out the commuters who can afford other modes of transport such as personal cars and taxis.

In this environment, we focus on whether the public transport provider can leverage different pricing strategies to attain the intended objectives. We first develop a strategic queueing model consisting of two commuter types: commuters with alternative travel options and commuters with no alternative travel options. Subsequently, we analyze how different pricing strategies influence the equilibrium behavior of the commuters. We find that decreasing the price from the current level can aid the public transport provider in filtering out the wealthy commuters who can afford private transport and in retaining the commuters with no alternatives.

The article is structured as follows. A review of literature on the analytical models developed to understand the impact of COVID-19 in different contexts and the motivation to develop a queueing game-theoretic model in the public transport queue setting is presented in Sect. 2. Subsequently, in Sect. 3, the queueing game-theoretic model is set up and the sequence of events in this environment is explained. The key results from the analysis are presented in Sect. 4. In Sect. 5, an extended model with three commuter types is explained. In the final section, a summary of the results and its implications for practitioners are provided.

2 Literature review

There have been several empirical studies which have looked at the effect of COVID-19 on changes in travel behavior and logistics and supply chain systems. The changes in travel mode choice after the advent of COVID-19 has been one major area of focus. With respect to urban travel during COVID-19, studies have looked at whether travelers prefer private transport over public transport and how travel mode choice behavior varies during lockdown restrictions and relaxations (Gkiotsalitis and Cats 2021a; Vickerman 2021). On the other hand, disruptions in the logistics and supply chain systems due to COVID-19 have also been analyzed based on empirical data (Grida et al. 2020; Paul et al. 2021; Goel et al. 2021; Atayah et al. 2022). Simulation models have also been developed to analyze the effect of COVID-19 on food supply chains (Singh et al. 2021; Burgos and Ivanov 2021).

With respect to public transport systems, various disruption management techniques based on mathematical programming and heuristics have been looked at to analyze how disruptions can be handled at various stages starting from prevention to reaction. In particular, a framework relying on the complementary nature of complexity science and operations research in terms of monitoring and taking effective measures has been discussed to handle out-of-control situations during railway disruptions (Dekker et al. 2022; Ge et al. 2022).

Apart from these empirical and simulation studies in the context of COVID-19, researchers have developed analytical models to measure the effect of COVID-19 in different industries and understand its implications for the service provider. Choi (2020) analyzed and provided the conditions under which mobile service operations are profitable for the service provider using analytical models. Further, the effect of different governmental policies to subsidize the operations is also studied. Operations research-based mathematical models have also been implemented to arrive at appropriate strategies to manage the disruptions resulting from COVID-19 (Paul and Chowdhury 2020; Yazdekhasti et al. 2021; Ivanov and Dolgui 2021). Gkiotsalitis and Cats (2021b) developed a mixed-integer quadratic programming model to assess the impact of different social distancing policies on the operational and passenger costs and determine the optimal frequency of metro services during COVID-19. Srinivas and Marathe (2021a) analyzed how mobile warehouses can aid the e-commerce firms in handling the supply chain disruptions due to COVID-19 better using a stylized analytical model. In this context, we intend to develop a strategic queueing analytical model to examine how different pricing policies can result in different equilibrium behavior of commuters in a public transport setting during COVID-19. Earlier, Odlyzko (1999) presented the simple Paris Metro Pricing solution for differentiated services in packet networks. Paris Metro Pricing is based on the traditional pricing followed in the Paris Metro system (till September 1, 1999) consisting of two identical cars with identical seats—the 1st class car and the 2nd class car, with the only difference being that the 1st class seats were priced twice as much as the 2nd class seats. This pricing scheme ensured that only those commuters who wanted to get a seat travelled on the 1st class car, whereas the rest travelled on the 2nd class car. Overall, the 1st class car was less congested than the 2nd class car. We aim to understand how price changes impacts the travel mode choice behavior of commuters during COVID-19 using a strategic queueing model.

Naor (1969) introduced the notion of strategic behavior in queues wherein the arriving customers make decisions on whether to join the queue or balk based on their derived utilities. Subsequently, there have been interesting applications of such models in varied settings. The concert queueing game is an interesting development wherein the arriving customers make strategic decisions on arrival times at the service facility. The arrival time decision is important, since early arrivals - while ensuring the purchase of good seats in a concert - lead to long wait times. On the other hand, late arrivals ensure reduced wait times; however, the purchase of good seats may not be possible, since it could be already taken (Jain et al. 2011; Juneja and Shimkin 2013). Debo et al. (2012) considered a queueing system wherein the quality of the product is unknown to a proportion of strategic customers who are uninformed and rely on queue length information to update the quality of the product. In the presence of informed customers, there exists a hole in the uninformed customer's equilibrium strategy (when the equilibrium exists); the uninformed customers join at queue lengths lesser and greater than the hole queue length, but balk at the hole indicating the non-monotonic queue joining behavior of uninformed customers under certain conditions. Srinivas and Marathe (2020) analyzed the equilibrium in a Markovian queue when the service rates are unknown and the arriving customers in a railway station ticket purchase counter infer service rates from the length of the queue. While strategic queueing models have been applied to passenger-taxi matching problems (Wang et al. 2017; Jiang et al. 2021), the adoption of such queueing models to analyze the effect of pricing strategies and its resultant effect on the travel mode choice behavior of commuters, particularly during COVID-19, has been rare. To the best of our knowledge, ours is one of the first studies to look at the application of strategic queueing models to analyze the mode choice behavior of public transport commuters in response to different pricing schemes during the COVID-19 pandemic.

3 The queueing game-theoretic model

We consider an $M/M/1$ queue in front of a public transport ticket counter (for example, railway station). Commuters arrive at the public transport facility according to a Poisson process at the rate λ. The service times (μ^{-1}) are exponential. There are two types of commuters: commuters with no alternative (NC-commuter), and commuters with alternatives (C-commuter). It is evident from extant literature that age, income, working status and vehicle ownership play a key role in the travel mode choice behavior of commuters during COVID-19 (Bhaduri et al. 2020). Besides, a recent study in Chile suggests that lower income groups are not extremely sensitive to crowding in public transport (Basnak et al. 2022). Also, the perceived safety of public transport is influenced by the commuters' anxiety level and their attention to COVID-19-related information. In other words, the commuters who have a higher anxiety level and pay more attention to COVID-19-related information perceive the public transport service to be unsafe (Dong et al. 2021). In our model setting, the C-commuters are those who possess private transport options, and the commuters who cannot afford private transport modes constitute the NC-commuter segment. The C-commuters and the NC-commuters in our model are analogous to the wealthy patients and the poor patients in the analytical model developed by Srinivas and Marathe (2021b). In the context of the Pradhan Mantri Bhartiya Janaushadhi Pariyojana scheme which aims to provide affordable generic medicines to the poor, the wealthy patients are those who can afford to purchase branded medicines and the poor patients are those who cannot afford to purchase branded medicines (Srinivas and Marathe 2021b). In our case, the C-commuters and the NC-commuters are defined based on whether the commuters can afford private transport or not during COVID-19.

Let the price of the public transport be p. Both the commuters possess the same value for the service, V, and the same waiting cost per unit time for the service, w. However, the opportunity cost of forgoing private transport for public transport varies across the commuter types. The opportunity cost is a function of two factors: (1) the price disutility, α_p, which is the disutility incurred from paying a price p for public transport, and (2) the perceived crowdedness disutility, β_p, which is an indicator of crowd level in the public transport under price p. Note that the price disutility and the perceived crowdedness disutility are a function of the price, p. Let the opportunity cost for the C-commuter be $q_c(\alpha_p, \beta_p)$ and the opportunity cost for the NC-commuter be $q_{nc}(\alpha_p, \beta_p)$. Given the risk of contracting COVID-19 due to high contact with other commuters in public transport, the opportunity cost for the C-commuter, $q_c(\alpha_p, \beta_p)$, is always greater than the opportunity cost for the NC-commuter, $q_{nc}(\alpha_p, \beta_p)$. Further, the service value outscores the opportunity costs for the commuters and, therefore, they arrive at the public transport facility at a Poisson rate λ. This is summarized in Assumption 1.

Assumption 1. We assume that $V > q_c(\alpha_p, \beta_p) > q_{nc}(\alpha_p, \beta_p) > 0$ for all p.

However, an arriving commuter observes a queue of length n at the public transport ticket counter. The commuter decides to join the queue or balk based on the net value ($V - q_c(\alpha_p, \beta_p)$ or $V - q_{nc}(\alpha_p, \beta_p)$ based on the commuter type) and the waiting cost. The utility derived by the C-commuter by joining the queue can be written as:

$$U_c = V - q_c(\alpha_p, \beta_p) - \frac{n+1}{\mu}w \tag{1}$$

In this function, the term $\frac{n+1}{\mu}$ denotes the commuter's waiting time (including the commuter's service time). Similarly, the utility derived by the NC-commuter by joining the queue can be written as:

$$U_{nc} = V - q_{nc}(\alpha_p, \beta_p) - \frac{n+1}{\mu}w \tag{2}$$

We normalize the utility from not joining the queue to 0. The commuter joins the queue if the utility is positive; otherwise, the commuter balks.

4 Results and analysis

We first compute the balking threshold for both the commuter types. Balking threshold is the minimum queue length at which the commuter does not join the queue since the utility is negative. At queue lengths below the balking threshold, the utility is positive, and the commuter joins the queue. The balking threshold for the C-commuter is $n_c = \left\lfloor \frac{(V-q_c(\alpha_p,\beta_p))\mu}{w} \right\rfloor$ and the balking threshold for the NC-commuter is $n_{nc} = \left\lfloor \frac{(V-q_{nc}(\alpha_p,\beta_p))\mu}{w} \right\rfloor$.

Proposition 1. *The balking threshold for the NC-commuter is greater than the balking threshold for the C-commuter.*

Proof. Since $q_c(\alpha_p, \beta_p) > q_{nc}(\alpha_p, \beta_p)$, it follows that $n_{nc} > n_c$ implying that the NC-commuters always join at higher queue lengths than the C-commuters. □

With the risk of COVID-19 spread, policymakers suggest that the ticket prices need to be raised to discourage people from traveling and contain crowds. However, pricing decisions also need to account for the fact that there are commuters who cannot afford private transport and must go to work anyways (Partington 2020). In this context, we analyze how changing prices will influence the queue joining behavior of the commuters using our stylized model. First, we consider the conventional wisdom case where the prices are increased. Let p_i be the increased price. We assume that $V > q_c(\alpha_{p_i}, \beta_{p_i}) > q_{nc}(\alpha_{p_i}, \beta_{p_i}) > 0$. The opportunity costs for both the commuter types are influenced in two countervailing directions: (1) An increase in the price directly translates to an increase in the price disutility, i.e., $\frac{d\alpha_p}{dp} > 0$; (2) An increase in the price also leads to reduced crowds at the public transport facilities, thereby reducing the risk of contracting COVID-19 which results in a decrease in the perceived crowdedness disutility, i.e., $\frac{d\beta_p}{dp} < 0$. Following the assumption in the extant literature that the price elasticity is highest for the poor (Srinivas and Marathe 2021b), we consider that the NC-commuters are comparatively more price-sensitive, and the C-commuters are comparatively more crowd-sensitive. Specifically, the first effect dominates for the NC-commuters, since they cannot afford increased prices, which translates to $\frac{dq_{nc}(\alpha_p,\beta_p)}{dp} > 0 \Rightarrow q_{nc}\left(\alpha_{p_i}, \beta_{p_i}\right) > q_{nc}(\alpha_p, \beta_p)$. On the other hand, the second effect dominates for the C-commuters, since they can afford an increase in prices for reduced risk of contracting COVID-19, which translates to $\frac{dq_c(\alpha_p,\beta_p)}{dp} < 0 \Rightarrow q_c\left(\alpha_{p_i}, \beta_{p_i}\right) < q_c(\alpha_p, \beta_p)$.

Proposition 2. *With a price increase, the balking threshold for the C-commuter increases and the balking threshold for the NC-commuter decreases.*

Proof. Let $n_c = \left\lfloor \frac{(V - q_c(\alpha_p,\beta_p))\mu}{w} \right\rfloor$ and $n_{nc} = \left\lfloor \frac{(V - q_{nc}(\alpha_p,\beta_p))\mu}{w} \right\rfloor$ be the balking thresholds before the price increase. With a price increase, the balking thresholds become $n_{c,i} = \left\lfloor \frac{\left(V - q_c\left(\alpha_{p_i},\beta_{p_i}\right)\right)\mu}{w} \right\rfloor$ and $n_{nc,i} = \left\lfloor \frac{\left(V - q_{nc}\left(\alpha_{p_i},\beta_{p_i}\right)\right)\mu}{w} \right\rfloor$. Since $q_c\left(\alpha_{p_i}, \beta_{p_i}\right) < q_c\left(\alpha_p, \beta_p\right)$ and $q_{nc}\left(\alpha_{p_i}, \beta_{p_i}\right) > q_{nc}\left(\alpha_p, \beta_p\right)$, it follows that $n_{c,i} > n_c$ and $n_{nc,i} < n_{nc}$.

It is apparent from Proposition 2 that while the C-commuters are encouraged to travel on public transport, the NC-commuters are discouraged to travel on public transport. It is important to note that the NC-commuters are prevented from traveling with a price increase, which is not the objective of public transport providers. We next consider the case where the prices are decreased. Let p_d be the decreased price. We assume that $V > q_c(\alpha_{p_d}, \beta_{p_d}) > q_{nc}(\alpha_{p_d}, \beta_{p_d}) > 0$. With a decrease in price, the opportunity costs for both the commuter types are again influenced in two countervailing directions: (1) A decrease in price directly translates to a decrease in the price disutility, i.e., $\frac{d\alpha_p}{dp} > 0$; (2) A decrease in price also leads to increased crowds at the public transport facilities, thereby increasing the risk of contracting COVID-19 which results in an increase in the perceived crowdedness disutility, i.e., $\frac{d\beta_p}{dp} < 0$. Specifically, the first effect dominates for the NC-commuters since they would be delighted with a decrease in prices, which translates to $\frac{dq_{nc}(\alpha_p,\beta_p)}{dp} > 0 \Rightarrow q_{nc}\left(\alpha_{p_d}, \beta_{p_d}\right) < q_{nc}(\alpha_p, \beta_p)$. On the other hand, the second effect dominates for the C-commuters since they cannot afford a decrease in prices for increased risk of contracting COVID-19, which translates to $\frac{dq_c(\alpha_p,\beta_p)}{dp} < 0 \Rightarrow q_c\left(\alpha_{p_d}, \beta_{p_d}\right) > q_c(\alpha_p, \beta_p)$.

Proposition 3. *With a price decrease, the balking threshold for the C-commuter decreases and the balking threshold for the NC-commuter increases.*

Proof. Let $n_c = \left\lfloor \frac{(V-q_c(\alpha_p,\beta_p))\mu}{w} \right\rfloor$ and $n_{nc} = \left\lfloor \frac{(V-q_{nc}(\alpha_p,\beta_p))\mu}{w} \right\rfloor$ be the balking thresholds before the price decrease. With a price decrease, the balking thresholds become $n_{c,d} = \left\lfloor \frac{\left(V-q_c\left(\alpha_{p_d},\beta_{p_d}\right)\right)\mu}{w} \right\rfloor$ and $n_{nc,d} = \left\lfloor \frac{\left(V-q_{nc}\left(\alpha_{p_d},\beta_{p_d}\right)\right)\mu}{w} \right\rfloor$. Since $q_c\left(\alpha_{p_d}, \beta_{p_d}\right) > q_c\left(\alpha_p, \beta_p\right)$ and $q_{nc}\left(\alpha_{p_d}, \beta_{p_d}\right) < q_{nc}\left(\alpha_p, \beta_p\right)$, it follows that $n_{c,d} < n_c$ and $n_{nc,d} > n_{nc}$.

It is apparent from Proposition 3 that while the C-commuters are discouraged to travel on public transport, the NC-commuters are encouraged to travel on public transport. In the presence of both the C-commuters and the NC-commuters, an intricate approach of price decrease is required to discourage the C-commuters from using public transport and encourage the NC-commuters in using public transport. This phenomenon of filtering out the C-commuters from using public transport under certain conditions is along the lines of screening the wealthy patients from the poor patients in the Pradhan Mantri Bhartiya Janaushadhi Pariyojana scheme, wherein the wealthy patients who can afford to purchase branded medicines are filtered out and the poor patients who cannot afford branded medicines become beneficiaries of the scheme which provides generic medicines at affordable prices (Srinivas and Marathe 2021b). While the screening in Srinivas and Marathe (2021b) is achieved with the management of apprehensions regarding the perceived quality of generic medicines, the C-commuters are screened from the NC-commuters with pricing decisions in this case.

5 Extended model: the case of three commuter types

In addition to the existing C-commuter and NC-commuter types, we consider an intermediate I-commuter type who can afford private transport options; however, the opportunity cost is lesser than that of the C-commuter's opportunity cost and greater than that of the NC-commuter's opportunity cost. For example, the I-commuters (which includes students and elderly among others) can afford an alternative private transport and hire taxis among others; however, they prefer public transport due to convenience, lack of driving skills, etc. Let $q_i(\alpha_p, \beta_p)$ be the opportunity cost of the intermediate commuter type. We extend Assumption 1 to consider three commuter types and come up with the following assumption.

Assumption 2 We assume that $V > q_c(\alpha_p, \beta_p) > q_i(\alpha_p, \beta_p) > q_{nc}(\alpha_p, \beta_p) > 0$ for all p.

Under this assumption, we can find that the balking threshold for the I-commuter is $n_i = \left\lfloor \frac{(V - q_i(\alpha_p, \beta_p))\mu}{w} \right\rfloor$ when the utility derived from joining the queue for the I-commuter is given by $U_i = V - q_i(\alpha_p, \beta_p) - \frac{n+1}{\mu} w$.

Proposition 4 *The balking threshold for the I-commuter is in between the balking thresholds for the NC-commuter and the C-commuter, wherein the balking threshold for the NC-commuter is highest and the balking threshold for the C-commuter is lowest.*

Proof. Since $q_c(\alpha_p, \beta_p) > q_i(\alpha_p, \beta_p) > q_{nc}(\alpha_p, \beta_p)$, it follows that $n_{nc} > n_i > n_c$ implying that the NC-commuters always join at queue lengths greater than that of the I-commuters which in turn is greater than that of the C-commuters.

From our earlier discussion, we infer that decreasing the price discourages the C-commuters from using public transport and encourages the NC-commuters to use public transport. With respect to the I-commuters, their sensitivity to price changes depends on their opportunity cost of foregoing private transport for public transport, which is a function of the price changes and the perceived crowdedness in public transport. If the I-commuters value the price decrease more than the increase in perceived crowds on public transport, they will be further encouraged to use public transport. Instead, if the I-commuters are apprehensive regarding the perceived crowds on public transport and the price decrease does not reduce their opportunity cost significantly, they will be discouraged from using public transport. In this regard, the travel choice of I-commuters is strictly in between the NC-commuters and the C-commuters, and hinges on their opportunity costs.

6 Conclusion and discussion

Public transport ridership has been affected due to the risk associated with COVID-19 infection spread. Studies in the past year have provided a variety of policy prescriptions which will enable the public transport ridership to increase. Dong et al. (2021) suggest that proper communication of information and restoring trust in public transport, obtaining regular feedback, increasing the service frequency to maintain social distancing, and avoiding crowds in the waiting area are some of the measures required to alleviate fears regarding COVID-19 spread in public transport. With social distancing considerations in focus, Gkiotsalitis and Cats (2021a) discuss how planning at the strategic (design of public transport networks), tactical (determining the optimal frequency and timetables of metro services) and operational levels (crowd management) is essential to revive public transport in the COVID-19 era. In this context, we developed a strategic queueing model to understand how pricing can influence the behavior of commuters during COVID-19. We establish a counterintuitive proposition wherein the public transport provider should not increase the prices to prevent overcrowding and in contrast, decrease the prices to filter out the commuters who can afford other modes of transport and provide services to the commuters who cannot afford other modes of transport. Interestingly, public transport fares have been reduced across various places in recent times. With the objectives set to minimizing energy use amidst the global energy crisis and reducing the cost of living for households, the German federal government in 2022 came up with the 9 EUR-Ticket wherein commuters can travel for 9 EUR per month across Germany in public transport except for long-distance trains, and a tax cut on diesel and gasoline for car drivers from June 2022 to August 2022 (3-month period). While the fuel tax cut failed to reach end consumers, several million public transport tickets were sold in this period. Based on surveys, it is further expected that a substantial increase in travel pass ownership can be observed in Germany when a 49 EUR-Ticket is succeeded by the 9 EUR-Ticket or a new local travel pass of 30 EUR per month is introduced (Loder et al. 2022). Along similar lines, ticket prices have been reduced significantly in Barcelona by the Metropolitan Transport Authority and the Barcelona Metropolitan Area[1] and in Ireland to encourage commuters to shift to public transport and reduce the reliance on private transport[2].

Our model and analysis come with certain limitations. In this analysis, we consider that the waiting area capacity at the public transport ticket counter is infinite. Consequently, any number of commuters can utilize the public transport service. However, in order to implement social distancing in rail compartments and buses, capacity limits on the number of commuters have been established by various governments worldwide (Gkiotsalitis and Cats 2021a). As an extension to the current model, we can consider the case where the waiting area capacity is finite and understand the resultant equilibrium behavior of the commuters. Further, this study aims to filter out the commuters who possess alternative travel options from the commuters who can afford only public transport. As an extension to this model, we can consider specific objectives for the public transport provider and analyze how the pricing decisions of the profit maximizing and social welfare maximizing public transport providers differ from the prices in the current model which filters out the wealthy commuters. Further, we do not delve into specific functional relationships and conditions under which the price disutility factor dominates for the NC-commuters and the perceived crowdedness disutility factor dominates for the C-commuters. An analysis of the conditions under which the price disutility or the perceived

[1] See https://www.tmb.cat/en/barcelona-fares-metro-bus/single-and-integrated/transport-fares-reduction — accessed November 10, 2022

[2] See https://www.gov.ie/en/press-release/1a6f7-reduced-public-transport-fares-to-roll-out-from-april/ — accessed November 10, 2022

crowdedness disutility dominates, and their resultant impact on the opportunity costs and the balking thresholds of the commuters is also left for further research.

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