On-Demand Ride-Hailing Service Platforms With Hired Drivers During Coronavirus (COVID-19) Outbreak: Can Blockchain Help?

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Abstract—**During the recent COVID-19 (CoV) global outbreak, there is a sharp decline of revenue of on-demand ride-hailing (ODR) platforms because people have serious worries of infection in the shared vehicles. Blockchain, which supports cryptocurrency and creates full traceability of the service history of each car and driver, may come to rescue by allowing the platform to offer only the "safe cars" to consumers. Motivated by the real world challenges associated with the CoV outbreak for the ODR platform, we build game-theoretical models based on the M/M/n queuing system to explore if and how blockchain can help. In the basic model, the ODR platform decides the service price and special hygiene level. Comparing between the cases with and without blockchain, we find that blockchain implementation increases both the service price and hygiene level. In addition, when the consumers' inherent worry of infection is substantially large, implementing blockchain achieves all-win for the ODR platform, drivers and consumers. In the extended models, we first consider the case when the special hygiene level is determined by the drivers under a mixed-leadership game and then explore the case when customers are risk averse. The main findings about blockchain adoption remain valid in both cases. However, when the drivers take charge of the special hygiene level, both optimal decisions are lower in most cases. It is also important to make efforts to reduce consumers' feeling volatility toward service valuation for improving the value of blockchain adoption and related performances.**

Index Terms—**Blockchain, coronavirus outbreak, pricing, ride-hailing platform operations.**

I. Introduction

A. Background and Motivation

UBER and Alto are popular on-demand ride-hailing (ODR) service platforms. They used to have a solid business in normal market environments. However, with the recent global COVID-19 outbreak, the ride-hailing industry deeply suffered and the ride-hailing platform Alto's CEO even claimed that "Ride volume had fallen by about 75%."[1] These may be related to the regulations or public awareness that consumers were encouraged to follow "social distancing" rules, including staying at home orders, public school closures, and other restrictions [16]. More importantly, consumers who need to go out have deep worries about hygiene and the risk of being infected. A recent report by Washington Post is very pessimistic toward Uber's ride-ship business.[2]

Under COVID-19, some car-hailing platforms, such as Alto, hire and train their own drivers with "background checked" as shown from the official websites. For other platforms like Didi and Uber, they have hired their own trained drivers under the "Didi" and "Uber Black" premium service schemes for ODR services [12]. A big decline of demand directly hurts the drivers and ODR platform. Consumers also suffer by the inconvenience caused. Expecting the coronavirus outbreak will continue for some time and similar disease cases may appear from time to time in the future, it is critically important to think of a solution to this challenge. It is noticed that the spread of pandemic has pushed ODR platforms to invest substantially in health safety programs, such as special hygiene for protection. It is reported that Uber has spent US$50 million on health-protection related resources, including face masks, hand sanitizers, and bleach wipes, so as to lift the extra hygiene level during the COVID-19 pandemic. From Uber (Hong Kong)'s website, we can see that Uber (Hong Kong) has imposed extra measures to enhance the hygiene level like providing and using special cleaning and sterilizing materials and procedures.[3] A recently launched ODR platform with a focus on safety, Alto, has well survived and gained market share in the global COVID-19 pandemic. Besides providing masks, gloves, and sanitation training for its drivers, Alto also checks the drivers' temperatures before each shift, installs "plexiglass" barriers between drivers and riders, and offers a hospital-grade high-performance sanitizing mist that kills 99.9% of bacteria and viruses, including COVID-19. The company even implements high efficiency particulate air filters

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[1] Accessed: Sep. 29, 2020. [Online]. Available: https://edition.cnn.com/2020/03/27/tech/drivers-delivery-workers/index.html

[2] Accessed: Oct. 18, 2020. [Online]. Available: https://www.washingtonpost.com/technology/2020/08/10/uber-coronavirus-lockdowns/

[3] Accessed: Oct. 18, 2020. [Online]. Available: https://www.uber.com/hk/zh-hk/coronavirus/?_ga=2.85499225.117759456.1602996145-231336113.1602996145&uclick_id=f5736ccf-4d3f-484d-8ece-e56b5aa7e68f

(that are used in hospitals) to provide clean air. It recorded an impressive 300% increase in demand in May 2020 compared to April 2020, because Uber and Lyft both fell behind in terms of hygiene related "health-safety" measures. It is also observed that some platforms encourage drivers to take responsibility for the health-safety issues.[4] This is especially true if the vehicles are owned by the drivers. Didi provides guidance for drivers to keep them and passengers protected from COVID-19 "without enforcement." For example, it recommends drivers to wear personal protective equipment (PPE) such as masks if they feel comfortable. Moreover, drivers are recommended to install in-vehicle plastic protective sheets at their own discretions. Lyft, another well-established rideshare platform, also spent nearly US$2.5 million to purchase hand sanitizers, masks, disinfectants, etc. and offered them to its drivers for their usage[3]. However, Lyft does not have the legal power to force its drivers to fully use these resources as well as undertake the extra hygiene requirements such as regular temperature check or plastic protective sheet installation. In addition, although many platforms provide guidance to drivers and may request for reporting, the drivers may not faithfully follow and some may even provide fake reports and information. Though many ODR platforms have already claimed that they are clean and safe with a high hygiene level, consumers may still doubt because all kinds of passengers may have taken the vehicles before and whether the vehicles are really properly sterilized is unknown. All these motivate the need to have new technologies for traceability of reliable and trustworthy information on both drivers and customers.

In ride-hailing and logistics industries, the distributed ledger technology blockchain has been well-proposed for different functions. The new technologies enable firms and platforms to operate more efficiently and effectively [17], [12]. The current "news-reported" proposal mainly focuses on cryptocurrency such as "Uber dollar" which may create benefits and convenience to the drivers, consumers and ODR platform. In fact, in early 2021, Uber's CEO Dara Khosrowshahi said on CNBC that Uber is considering "accepting cryptocurrencies including bitcoin as a form of payment" with the support of blockchain.[5, 6] RideX, an Ethereum blockchain based platform for taxi-services, has planned to use cryptocurrency in its operations with the crypto-wallets.[7] Both drivers and passengers are benefited with the use of cryptocurrency, which also helps achieve the contactless payment scheme. Arcade City has launched the blockchain ride hailing and deliveries app.[8] This platform uses to be Ethereum blockchain-powered application that allows users to pay for their rides through the integrated Airbitz login-enabled Bitcoin wallets. Nowadays, it has further developed and established its own blockchain ecosystem and declared that the scalability and usability challenges, such as privacy issues, drivers' instant payment, and integration of credit card and crypto payments, are well solved.

Blockchain, in fact, has many other critical functions. For instance, using a private permissioned blockchain can create full traceability of the reliable and trustworthy sterilization information as well as service history of each car and every driver. To be specific, for customers (i.e., passengers), to use the ride hailing services, their phone numbers will naturally be recorded and put into the blockchain with code. This makes it easy to trace when there are valid business/health-safety needs. The same applies to drivers in which their working schedule with respect to the vehicle will also be recorded in the blockchain. If the process of data registration is well designed in which each step taken during the sterilization process is well-documented in the blockchain based system, drivers dare not fake the related information as the records are all kept permanently and governing bodies can always trace and inspect the corresponding data records. Drivers will need to face very serious consequences if they provide fake information and blockchain's data records are the strongest evidence. This is critical as it helps foster trust of consumers and it allows the ODR platform to offer only the safe and well-sterilized cars to consumers, as the cars associated with infected/suspected passengers or drivers can quickly be identified and further sterilized. In the real world, platforms, such as RideX and Acrade City, reveal the features and benefits of blockchain adoption on their official websites. This would naturally help reduce consumers' worry and foster trust.

Moreover, drivers' wages are reduced significantly due to the epidemic. In order to make compensation, instant payment is actually a feature that drivers in ride hailing platforms' loyalty program will have access to. We have conducted an interview with a senior data scientist in Uber to obtain the needed industrial inputs. According to the interview, blockchain implementation is effective and helpful because platforms can foster consumers' trust during COVID-19 and smart contracting function of blockchain can achieve instant payments. Note that to the best of our knowledge, the only technology which possesses all these features is blockchain. To be specific, the only technology to support cryptocurrency is blockchain, which enables efficient and accurate payment (no cheating and quick). For example, in the RideX platform, which has implemented blockchain, it is reported that, *"when the user makes a transaction, an Ethereum Smart-contract is written in such a way that 80% of the bill amount goes to the Taxi Driver, 11% of it goes to the Government's Wallet address (Futuristic scenario), and the rest of the 9% funds are transferred to RideX community funds.[7]"* The only technology, which can guarantee full trust and permanent information, as evidenced in applications in diamond supply chains (see Everleger[9]), and food industries (IBM and Walmart case), is also blockchain. Blockchain is well known as a decentralized system and related information, can be shared with all relevant parties easily. According to our investigation, all these features will reduce consumers' worry and enhance information transparency. Using blockchain here is hence not a simple "buzz word" or "gimmick" or "garbage-in garbage-out,"

[4]For Alto's case, we thank a manager from a popular website for drivers and a senior executive of Alto for their industrial inputs. For the other cases, the practices are observed from the platforms' blogs and official websites.

[5]Accessed: Jun. 3, 2021. [Online]. Available: https://www.coindesk.com/uber-crypto-payments

[6]Accessed: Nov. 2, 2020. [Online]. Available: https://bitcoinist.com/an-uber-crypto-future-could-be-closer-than-you-think/

[7]Accessed: Jun. 3, 2021. [Online]. Available: https://uxplanet.org/ridex-taxi-service-on-ethereum-blockchain-fecee1879a23?gi=3406a8a15234

[8]Accessed: Jun. 12, 2021. [Online]. Available: https://www.newsbtc.com/sponsored/arcade-city-taps-blockchain-technology-create-new-age-uber/

[9]Accessed: Jun. 3, 2021. [Online]. Available: https://www.everledger.io/

because it cannot be replaced by another technology like AI or big data analytics [13], [32]. However, the use of blockchain in ride-hailing platforms as well as the challenges they faced under CoV are not yet systematically explored in the literature.

B. Research Questions and Contribution

Motivated by the challenges created by the CoV outbreak as well as the probable help brought by blockchain, we build consumer utility based theoretical models with the goal of addressing the research questions as follows.

1) For the ODR platform: What are the optimal pricing and hygiene level decisions under the CoV outbreak with and without implementing blockchain?
2) When will the implementation of blockchain help the ride-hailing platform? What will be the situation in which deploying blockchain becomes an all-win solution (i.e., consumers, drivers, and ODR platform all get benefited)?
3) How robust are the findings when we generalize the models to different settings such as a) the case when the special hygiene level is the decision made by the drivers, and b) consumers are risk averse? What additional insights can be uncovered regarding the benefits and values of blockchain?

The objective of this article is to identify solutions for ride-hailing platforms under CoV and uncover whether and when blockchain can create “all-win” so that consumers, drivers and the ODR platform are all benefited. By exploring the answers to the above research questions, we theoretically establish analytical basic models based on an M/M/n queueing system, in which the special hygiene measures and pricing policies are imposed by the ODR platform. We investigate the platform’s incentive to adopt blockchain, which fosters consumers’ trust under CoV by significantly reducing their worry of infection. Blockchain implementation is expected to increase the service price and hygiene level at the same time. We also analytically find that if the consumers’ inherent worry of infection is substantially large, implementing blockchain is beneficial to the ODR platform, drivers and consumers (i.e., it achieves all-win). If this situation is not satisfied, we uncover the situation in which government sponsors are needed in order to achieve all-win. The amount of sponsor needed is also derived in closed-form. Regarding the impacts brought by two critical factors in the problem, namely the number of drivers and the effective demand arrival rate, we have the following findings. First, we find that when the number of drivers increases, the optimal price, optimal special hygiene level, and the respective ODR platform’s profit, drivers’ profit and consumer surplus all go up. Second, for blockchain adoption, when the number of drivers increases, the values of blockchain for the ODR platform, drivers and consumers are more likely to be positive. For the effective demand arrival rate, it has polarized influences. These results show that if the number of drivers is relatively large or the effective demand arrival rate is low, an all-win situation by blockchain adoption is easier to be achieved. This situation well reflects what is happening during COVID-19. Hence, we urge car-hailing platforms to adopt blockchain under the epidemic.

In the extended models and analyses, we consider various important extensions. In the first extended model (Model DVD) in which the drivers determine the special hygiene level themselves, we model it as a mixed-leadership game. In the absence of blockchain, we find that both the optimal service price and special hygiene level are lower under Model DVD compared to the basic models in which the ODR platform decides the special hygiene level. For the case when blockchain is present, comparing to the basic model, we find the conditions under which the optimal service price and special hygiene level are lower under Model DVD. Moreover, we analytically prove that under Model DVD, the blockchain adoption increases both the optimal service price and special hygiene level. After robustness checking, we show the findings about the value of blockchain implememtation under the basic models remain valid even if the special hygiene level decision is made by the drivers, rather than the ODR platform.

In the second extended model, we consider the situation with risk averse consumers (i.e., Model RA). We find that no matter whether blockchain is present or absent, for the case in which consumers are risk averse, the optimal service price, special hygiene level, profits of the ODR platform and drivers, and consumer welfare are lower compared to the respective case in which consumers are risk neutral. In addition, the risk attitude of consumers does not affect the impact of blockchain implementation on the optimal service price and special hygiene level. Last but not least, we suggest the platform make efforts in reducing consumers’ feeling volatility toward service valuation, as their risk attitude blunts the value of blockchain for all parties.

To the best of our knowledge, this is the first analytical study that explores the application of blockchain as a solution to deal with the CoV outbreak for ODR platforms in logistics. All the results and insights are mathematically proven in closed-form. The findings not only contribute to the literature but also provide insights to enhance practices, which help the ODR platforms to better cope with the CoV outbreak.

C. Organization

This article is organized as shown in the following. After presenting the background and introduction in Section I, we review related studies in the literature in Section II. We establish the basic models in Section III, in which features of the ODR operations with and without blockchain are developed. We investigate when blockchain will create the all-win situations in Section IV. When blockchain can help consumers and drivers but not the ODR platform, we propose how governments may provide sponsorship to help. For robustness checking and deriving more insights, we explore various extensions in Section V. Section VI concludes this article. To improve readability, all technical derivations as well as analytical proofs are placed in the online appendix (A2).

II. Literature Review

A. Ride-Hailing Platforms Operations

Over the past few years, studies on ride-hailing platforms are very popular in the literature. The earliest studies focus on the optimal pricing decisions for the ODR services. For instance, Bellos *et al.* [3] analytically explore via stylized models the vehicle-sharing problem with respect to "product line design." Cachon *et al.* [4] theoretically examine the optimal "surge pricing policies" on a service platform in the presence of a "self-scheduling control" capacity. Taylor [44] studies the "supply demand matching" issues for on-demand platforms, including ride-hailing platforms. The author considers the case in which consumers possess the "high-low" utility function and derives the optimal pricing policies. Most recently, Hu *et al.* [24] analytically study the optimal surge pricing decisions in ride-hailing platform operations. The authors interestingly explore the "two-sided temporal responses" in their model.

After that, many recent studies emerge to examine various important consumer behaviors related issues or innovative strategies in ODR platforms. For example, considering the impatient consumer behaviors, Bai *et al.* [2] investigate the optimal pricing scheme and ODR platform with data from Didi. The authors uncover the insights regarding the situation when customers possess the impatient behavior. Nourinejad and Ramezani [37] analytically study the ride-sourcing model. They argue that the long-term "daily profit" of the platform with the dynamic pricing policy can be improved after relaxing the constraint governing the charged price and agents' wage. Sun *et al.* [43] study labor supply on ride-sharing platforms. The authors consider both participation and working-hour decisions in the model with "sample self-selection bias" of driver participation and the income rate is endogenous. Sun *et al.* [42] examine ride-sourcing platform operations and prove that consumers will suffer a loss if the "closest drivers are chosen" by the platform. Choi *et al.* [12] explore the on-demand service platform with risk-sensitive consumers. The authors prove that customized pricing using blockchain technology can help improve revenue for the platform. Chen *et al.* [7] study the optimal dynamic policies for best matching supply and demand in real time for an ODR platform. The authors propose an "approximate dynamic programming" algorithm to solve the problem and generate insights regarding the optimal commission rate and surge price. Most recently, Yu *et al.* [50] examine the issues on regulating "ODR services". The authors propose an insightful result that to improve total social welfare, the government may in fact reform the taxi industry, rather than putting stricter rules toward the on-demand ride services.

Similar to the above examined studies, this article explores ride-hailing platform service operations. In particular, we also focus on studying the optimal pricing decisions. However, different from all of the reviewed papers, we investigate the special hygiene level, which is a crucial aspect under the CoV outbreak. We also focus on uncovering the impacts brought by blockchain technologies. Other considerations, such as the hygiene level decision making role (the ODR platform versus drivers), and risk attitudes of customers, which are important under the CoV outbreak and studied in this article, are not explored in the extant literature.

B. Logistics Operations Under Disasters

The second area, which relates to this article, is on supply chain and logistics service operations under disasters [22]. Gupta *et al.* [21] classify the disaster management research by highlighting five critical attributes of a major disaster. Among them, disaster management function, which includes the decision-making process, prevention, and mitigation, is fundamentally important. Some research conducts game-theoretical analyses toward logistics systems in the presence of current or future disasters such as climate changes, natural disasters [46], or sudden disruptions in transportation [47]. Early studies have explored the development in information technology and quantified values of such investment on operations issues [40]. In recent years, more and more studies have paid attention to the deployment of technologies. For example, Yan and Pedraza-Martinez [48] examine the use of social media analytics for disasters related logistics planning. Mejia *et al.* [34] investigate how information transparency may yield higher donation for disasters via the crowdsourcing platform. Ivanov [26] proposes a simulation based approach to forecast impacts brought by the CoV outbreak on global distribution channels. Most recently, motivated by a real case in Hong Kong, Choi [10] investigates the situation of making stationary static services "mobile" and offering them via using a truck under the CoV outbreak. Using multiple methods, Bag *et al.* [1] empirically investigate the impact of "big data analytics" on healthcare supply chain operations to fight against pandemics. For a review and discussion of pandemic and the related operations and supply chain management studies, please refer to Craighead *et al.* [15] and Kaplan [29]. Regarding how on-demand service operations may continue under disasters or disease outbreaks like the CoV pandemic, to the best our knowledge, this article is the first one in the literature.

C. Operations Management With Blockchain Technologies

Blockchain technologies are widely used in logistics operations [8], [33], [38], as well as addressing the traceability problem in business operations [23]. Historically, the cryptocurrency, such as bitcoin, is closely related to blockchain. In fact, blockchain's rapid development is directly associated with the popularity of bitcoins. Nowadays, blockchain is no longer just a tool or system for secure financial transactions. It actually works for many different aspects in logistics and business operations [35], such as supply chain finance [18], information sharing [20], crowdsourcing [36], transport and logistics [31], and healthcare sector [41]. In the recent literature, Choi [9] mathematically explores the diamond supply chain with the use of an Everledger blockchain based platform. The authors show how blockchain can provide the needed information to enhance channel transparency. Orji *et al.* [38] examine the critical factors which affect the deployment of blockchain in transport. The authors provide a solid evaluation of these factors, which are crucial for freight logistics. Lopez and Farooq [33] study the "smartphone based mobility data blockchain" as an emerging technology in logistics networks. The authors pay attention to privacy issues and derive a six-layer framework, which precisely describes the related "information flow". Choi *et al.* [12] propose to use blockchain to help on-demand service platforms to offer customized pricing schemes for different risk sensitive customers. The importance of blockchain is highlighted. Most recently, Cai *et al.* [5] study the use of blockchain to combat cheating behaviors in supply chains with the use of platforms. Pun *et al.* [39] investigate the value of blockchain in combatting counterfeiting with consideration of the interplay between a manufacturer and a counterfeiter.

Similar to the above reviewed papers using blockchain and its related technologies, this article also analytically studies the impacts and values of blockchain as a useful technological tool. However, this article focuses on dealing with the CoV outbreak for ride-hailing platform operations. The consideration of enhancing "safety" via information transparency, which is important in this study, is also not explored by the prior studies. As the impact of such digital transformation on the employees or agents is largely overlooked in the literature [15], this article contributes to fill this gap by exploring the drivers' incentives to make efforts in lifting the special hygiene level with the use of blockchain.

III. Basic Models

A. ODR Platform Operations Without Blockchain

We consider an ODR platform, which is similar to Uber, Didi and Alto, in which the ODR platform hires well-trained drivers to serve the market. Between the drivers and ODR platform, there is a revenue sharing scheme in which a proportion $0 < \alpha < 1$ of revenue generated by the rides will be shared with the drivers. This is a common practice in many ride-hailing platforms [12]. Following the observed industrial practice, the payment to the drivers will be made as a lump-sum periodically, e.g., on the last day every month. As such, when drivers receive the payment, owing to time value of money, they actually receive less money compared to the case when they can get a share of the revenue instantly. Without blockchain, the ODR platform hires a bank to help with financial matters and there is a fixed service fee of T_{FIN}. For the ODR platform, it has to make decisions on two things, namely the pricing p (for the ride service which is a critical part of revenue management [45]) and special hygiene level h, which represents the "extra" hygiene level compared with operations during the normal market conditions and is critical under the CoV outbreak. Based on the observations from industries, the special hygiene level refers to the PPE and related efforts (to cope with COVID-19), such as face covering, gloves, sanitization, and plexiglass barriers installation. In our model, we consider the case when the cost for achieving a special hygiene level h is a quadratic function as follows: $J(h) = kh^2/2$ [28]. This cost will be settled also on the last date of every month periodically. For consumers, under the CoV outbreak, they deeply worry about the risk of being infected. We call this worry the "consumers' inherent worry of infection" and represent it by w. Note that it is possible that there is no demand for car-hailing service even if it is free of charge, when the consumers have extremely serious concerns about being infected. Then, it is natural for the platform to turn to other solution such as blockchain implementation. We assume that the consumers' worry of being infected is in a reasonable range to avoid the trivial scenario, under which comparison with the blockchain adoption case becomes trivial. In addition, for ride-hailing services, consumers commonly do not want to wait and hence waiting time creates a disutility. In this article, we follow the standard and simple M/M/n queueing model (e.g., [12], [44],) the market demand for on-demand riding services to follow a standard "Poisson process" with "exponentially distributed" service time. For the standard parameters for the Poisson process, we have:

1) the number of hired drivers [representing the available service capacity (in hours)] $= n$,
2) the "effective demand arrival rate" is r under CoV outbreak, and
3) the "average service rate" is denoted by a, where $r/(na) < 1$[44].

As a result, the expected waiting time in the M/M/n queue can be found at the steady state (and we denote it by Θ). Following the standard results in the literature (see, e.g., [44], [12]), the expected waiting time Θ in this M/M/n queueing system is

$$\Theta = \left(\sum_{i=0}^{n-1} \frac{[r/a]^i}{i!} + \frac{[r/a]^n}{n!(1-(r/(na)))} \right)^{-1} \left(\frac{(r/a)^n}{n!(1-(r/(na)))^2 na} \right). \quad (1)$$

For the consumer, its valuation toward the ride service is denoted by v. We model v as a continuous variable following a density function $g(v)$. The consumer will pay for the ride service when its valuation is higher than its net cost, which includes the service payment p, expected waiting time scaled disutility $t\Theta$ (and $t > 0$ is the coefficient which maps and scales the waiting time to reflect the consumer disutility), and worry of being infected w. The consumer will be happy for riding on a "clean" vehicle and hence the special hygiene level h creates a utility. In general, a higher h improves the consumer utility and helps offset the worries. With the above formulations, the market demand for the case without blockchain under the CoV outbreak is

$$d_{\overline{\text{BCT}}} = \int_{p+t\Theta+w-h}^{1} g(v)dv. \quad (2)$$

Following the extant literature, we consider $g(v)$ to be a uniform distribution in the range of 0 to 1. Thus, (2) becomes

$$d_{\overline{\text{BCT}}} = 1 - t\Theta - w + h - p. \quad (3)$$

With (3) and the above descriptions, we can derive the profit functions for the ODR platform $\left(\Pi^{\text{PF}}_{\overline{\text{BCT}}}\right)$ and drivers $\left(\Pi^{\text{DV}}_{\overline{\text{BCT}}}\right)$ in the following:

$$\Pi^{\text{PF}}_{\overline{\text{BCT}}} = \phi p(1 - t\Theta - w + h - p) - J(h) - T_{\text{FIN}} - \Pi^{\text{DV}}_{\overline{\text{BCT}}} \quad (4)$$

$$\Pi^{\text{DV}}_{\overline{\text{BCT}}} = \alpha p(1 - t\Theta - w + h - p) \quad (5)$$

where $\phi > 1$ is a threshold representing the average gain in interests by the ODR platform as it receives payment from customers continuously and the other cost parameters are all calculated on the last date of every month. Accordingly, the first term in (4) represents the expected total revenue received by the platform with time value consideration. Note that the second and third terms in (4) are the special hygiene cost and a fixed service fee charged by the bank, respectively. As shown in (5), the revenue is shared to the drivers with a proportion α.

TABLE I
NOTATION EMPLOYED IN THE BASIC MODEL

Notation	Meaning
α	The percentage of revenue generated by the rides and shared with the drivers
v	Consumer's valuation towards the ride service
h	Special hygiene level
p	Service payment
w	Consumer's worry of being infected without blockchain adoption
m	Consumer's worry of being infected with blockchain adoption
a	Average service rate
n	The number of hired drivers
r	Effective demand arrival rate
Θ	Expected waiting time
t	Coefficient maps and scales the waiting time to reflect the consumer disutility
T_{FIN}	Fixed service fee paid to the bank
b	Unit operations cost of blockchain
T_{BCT}	Fixed cost incurred for basic systems maintenance and server hosting of blockchain adoption
$\Pi^{PF}_{\overline{BCT}}$	The profit function for the ODR platform without blockchain
$\Pi^{DV}_{\overline{BCT}}$	The profit function for the drivers without blockchain
$\Gamma_{\overline{BCT}}$	Consumer surplus without blockchain
Π^{PF}_{BCT}	The profit function for the ODR platform with blockchain
Π^{DV}_{BCT}	The profit function for the drivers with blockchain
Γ_{BCT}	Consumer surplus with blockchain

Checking the structural properties shows that $\Pi^{\mathrm{PF}}_{\overline{\mathrm{BCT}}}$ is a concave function when $k > (\phi - \alpha)/2$. This reflects the situation when achieving the special hygiene level h is sufficiently expensive, which means it is economically unwise to achieve a special hygiene level to its upper limit.

It is also straightforward to find the consumer surplus as follows:

$$\Gamma_{\overline{\mathrm{BCT}}} = \frac{(1-(p-h+t\Theta+w))^2}{2}. \tag{6}$$

Note that in this article, we focus on exploring the measures, which can create all win to the consumers, drivers, and ODR platform. Thus, (4), (5), and (6) are the important performance measures under the case without blockchain. To enhance readability, we present Table I, which shows a summary of the major notation and symbols employed in this article.

B. ODR Platform Operations With Blockchain

When blockchain is implemented, several changes appear. First, the ODR platforms can now pay the drivers using cryptocurrency. As what the ride-hailing platform RideX has implemented in practice, the platform can pay the drivers using smart contracting mechanism, which means the drivers can instantly get a share of revenue from each ride in cryptocurrency. This brings an additional benefit to the drivers. For the ODR platform, it also saves the service fee required by the bank. In addition, the utilization of cryptocurrency achieves contactless payment naturally, which is one proposed measure by the car-hailing platforms under CoV (see Section I). Moreover, blockchain can support the full traceability of prior passenger information and disclose transparent information regarding sterilization details. After the platform highlighting these features and benefits of blockchain on the platform's official websites and promoting related feature with news, consumers will be informed about blockchain implementation and related benefits, which will significantly reduce their worry of being infected as a result. Thus, the reduced parameter on "worry of being infected" is represented by m, and $m \ll w$. Third, blockchain is not free. For instance, using IBM blockchain cloud service incurs a service fee per unit time. Blockchain, despite having many appealing features, is known to be "expensive" because it takes time to create a block and establish the hashtags, etc. Thus, a unit blockchain operations cost b is incurred (per demand or usage CPU time). In addition, a fixed cost T_{BCT} is incurred for basic systems maintenance, server hosting, etc.

With the above description, the market demand for the case with blockchain under the CoV outbreak is

$$d_{\mathrm{BCT}} = \int_{p+t\Theta+m-h}^{1} g(v)dv = 1 - t\Theta - m + h - p. \tag{7}$$

Note that the linear additive demand is derived following the consumer utility approach, which is also in line with the commonly seen linear demand function in the literature. This is a rather standard result in operations management. Observe that in the literature, some studies also employ the multiplicative demand (e.g., with the product quality decision [11]) but we do not have any reasons to say the commonly seen linear demand is not applicable here.

With (7), we can obtain the profit functions for the ODR platform ($\Pi^{\mathrm{PF}}_{\mathrm{BCT}}$) and drivers ($\Pi^{\mathrm{DV}}_{\mathrm{BCT}}$) to be the following:

$$\Pi^{\mathrm{PF}}_{\mathrm{BCT}} = (\phi p - b)(1 - t\Theta - m + h - p) - J(h) - T_{\mathrm{BCT}} - \Pi^{\mathrm{DV}}_{\mathrm{BCT}} \tag{8}$$

$$\Pi^{\mathrm{DV}}_{\mathrm{BCT}} = \alpha\phi p(1 - t\Theta - m + h - p) \tag{9}$$

where the first term in (8) is the expected profit margin received by the platform with the consideration of time value and the variable cost of blockchain adoption. The second and third terms in (8) are the special hygiene cost and a fixed cost of blockchain adoption, respectively. Compared with the platform's objective function (4) in the absence of blockchain, the service fee required by banks (T_{FIN}) is waived with blockchain implementation. As shown in (9), the revenue is shared to the drivers with proportion α.

Similar to $\Pi^{\mathrm{PF}}_{\overline{\mathrm{BCT}}}$, checking the structural properties of $\Pi^{\mathrm{PF}}_{\mathrm{BCT}}$ shows that it is a concave function when $k > \phi(1-\alpha)/2$. In this article, we assume that the cost of establishing a special hygiene level is substantially expensive, which implies that $\Pi^{\mathrm{PF}}_{\mathrm{BCT}}$ and $\Pi^{\mathrm{PF}}_{\mathrm{BCT}}$ are both concave.

We can also derive the consumer surplus as follows:

$$\Gamma_{\mathrm{BCT}} = \int_{p-h+t+m}^{1} (v - (p - h + t\Theta + m))g(v)dv = \frac{(1-(p-h+t\Theta+m))^2}{2}. \tag{10}$$

TABLE II
OPTIMAL PRICING AND SPECIAL HYGIENE DECISIONS AS WELL AS THE CORRESPONDING PROFITS AND CONSUMER SURPLUS FOR THE CASES WITH AND WITHOUT BLOCKCHAIN

	With Blockchain ($i=BCT$)	**Without Blockchain** ($i=\overline{BCT}$)
p_i^*	$\frac{b}{\phi(1-\alpha)}+\frac{k\{(1-t\Theta-m)-b/(\phi(1-\alpha))\}}{2k-\phi(1-\alpha)}$	$\frac{k(1-t\Theta-w)}{2k-(\phi-\alpha)}$
h_i^*	$\frac{\phi(1-\alpha)(1-t\Theta-m)-b}{2k-\phi(1-\alpha)}$	$\frac{(\phi-\alpha)(1-t\Theta-w)}{2k-(\phi-\alpha)}$
Π_i^{PF*}	$\frac{\phi(1-\alpha)k\{(1-t\Theta-m)-b/(\phi(1-\alpha))\}^2}{2\{2k-\phi(1-\alpha)\}}-T_{BCT}$	$\frac{k(\phi-\alpha)(1-t\Theta-w)^2}{2\{2k-(\phi-\alpha)\}}-T_{FIN}$
Π_i^{DV*}	$\frac{\phi\alpha k^2\{(1-t\Theta-m)-b/(\phi(1-\alpha))\}^2}{\{2k-\phi(1-\alpha)\}^2}+\frac{\phi\alpha bk\{(1-t\Theta-m)-b/(\phi(1-\alpha))\}}{\phi(1-\alpha)\{2k-\phi(1-\alpha)\}}$	$\frac{\alpha k^2(1-t\Theta-w)^2}{\{2k-(\phi-\alpha)\}^2}$
Γ_i^*	$\frac{k^2\{(1-t\Theta-m)-b/(\phi(1-\alpha))\}^2}{2\{2k-\phi(1-\alpha)\}^2}$	$\frac{k^2(1-t\Theta-w)^2}{2\{2k-(\phi-\alpha)\}^2}$

Comparing the cases with and without blockchain, we can see that the consumer's worry is reduced to be m under the case with blockchain, the drivers are benefited with the fast payment as well as a potentially larger demand derived from the reduced consumers' worry. The ODR platform can save the fixed service fee for banks while it does need to bear the fixed cost as well as the unit operations cost of blockchain. We summarize the critical features of ODR services under the CoV outbreak captured by the analytical model and related assumptions in Online Appendix (A1).

IV. ANALYSES

A. Optimal Decisions, Profits, and Consumer Surplus

As the ODR platform's profit functions (in the presence and absence of blockchain) are concave, we can easily find the optimal pricing and special hygiene level decisions by solving the respective first order conditions. The results (as well as their definitions) are summarized in Table II.

From Table II, it is easy to show that the blockchain adoption increases the optimal special hygiene level and price at the same time (i.e., $p^*_{\mathrm{BCT}} > p^*_{\overline{\mathrm{BCT}}}$ and $h^*_{\mathrm{BCT}} > h^*_{\overline{\mathrm{BCT}}}$). The main reason explaining this finding is the fact that the "worry of being infected" is significantly reduced (i.e., $m \ll w$). It hints that the consumers have to pay more for the blockchain adoption but their worry about the infection is significantly reduced and the ODR platform increases the special hygiene level as well. Therefore, it is neither clear nor intuitive whether the blockchain adoption benefits the ODR platform and drivers, as well as the consumers. As such, we discuss whether an all-win situation can be achieved via blockchain adoption in the following subsection.

B. All-Win Situation and Government Sponsor

From Table II, we can see the analytical expressions of the ODR platform's profits, drivers' profits, and consumer surplus functions at the optimal decisions. Define: $V^{\mathrm{PF}*}{=}\Pi^{\mathrm{PF}*}_{\mathrm{BCT}} - \Pi^{\mathrm{PF}*}_{\overline{\mathrm{BCT}}}$, $V^{DV*}{=}\Pi^{\mathrm{DV}*}_{\mathrm{BCT}} - \Pi^{\mathrm{DV}*}_{\overline{\mathrm{BCT}}}$, $V^{\mathrm{CS}*}{=}\Gamma^*_{\mathrm{BCT}} - \Gamma^*_{\overline{\mathrm{BCT}}}$, which correspondingly represent the values of blockchain for the ODR platform, drivers, and consumers. With simple algebra, we can find the closed form expressions of these values of blockchain functions as follows:

$$V^{\mathrm{PF}*} = T_{\mathrm{FIN}} - T_{\mathrm{BCT}} + \tfrac{\phi(1-\alpha)k((2k-(\phi-\alpha)))B^2-(\phi-\alpha)k(2k-\phi(1-\alpha))(1-t\Theta-w)^2}{2(2k-\phi(1-\alpha))(2k-(\phi-\alpha))}$$

where

$$B = (1-t\Theta-m-[b/(\phi(1-\alpha))])$$

$$V^{\mathrm{DV}*} = \left(\frac{\alpha kB}{2k-\phi(1-\alpha)}\right)\left(\frac{\phi kB}{2k-\phi(1-\alpha)}+\frac{\phi b}{\phi(1-\alpha)}\right) - \alpha\left(\frac{k(1-t\Theta-w)}{2k-(\phi-\alpha)}\right)^2$$

$$V^{\mathrm{CS}*} = \frac{k^2}{2}\left(\frac{B}{2k-\phi(1-\alpha)}-\frac{1-t\Theta-w}{2k-(\phi-\alpha)}\right)\left(\frac{B}{2k-\phi(1-\alpha)}+\frac{1-t\Theta-w}{2k-(\phi-\alpha)}\right).$$

We further define three critical thresholds as follows and then present Proposition 4.1

Proposition 4.1: Under the basic models: (a) $V^{\mathrm{PF}*}\begin{pmatrix}>\\=\\<\end{pmatrix}0 \Leftrightarrow w\begin{pmatrix}>\\=\\<\end{pmatrix}\bar{w}_{\mathrm{PF}}$, $V^{\mathrm{DV}*}\begin{pmatrix}>\\=\\<\end{pmatrix}0 \Leftrightarrow w\begin{pmatrix}>\\=\\<\end{pmatrix}\bar{w}_{\mathrm{DV}}$, $V^{\mathrm{CS}*}\begin{pmatrix}>\\=\\<\end{pmatrix}0 \Leftrightarrow w\begin{pmatrix}>\\=\\<\end{pmatrix}\bar{w}_{\mathrm{CS}}$. (b) The ODR platform, drivers and consumers are all benefited by the

$$\bar{w}_{\mathrm{PF}} = 1-t\Theta-\sqrt{\left(\frac{(2k-(\phi-\alpha))}{(\phi-\alpha)}\right)\left\{\left(\frac{\phi(1-\alpha)(1-t\Theta-m-[b/(\phi(1-\alpha))])^2}{(2k-\phi(1-\alpha))}\right)+\left(\frac{2(T_{\mathrm{FIN}}-T_{\mathrm{BCT}})}{k}\right)\right\}}$$

$$\bar{w}_{\mathrm{DV}} = 1-t\Theta-\sqrt{\left(\frac{kB}{2k-\phi(1-\alpha)}\right)\left(\frac{\phi kB}{2k-\phi(1-\alpha)}+\frac{\phi b}{\phi(1-\alpha)}\right)\left(\frac{(2k-(\phi-\alpha))}{k}\right)^2}$$

$$\bar{w}_{\mathrm{CS}} = \left(\frac{1}{2k-\phi(1-\alpha)}\right)\left(2k\left(m+\frac{b}{\phi(1-\alpha)}\right)+(\phi-\alpha)\left(1-t\Theta-m-\frac{b}{\phi(1-\alpha)}\right)\right).$$

implementation of blockchain if and only if the consumers' inherent worry of infection $w > \max(\bar{w}_{\rm PF}, \bar{w}_{\rm DV}, \bar{w}_{\rm CS})$.

Proposition 4.1 is a very important result. It highlights the necessary and sufficient condition under which an all-win situation can be achieved with the use of blockchain. To be specific, if the consumers' inherent worry of infection is substantially large, implementing blockchain is beneficial to the ODR platform, drivers and consumers. This has a very good implication to the case under the CoV outbreak as the consumers' inherent worry of infection should be very large. Proposition 4.1 hence provides a scientifically solid evidence to support the use of blockchain as a good measure to deal with the CoV outbreak as it can benefit the consumers, drivers, and ODR platform altogether. For the consumers, though they have to pay a higher service price with blockchain, their worries of infection are significantly reduced by the improved special hygiene level and the beneficial features of blockchain implementation. Although the adoption costs of blockchain are high, the platform still has incentives to implement it to foster consumers' trust, by reducing their inherent worry of infection from a sufficiently high level. Moreover, the incremental demand brought by blockchain implementation and the enhanced service price would benefit the drivers. An additional benefit to the platform and drivers comes from the instant payment enabled by blockchain technology. This result is consistent to our interview with the senior data scientist in Uber: blockchain implementation is promising by achieving instant payment.

Though the consumers' inherent worry of infection plays a significant role in evaluating blockchain implementation, there are some other influencing factors that have impacts on the platform's incentive for blockchain adoption and the drivers' and consumers' preferences of this technology.

Corollary 4.1: Under the basic models: (a) The ODR platform's incentive and the drivers' preferences for blockchain adoption are strengthened when the consumers are less sensitive to expected waiting time, or the variable costs of this technology reduce. (b) The consumers' preference of blockchain adoption is weakened when the consumers are less sensitive to expected waiting time or the variable costs of this technology increase.

Corollary 4.1 shows the joint effects of the above-mentioned influencing factors on the value of blockchain adoption. When the consumers become more serious about waiting time, this attitude blunts the platform's incentive and the drivers' preferences for blockchain adoption. However, the consumers' increasingly serious concerns about expected waiting time strengthen their preference of blockchain adoption, which significantly helps reduce their worry of being infected.

From Proposition 4.1, we can see that one situation may appear in which the consumers and drivers are benefited with the implementation of blockchain but the ODR platform suffers. This case occurs when consumers' inherent worry of infection is bounded as follows: $\max(\bar{w}_{\rm DV}, \bar{w}_{\rm CS}) < w < \bar{w}_{\rm PF}$. This case will occur, e.g., when the fixed cost of $T_{\rm BCT}$ is very high. In this situation, we propose the government to consider providing sponsorship to the ODR platform to help. Governments in Australia, China, and Germany have revealed funding boosts to support the development of blockchain technology and its application in industries and public services.[10,11] The sponsorship or investment arranged by governments essentially covers partial implementation costs of blockchain technology. To be specific, we define the following notation $\Phi = \frac{k\{\phi(1-\alpha)((2k-(\phi-\alpha)))B^2-(\phi-\alpha)(2k-\phi(1-\alpha))(1-t\Theta-w)^2\}}{2(2k-\phi(1-\alpha))(2k-(\phi-\alpha))} > 0$ and then present Proposition 4.2.

TABLE III
VALUES OF BLOCKCHAIN FOR THE ODR PLATFORM, DRIVERS, AND CONSUMERS

Consumers' inherent worry of infection	ODR platform	Drivers	Consumers
Large $w > \max(\bar{w}_{DV}, \bar{w}_{CS}, \bar{w}_{PF})$	+	+	+
Medium $\max(\bar{w}_{DV}, \bar{w}_{CS}) < w < \bar{w}_{PF}$	-	+	+
	+ with government sponsors		

*The notation "+"/ "-" represents that the value of blockchain is positive/negative.

Proposition 4.2: Under the basic models, when $\max(\bar{w}_{\rm DV}, \bar{w}_{\rm CS}) < w < \bar{w}_{\rm PF}$, the government can provide a sponsor of $S_{\rm PF} > \bar{S}_{\rm PF}$ to the ODR platform so that the ODR platform, drivers, and consumers are all guaranteed to be benefited by the implementation of blockchain, where $\bar{S}_{\rm PF} = T_{\rm BCT} - T_{\rm FIN} - \Phi$.

Proposition 4.2 indicates a case in which governments should consider helping. This case appears when the consumers' inherent worry of infection is medium. Under this situation, the benefit by adopting blockchain cannot dominate the substantial cost for the ODR platform. To overcome this challenge, the amount of needed sponsors by the government is uncovered in Proposition 4.2. Policy makers of the government can hence make reference to it for setting the right amount of sponsors.

As a remark, in Proposition 4.2, we focus on the sponsorship scheme to the ODR platform (i.e., the firm), which is commonly seen in many places. However, we may also have the cases such as $\max(\bar{w}_{\rm DV}, \bar{w}_{\rm PF},) < w < \bar{w}_{\rm CS}$ and $\max(\bar{w}_{\rm CS}, \bar{w}_{\rm PF}) < w < \bar{w}_{\rm DV}$ in which to achieve all-win, the government needs to sponsor the consumers and drivers to make the implementation of blockchain an all-win measure. However, these cases should be rare in practice, because the fixed cost of blockchain implementation should be high which means the platform's benefit should be under threat most (rather than the consumers and drivers). Anyhow, if these rare cases do occur, theoretically, arrangements in the form of sponsors to consumers/drivers (similar to Proposition 4.2) can be made.

Table III summarizes the main results obtained in the basic models in which the special hygiene measures are imposed by the ODR platform. If the consumers' inherent worry of infection

[10]Accessed: Oct. 18, 2021. [Online]. Available: http://www.xinhuanet.com/english/2020-07/06/c_139190439.htm

[11]Accessed: Oct. 18, 2021. [Online]. Available: https://cointelegraph.com/news/new-zealand-blockchain-group-to-request-government-blockchain-strategy

is substantially large, an all-win scenario can be achieved by implementing blockchain. If this situation is not satisfied, sponsors from government are needed in order to achieve all-win.

C. Discussions and Effects of Critical Factors

We now proceed to explore how various critical factors affect the optimal decisions as well as the achievability of all-win. We first look at the effects brought by the number of drivers n and arrival rate r. We have Proposition 4.3.

Proposition 4.3: Under the basic models, no matter whether blockchain is present or absent: (a) When the number of drivers n increases (resp. decreases), the optimal price, optimal special hygiene level, and the respective ODR platform's profit, drivers' profit, and consumer surplus all go up (resp. down). (b) When the effective demand arrival rate r increases (resp. decreases), the optimal price, optimal special hygiene level, and the respective ODR platform's profit, drivers' profit, and consumer surplus all go down (resp. up).

Proposition 4.3 shows several important results regarding the effects of n and r. For example, if n increases (i.e., when the number of hired drivers increases), not only the optimal price, but also the special hygiene level as well as the benefits of ODR platform, drivers, and consumers will all go up[12]. For the effective arrival rate r, if it increases, the optimal price, special hygiene level and benefits of all related parties (i.e., ODR platform, drivers and consumers) will go down. This finding is a bit surprising which is also different from the "supply-demand matching" theory. When the effective arrival rate goes up, "demand" goes up and one would expect that price will go up to balance supply and demand. However, the opposite happens. This finding is in fact related to the presence of "special hygiene level," which makes the "supply-demand matching" problem different from the one when pricing is the sole decision. Specifically, the platform prefers to reduce the service price to induce consumers' demand rather than raise the special hygiene level when the potential demand (i.e., effective arrival rate r) is large, as it faces the tradeoff between an increment of demand by reducing worry of infection and related costs to achieve a certain special hygiene level. However, as the effective arrival rate r goes down naturally during the pandemic, it is suggested that the platform should increase the special hygiene level to foster consumers' trust, which leads to a higher service price, based on the results in Proposition 4.3. In addition, the raised demand yields a higher expected waiting time, which leads to a lower utility and service price as a result. It implies that though we consider consumers' worry of infection under the epidemic, consumers' dislike of expected waiting time still plays a crucial role in ODR platforms' operations.

Next, we examine the effects brought by the number of drivers and effective demand arrival rate on the values of blockchain adoption, respectively. Note that the three critical thresholds of infection (i.e., $\bar{w}_{\mathrm{PF}}, \bar{w}_{\mathrm{DV}}, \bar{w}_{\mathrm{CS}}$) are all decreasing in the expected waiting time Θ, which by itself decreases in n and increases in r.

[12]The results here refer to the aggregated profit across all drivers. For the average profit for each driver, the same results would still hold because Θ/n also decreases in n. Interested readers may refer to Taylor (2018) and Choi *et al.* (2020) for details of this argument.

TABLE IV
IMPACTS OF THE NUMBER OF DRIVERS AND EFFECTIVE DEMAND ARRIVAL RATE ON THE PLATFORM, DRIVERS, AND CONSUMERS

	Profits		**Consumer surplus**	**Values of blockchain**		
	Π_i^{PF*}	Π_i^{DV*}		V^{PF*}	V^{DV*}	V^{CS*}
n	↑	↑	↑	↑	↑	↑
r	↓	↓	↓	↓	↓	↓

∗The notation "↑"/ "↓" represents that the index increases/decreases in the number of drivers/effective demand arrival rate.

Proposition 4.4: Under the basic models: (a) When the number of drivers n increases (resp. decreases), the values of blockchain for the ODR platform, drivers and consumers increase (resp. decrease) and are more (resp. less) likely to be positive. (b) When the effective demand arrival rate r increases (resp. decreases), the optimal price, the values of blockchain for the ODR platform, drivers, and consumers decrease (resp. increase) and are less (resp. more) likely to be positive.

Proposition 4.4 implies that a relatively large number of drivers or a relatively low arrival rate makes the all-win situation by blockchain adoption easier to be achieved. As the arrival rate drops significantly due to the CoV outbreak, the adoption of blockchain becomes more valuable for the ODR platform, drivers, and consumers. This directly implies that it is easier to achieve "all-win" under the epidemic. According to a survey, which focuses on the satisfaction of drivers and customers of Uber, these efforts to protect health during COVID-19 are viewed as the second important aspect that contributes to satisfaction on the app[13]. Note that this important insight is in line with Proposition 4.2, as the lower bound for government sponsor to achieve the all-win situation (i.e., $\bar{S}_{\mathrm{PF}}$) increases in the arrival rate, which hints that the government sponsor plays a less crucial role under the CoV outbreak, because the ODR platform has stronger motivation to adopt the blockchain when there is a significant drop of arrival rate. We summarize the impacts of the number of drivers and effective demand arrival rate in Table IV.

V. Extended Models and Analyses

A. Model DVD: Drivers Decide the Special Hygiene Level

In the basic models, we assume that the ODR platform is responsible for determining the special hygiene level of vehicles; however, another scenario exists in which the drivers are the ones who are responsible for it. This case is especially relevant if the vehicles are owned by the drivers. For example, drivers are encouraged to purchase face coverings, partitions, and cleaning

[13]Accessed: Feb. 24, 2021. [Online]. Available: https://www.uber.com/blog/uber-experience-survey/

TABLE V
OPTIMAL PRICING AND SPECIAL HYGIENE DECISIONS UNDER MODEL DVD

	With Blockchain ($i = BCT$)	Without Blockchain ($i = \overline{BCT}$)
$\hat{p}_i^*$	$\frac{kb}{\phi(1-\alpha)(2k-\phi\alpha)} + \frac{k(1-t\Theta-m)}{(2k-\phi\alpha)}$	$\frac{k(\phi-\alpha)(1-t\Theta-w)}{2k-\alpha(\phi-\alpha)}$
$\hat{h}_i^*$	$\frac{\alpha b}{(1-\alpha)(2k-\phi\alpha)} + \frac{\phi\alpha(1-t\Theta-m)}{2k-\phi\alpha}$	$\frac{\alpha(\phi-\alpha)(1-t\Theta-w)}{2k-\alpha(\phi-\alpha)}$

supplies at wholesale prices directly from the app of Lyft[14]. In this situation, the decision making process will be different. To be specific, the drivers and ODR platform will make their own decisions simultaneously and engage in a mixed-leadership game in which the ODR platform leads in making the "pricing" decision and drivers lead in deciding the special hygiene level. Here, the ODR platform decides the optimal price (i.e., service fee) and the drivers decide the optimal special hygiene level. We name this scenario where drivers decide the special hygiene level as Model DVD.

Under Model DVD, similar to the basic models, we have the ODR platform's profit functions, drivers' profit functions, and consumer surplus functions for the cases with and without blockchain as follows:

$$\hat{\Pi}^{\mathrm{PF}}_{\overline{\mathrm{BCT}}} = (\phi - \alpha)p(1 - t\Theta - w + h - p) - T_{\mathrm{FIN}}$$

$$\hat{\Pi}^{\mathrm{DV}}_{\overline{\mathrm{BCT}}} = \alpha p(1 - t\Theta - w + h - p) - (kh^2/2)$$

$$\hat{\Gamma}_{\overline{\mathrm{BCT}}} = \Gamma_{\overline{\mathrm{BCT}}} = \frac{(1 - (p - h + t\Theta + w))^2}{2}$$

$$\hat{\Pi}^{\mathrm{PF}}_{\mathrm{BCT}} = (\phi(1 - \alpha)p - b)(1 - t\Theta - m + h - p) - T_{\mathrm{BCT}}$$

$$\hat{\Pi}^{\mathrm{DV}}_{\mathrm{BCT}} = \alpha\phi p(1 - t\Theta - m + h - p) - (kh^2/2)$$

$$\hat{\Gamma}_{\mathrm{BCT}} = \Gamma_{\mathrm{BCT}} = \frac{(1 - (p - h + t\Theta + m))^2}{2}.$$

The optimal decisions are summarized in Table V. Moreover, checking the optimal decisions, we have Proposition 5.1.

Proposition 5.1 (Blockchain is absent): When blockchain is absent, compared to the basic models in which the ODR platform decides the special hygiene level, both the optimal service price and special hygiene level are lower under Model DVD.

Proposition 5.1 shows that when the drivers make decisions on special hygiene level under Model DVD, in the absence of blockchain, the optimal service price as well as special hygiene level would become lower than the case in which these decisions are made by the ODR platform. The result indicates that "who decides the special hygiene level" does matter while a bit surprisingly, when the drivers are in charge, the special hygiene level in fact gets worse for the case without using blockchain.

Proposition 5.2 (Blockchain is present): Under Model DVD, when blockchain is present, comparing to the basic models in which the ODR platform decides the special hygiene level. (a) The optimal service price is lower (resp. higher) under Model DVD if $b > \hat{b}_p$ (resp. $b < \hat{b}_p$). (b) the optimal special hygiene level is lower (higher) under Model DVD if $b > \hat{b}_h$(resp. $b < \hat{b}_h$), where $\hat{b}_p$ and $\hat{b}_h$solves $p^*_{\mathrm{BCT}} = \hat{p}^*_{\mathrm{BCT}}$and $h^*_{\mathrm{BCT}} = \hat{h}^*_{\mathrm{BCT}}$, respectively.

When blockchain is present, Proposition 5.2 reveals how the unit blockchain operations cost plays a role in affecting whether or not the optimal service price as well as the optimal special hygiene level will be larger under Model DVD than under the basic models. This also indicates the importance of "who controls the special hygiene level." To be specific, allowing drivers to make decision on special hygiene level (i.e., under Model DVD) will lead to higher special hygiene level if the unit blockchain operations cost is sufficiently low (i.e., $b < \hat{b}_h$). Comparing with the case without blockchain, we find that the implementation of blockchain incentivizes the drivers to increase the special hygiene level voluntarily, when the unit blockchain operations cost is low enough. If the unit blockchain operations cost is truly sufficiently low (i.e., $b < \hat{b}_h$ and $b < \hat{b}_p$), then Proposition 5.2 reveals that both the selling price and hygiene level would be higher when the drivers make the extra hygienve level decision (i.e., under Model DVD). However, the opposite case appears if the unit blockchain operations cost is sufficiently high.

Proposition 5.3: Under Model DVD, the blockchain adoption increases both the optimal service price and the special hygiene level $\left(i.e., \hat{p}^*_{\mathrm{BCT}} > \hat{p}^*_{\overline{\mathrm{BCT}}}\ and\ \hat{h}^*_{\mathrm{BCT}} > \hat{h}^*_{\overline{\mathrm{BCT}}}\right)$.

Proposition 5.3 shows the impact of blockchain on the optimal decisions. Though the blockchain adoption enables the ODR platform to charge a higher service price, it provides a higher special hygiene level as well. Therefore, it is not straightforward to see whether or not implementing blockchain is beneficial to the ODR platform, drivers, and consumers. Similar to the basic models, we measure the values of blockchain adoption from different perspectives.

For a notational purpose, define the following: $\hat{\Pi}^{\mathrm{PF}*}_{\overline{\mathrm{BCT}}} = \hat{\Pi}^{\mathrm{PF}}_{\overline{\mathrm{BCT}}}\left(\hat{p}^*_{\overline{\mathrm{BCT}}}, \hat{h}^*_{\overline{\mathrm{BCT}}}\right)$, $\hat{\Pi}^{\mathrm{DV}*}_{\overline{\mathrm{BCT}}} = \hat{\Pi}^{\mathrm{DV}}_{\overline{\mathrm{BCT}}}\left(\hat{p}^*_{\overline{\mathrm{BCT}}}, \hat{h}^*_{\overline{\mathrm{BCT}}}\right)$, $\hat{\Gamma}^*_{\overline{\mathrm{BCT}}} = \hat{\Gamma}_{\overline{\mathrm{BCT}}}\left(\hat{p}^*_{\overline{\mathrm{BCT}}}, \hat{h}^*_{\overline{\mathrm{BCT}}}\right)$, $\hat{\Pi}^{\mathrm{PF}*}_{\mathrm{BCT}} = \hat{\Pi}^{\mathrm{PF}}_{\mathrm{BCT}}\left(\hat{p}^*_{\mathrm{BCT}}, \hat{h}^*_{\mathrm{BCT}}\right)$, $\hat{\Pi}^{\mathrm{DV}*}_{\mathrm{BCT}} = \hat{\Pi}^{\mathrm{DV}}_{\mathrm{BCT}}\left(\hat{p}^*_{\mathrm{BCT}}, \hat{h}^*_{\mathrm{BCT}}\right)$, $\hat{\Gamma}^*_{\mathrm{BCT}} = \hat{\Gamma}_{\mathrm{BCT}}\left(\hat{p}^*_{\mathrm{BCT}}, \hat{h}^*_{\mathrm{BCT}}\right)$. We can derive $\hat{\Pi}^{\mathrm{PF}*}_{\overline{\mathrm{BCT}}}$, $\hat{\Pi}^{\mathrm{DV}*}_{\overline{\mathrm{BCT}}}$, and $\hat{\Gamma}^*_{\overline{\mathrm{BCT}}}$ to be the following:

$$\hat{\Pi}^{\mathrm{PF}*}_{\overline{\mathrm{BCT}}} = (2 - (\phi - \alpha))\left(\frac{k(1 - t\Theta - w)(\phi - \alpha)}{2k - \alpha(\phi - \alpha)}\right)^2 - T_{\mathrm{FIN}}$$

$$\hat{\Pi}^{\mathrm{DV}*}_{\overline{\mathrm{BCT}}} = \left(\frac{k\alpha(1-t\Theta-w)^2}{[2k-\alpha(\phi-\alpha)]^2}\right)\left(\frac{2k(2-(\phi-\alpha))-\alpha(\phi-\alpha)}{2}\right)$$

$$\hat{\Gamma}^*_{\overline{\mathrm{BCT}}} = \frac{1}{2}\left(\frac{k(1 - t\Theta - w)[2 - (\phi - \alpha)]}{2k - \alpha(\phi - \alpha)}\right)^2.$$

Define the following thresholds

$$\hat{w}_{DV} = 1 - t\Theta - (2k - \alpha(\phi - \alpha))$$

$$\sqrt{\left(\frac{1}{k\alpha(\phi - \alpha)}\right)\left(\frac{2\hat{\Pi}^{\mathrm{DV}*}_{\mathrm{BCT}}}{2k(2 - (\phi - \alpha)) - \alpha(\phi - \alpha)}\right)}$$

[14]Accessed: Nov. 24, 2020. [Online]. Available: https://www.lyft.com/blog/posts/expanding-our-health-safety-program

$$\hat{w}_{\mathrm{PF}} = 1 - t\Theta - \left(\frac{2k - \alpha(\phi - \alpha)}{k(\phi - \alpha)}\right)\sqrt{\frac{\hat{\Pi}^{\mathrm{PF}*}_{\mathrm{BCT}} + T_{\mathrm{FIN}}}{2 - (\phi - \alpha)}}$$

$$\hat{w}_{\mathrm{CS}} = 1 - t\Theta - \sqrt{2\hat{\Gamma}^{*}_{\mathrm{BCT}}}\left(\frac{2k - \alpha(\phi - \alpha)}{k(2 - (\phi - \alpha))}\right).$$

We further define the values of blockchain as follows: $\hat{V}^{\mathrm{PF}*}=\hat{\Pi}^{\mathrm{PF}*}_{\mathrm{BCT}} - \hat{\Pi}^{\mathrm{PF}*}_{\overline{\mathrm{BCT}}}$, $\hat{V}^{\mathrm{DV}*} = \hat{\Pi}^{\mathrm{DV}*}_{\mathrm{BCT}} - \hat{\Pi}^{\mathrm{DV}*}_{\overline{\mathrm{BCT}}}$, $\hat{V}^{\mathrm{CS}*}=\hat{\Gamma}^{*}_{\mathrm{BCT}} - \hat{\Gamma}^{*}_{\overline{\mathrm{BCT}}}$. We have Proposition 5.4.

Proposition 5.4: Under Model DVD: (a) $\hat{V}^{\mathrm{PF}*} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0 \Leftrightarrow w \begin{pmatrix} > \\ = \\ < \end{pmatrix} \hat{w}_{\mathrm{PF}}$, $\hat{V}^{\mathrm{DV}*} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0 \Leftrightarrow w \begin{pmatrix} > \\ = \\ < \end{pmatrix} \hat{w}_{\mathrm{DV}}$, $\hat{V}^{\mathrm{CS}*} \begin{pmatrix} > \\ = \\ < \end{pmatrix} 0 \Leftrightarrow w \begin{pmatrix} > \\ = \\ < \end{pmatrix} \hat{w}_{\mathrm{CS}}$. (b) The ODR platform, drivers, and consumers are all benefited by the implementation of blockchain if and only if the consumers' inherent worry of infection $w > \max(\hat{w}_{\mathrm{PF}}, \hat{w}_{\mathrm{DV}}, \hat{w}_{\mathrm{CS}})$.

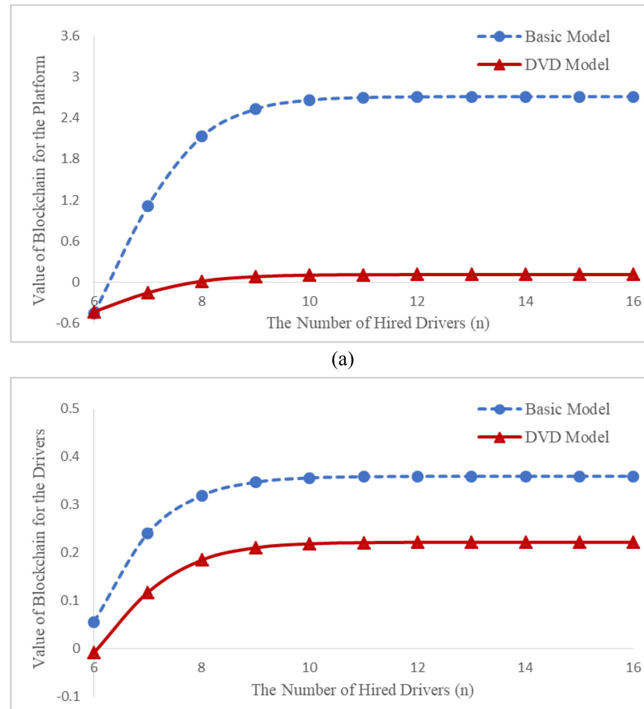
Proposition 5.4 shows that the findings under the basic models remain valid even if we change the decision role. The respective insights are hence robust with respect to who makes the special hygiene level decision.

Next, we show how the Model DVD affects the values of blockchain for the ODR platform, drivers, and consumers. Based on the definition, there is no difference between formations of consumer surplus in the basic models and Model DVD. Therefore, we focus on the perspectives from the platform and drivers. As the comparison is analytically intractable, we conduct a numerical analysis to compare the values of blockchain for the platform and drivers under the basic and DVD models.

Recall that in Section IV, the crucial influential parameters are the number of hired drivers (n) and effective arrival rate (r), respectively. We check in this numerical analysis the values of blockchain for the platform and drivers under the basic models and Model DVD by varying n and r. The numerical examples use the following parameter values initially: $a = 4$, $\varphi = 3$, $\alpha = 0.5$, $w = 0.7$, $m = 0.001$, $t = 0.2$, $b = 0.8$, and $k = 3$. Note that these parameter values well-satisfy the models assumptions and are realsitic with respect to the corresponding physical meanings. Keeping these parameters unchanged and setting the arrival rate as $r = 12$, we conduct the numerical analysis by varying the number of hired drivers from 6 to 16 to guarantee the queueing system is stable, and obtain Fig. 1(a) and (b).

Fig. 1(a) shows that adopting blockchain hurts the ODR platform when the number of hired drivers is small under both the basic models and Model DVD. In addition, from both Fig. 1(a) and (b), we can see that the values of blockchain for both the ODR platform and drivers are lower under Model DVD compared with that under the basic models. It is interesting to observe that the gap becomes more significant as the number of hired drivers increases.

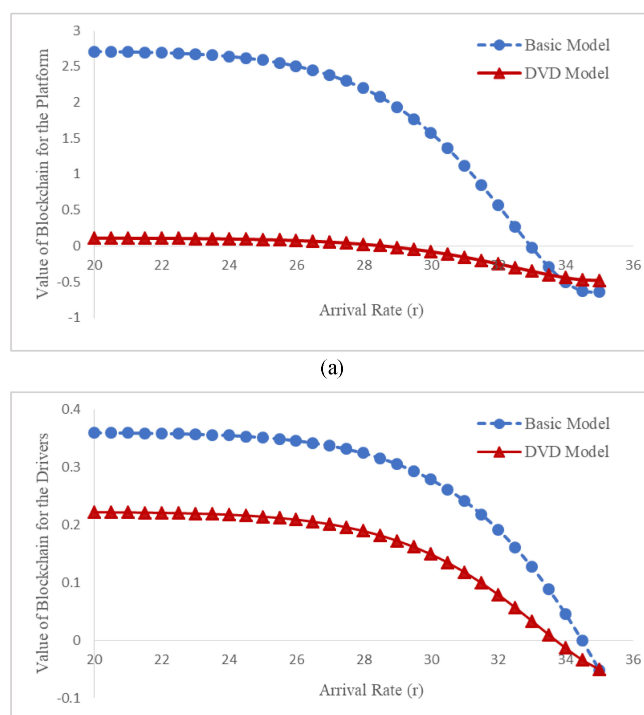
Keeping the other parameters unchanged, we vary the value of arrival rate (r) from 20 to 36 and set the number of drivers to be 20. The results are presented in Fig. 2(a) and (b). From Fig. 2(a) and (b), we can observe that the values of blockchain for the platform and drivers decrease in the arrival rate under



(a)

(b)

Fig. 1. (a) Impacts of the number of hired drivers on the value of blockchain for the platform under the basic models and Model DVD. (b) Impacts of the number of hired drivers on the value of blockchain for the drivers under the basic models and Model DVD.



(a)

(b)

Fig. 2. (a) Impacts of the arrival rate on the value of blockchain for the platform under basic and DVD models. (b) Impacts of the arrival rate on the value of blockchain for the drivers under basic and DVD models.

both the basic models and Model DVD, respectively. Adopting blockchain eventually hurts the ODR platform and drivers under both models as the arrival rate raises. However, the platform is hurt more significantly under the basic models compared to Model DVD, when the arrival rate is sufficiently high. Moreover, Fig. 2(a) and (b) also show that although the values of blockchain are lower under Model DVD, the gap shrinks as the arrival rate increases.

B. Model RA: Risk Averse Consumers

Risk averse decision making is a common behavior in both logistics systems (Fahimnia *et al.*, [19]; Jose and Zhuang, [27]) and on-demand platform operations (Choi *et al.*, [12]). In the basic models, we assume that the consumers are risk neutral and they will pay for the ride-hailing service if their service valuation (i.e., *v*) with additional utility from the special hygiene level exceeds the price and scaled disutility due to the expected waiting time and infection concerns. We now explore the scenario when the consumers are risk averse by directly extending the basic models with the only change in terms of the consumers' risk attitude (from risk neutral to be risk averse). We argue that risk aversion behavior of consumers should be important under the CoV outbreak because consumers tend to be more conservative in making decisions. Following the similar approach in the literature (see Kazaz *et al.*, [30]), we assume that consumers' risk premium is represented by $\beta\sigma_v$, where the consumers' risk averse degree is denoted as β and the risk is captured by the standard deviation of service valuation (σ_v). It is important to take the variation of service valuation into consideration under COVID-19, because consumers' value toward searching car-hailing services varies significantly due to the epidemic status. Under these models, consumers do not welcome volatility of service valuation, which follows the standard Nobel prize winning Markowitz' mean-variance theory. As a remark, we do not consider risk aversion of the drivers because in this article, they are the hired agents who are actually paid to work. They do not have the right to decline the job assignment, etc.

When the risk averse consumers search for service, the market demand for the case without and with blockchain under the CoV outbreak, respectively become

$$d^{\mathrm{RA}}_{\overline{\mathrm{BCT}}} = \int_{p+t\Theta+w-h+\beta\sigma_v}^{1} g(v)dv \tag{11}$$

$$d^{\mathrm{RA}}_{\mathrm{BCT}} = \int_{p+t\Theta+m-h+\beta\sigma_v}^{1} g(v)dv. \tag{12}$$

Similar to the previous analysis, we consider $g(v)$ as a uniform distribution in the range of 0 to 1. Thus, (11) and (12) become

$$d^{\mathrm{RA}}_{\overline{\mathrm{BCT}}} = 1 - t\Theta - w + h - p - \frac{\beta}{12} \tag{13}$$

$$d^{\mathrm{RA}}_{\mathrm{BCT}} = 1 - t\Theta - w + h - p - \frac{\beta}{12}. \tag{14}$$

Then, if the consumers are risk averse, under the case without blockchain, the profit functions for the ODR platform ($\Pi^{\mathrm{PF,RA}}_{\overline{\mathrm{BCT}}}$) and drivers ($\Pi^{\mathrm{DV,RA}}_{\overline{\mathrm{BCT}}}$) as well as the consumer welfare are hence given as follows:

$$\Pi^{\mathrm{PF,RA}}_{\overline{\mathrm{BCT}}} = \phi p(1 - t\Theta - w + h - p - \frac{\beta}{12}) - (kh^2/2) - T_{\mathrm{FIN}} - \Pi^{\mathrm{DV,RA}}_{\overline{\mathrm{BCT}}} \tag{15}$$

$$\Pi^{\mathrm{DV,RA}}_{\overline{\mathrm{BCT}}} = \alpha p(1 - t\Theta - w + h - p) \tag{16}$$

$$\Gamma^{\mathrm{RA}}_{\overline{\mathrm{BCT}}} = \frac{\left(1 - (p - h + t\Theta + w + \frac{\beta}{12})\right)^2}{2}. \tag{17}$$

Now, when the blockchain is implemented, we can derive the profit functions for the ODR platform ($\Pi^{\mathrm{PF,RA}}_{\mathrm{BCT}}$) and drivers ($\Pi^{\mathrm{DV,RA}}_{\mathrm{BCT}}$) as well as the consumer welfare in the following:

$$\Pi^{\mathrm{PF,RA}}_{\mathrm{BCT}} = (\phi p - b)\left(1 - t\Theta - m + h - p - \frac{\beta}{12}\right) - (kh^2/2) - T_{\mathrm{BCT}} - \Pi^{\mathrm{DV,RA}}_{\mathrm{BCT}} \tag{18}$$

$$\Pi^{\mathrm{DV,RA}}_{\mathrm{BCT}} = \alpha\phi p\left(1 - t\Theta - m + h - p - \frac{\beta}{12}\right) \tag{19}$$

$$\Gamma^{\mathrm{RA}}_{\mathrm{BCT}} = \frac{\left(1 - (p - h + t\Theta + m + \frac{\beta}{12})\right)^2}{2}. \tag{20}$$

The ODR platform's profit functions under both the cases with and without blockchain adoption are concave with the consideration of consumers' risk attitude. We can hence easily find the optimal pricing and special hygiene level decisions by solving the respective first order conditions. The results (as well as their definitions) are summarized in Table VI.

We have Proposition 5.5.

Proposition 5.5: (a) No matter whether blockchain is present or absent, for the case in which consumers are risk averse (i.e., under Model RA), the optimal service price, special hygiene level, profits of the ODR platform and drivers and consumer welfare are lower compared to the respective case in which consumers are risk neutral. (b) No matter whether the consumers are risk neutral or risk averse, adopting blockchain will always yield the higher optimal selling price and special hygiene level (i.e., $p^*_{\mathrm{BCT}} > p^*_{\overline{\mathrm{BCT}}}$ and $h^*_{\mathrm{BCT}} > h^*_{\overline{\mathrm{BCT}}}$, and $p^{\mathrm{RA}*}_{\mathrm{BCT}} > p^{\mathrm{RA}*}_{\overline{\mathrm{BCT}}}$ and $h^{\mathrm{RA}*}_{\mathrm{BCT}} > h^{\mathrm{RA}*}_{\overline{\mathrm{BCT}}}$). Thus, the risk attitude of consumers does not affect this result.

Proposition 5.5(a) highlights a solid result on the impacts brought by the risk averse attitudes of consumers, which would drive all optimal decisions and benefits of all parties lower. Proposition 5.5(b) interestingly reveals that in terms of the impacts brought by adopting blockchain on the optimal decisions, the risk attitudes of consumers do not matter. In other words, no matter whether the consumers are risk neutral or risk averse, both the optimal service price and special hygiene level are increased after adopting blockchain (i.e., $p^{\mathrm{RA}*}_{\mathrm{BCT}} > p^{\mathrm{RA}*}_{\overline{\mathrm{BCT}}}$ and $h^{\mathrm{RA}*}_{\mathrm{BCT}} > h^{\mathrm{RA}*}_{\overline{\mathrm{BCT}}}$).

Although the qualitative insights of comparison between cases with and without blockchain remain the same irrespective of the consumer risk attitude, we attempt to check further the

TABLE VI
OPTIMAL PRICING AND SPECIAL HYGIENE DECISIONS AS WELL AS THE CORRESPONDING PROFITS AND CONSUMER SURPLUS FOR THE CASES WITH AND WITHOUT BLOCKCHAIN WITH RISK AVERSE CONSUMERS

	With Blockchain ($i = BCT$)	**Without Blockchain ($i = \overline{BCT}$)**
p_i^{RA*}	$\frac{b}{\phi(1-\alpha)} - \frac{b/(\phi(1-\alpha)}{2k-\phi(1-\alpha)/k} + \frac{(1-t\Theta-m-\frac{\beta}{12})}{2k-\phi(1-\alpha)/k}$	$\frac{k(1-t\Theta-w-\frac{\beta}{12})}{2k-(\phi-\alpha)}$
h_i^{RA*}	$\frac{\phi(1-\alpha)(1-t\Theta-m-\frac{\beta}{12})-b}{2k-\phi(1-\alpha)}$	$\frac{(1-t\Theta-w-\frac{\beta}{12})}{(2k-(\phi-\alpha))/(\phi-\alpha)}$
$\Pi_i^{PF,RA*}$	$\frac{\{(1-t\Theta-m-\frac{\beta}{12})-b/(\phi(1-\alpha))\}^2}{2\{2k-\phi(1-\alpha)\}/\phi(1-\alpha)k} - T_{BCT}$	$\frac{(1-t\Theta-w-\frac{\beta}{12})^2}{2\{2k-(\phi-\alpha)\}/(k(\phi-\alpha))} - T_{FIN}$
$\Pi_i^{DV,RA*}$	$\frac{\{(1-t\Theta-m-\frac{\beta}{12})-b/(\phi(1-\alpha))\}^2}{\{2k-\phi(1-\alpha)\}^2/\phi\alpha k^2} + \frac{(1-t\Theta-m-\frac{\beta}{12})-b/(\phi(1-\alpha))}{\phi(1-\alpha)\{2k-\phi(1-\alpha)\}/\phi\alpha bk}$	$\frac{\alpha k^2(1-t\Theta-w-\frac{\beta}{12})^2}{\{2k-(\phi-\alpha)\}^2}$
Γ_i^{RA*}	$\frac{\{(1-t\Theta-m-\frac{\beta}{12})-b/(\phi(1-\alpha))\}^2}{2\{2k-\phi(1-\alpha)\}^2/k^2}$	$\frac{k^2(1-t\Theta-w-\frac{\beta}{12})^2}{2\{2k-(\phi-\alpha)\}^2}$

value of blockchain for the ODR platform, drivers, and consumers with risk consideration. Define: $V^{\mathrm{PF,RA}}=\Pi^{\mathrm{PF,RA*}}_{\mathrm{BCT}} - \Pi^{\mathrm{PF,RA*}}_{\overline{\mathrm{BCT}}}$, $V^{\mathrm{DV,RA}}=\Pi^{\mathrm{DV,RA*}}_{\mathrm{BCT}} - \Pi^{\mathrm{DV,RA*}}_{\overline{\mathrm{BCT}}}$, $V^{\mathrm{CS,RA}}=\Gamma^{\mathrm{RA*}}_{\mathrm{BCT}} - \Gamma^{\mathrm{RA*}}_{\overline{\mathrm{BCT}}}$, which correspondingly represent the values of blockchain for the ODR platform, drivers and consumers. With simple algebra, we can find the closed form expressions of these values of blockchain functions as follows and we present Proposition 5.6

$$V^{\mathrm{PF,RA}} = T_{\mathrm{FIN}} - T_{\mathrm{BCT}} + \frac{\phi(1-\alpha)k((2k-(\phi-\alpha)))B^{\mathrm{RA2}}}{2(2k-\phi(1-\alpha))\,(2k-(\phi-\alpha))} - \frac{(\phi-\alpha)k(2k-\phi(1-\alpha))(1-t\Theta-w-\frac{\beta}{12})^2}{2(2k-\phi(1-\alpha))(2k-(\phi-\alpha))}$$

where

$$B^{\mathrm{RA}} = \left(1 - t\Theta - m - \frac{\beta}{12} - [b/(\phi(1-\alpha))]\right)$$

$$V^{\mathrm{DV,RA}} = \left(\frac{\alpha k B^{\mathrm{RA}}}{2k-\phi(1-\alpha)}\right)\left(\frac{\phi k B^{\mathrm{RA}}}{2k-\phi(1-\alpha)} + \frac{\phi b}{\phi(1-\alpha)}\right) - \alpha\left(\frac{k(1-t\Theta-w-\frac{\beta}{12})}{2k-(\phi-\alpha)}\right)^2$$

$$V^{\mathrm{CS,RA}} = \frac{k^2}{2}\left(\frac{B^{\mathrm{RA}}}{2k-\phi(1-\alpha)} - \frac{1-t\Theta-w-\beta/12}{2k-(\phi-\alpha)}\right) \times \left(\frac{B^{\mathrm{RA}}}{2k-\phi(1-\alpha)} + \frac{1-t\Theta-w-\beta/12}{2k-(\phi-\alpha)}\right).$$

Proposition 5.6: For the case in which consumers are risk averse, the values of blockchain for the ODR platform, drivers and consumers are reduced *(* $V^{\mathrm{PF,RA}} < V^{\mathrm{PF*}}$ *,* $V^{\mathrm{DV,RA}} < V^{\mathrm{DV*}}$ *, and* $V^{\mathrm{CS,RA}} < V^{\mathrm{CS*}}$*)* compared to the case in which the consumers are risk neutral.

From Proposition 5.6, we find that the values of blockchain for all related parties become smaller when the consumers are risk averse, compared to the case when they are risk neutral. The impact of risk aversion is hence clear. As the consumers' risk averse behavior blunts the value of blockchain from all parties' perspective, it may be suggested that the platform should make efforts in reducing consumers' uncertain feeling toward the service valuation through promotions if consumers are found to be risk averse.

VI. CONCLUSION

A. Concluding Remarks and Managerial Insights

Today, ODR service platform operations are very common. However, during the recent CoV global outbreak, it is reported that people have serious worries of being infected as all kinds of passengers have taken the vehicles before. This directly leads to a huge challenge to the industry and the respective ride-hailing service operations. Motivated by the real world challenge associated with the CoV outbreak for the ODR platform, we theoretically explore this problem based on the M/M/n queuing models. We focus on whether the blockchain technology can come to the rescue.

In the basic models in which the special hygiene measures are imposed by the ODR platform, we have analytically proven that if the consumers' inherent worry of infection is substantially large, implementing blockchain is always beneficial to the ODR platform, drivers, and consumers. If this situation is not satisfied, we have found the situation in which government sponsors are needed in order to achieve all-win. In addition, the amount of sponsor needed has also been derived in closed-form.

After that, we have focused our investigation on two critical factors, namely the number of drivers and the effective demand arrival rate. We have first found that if the number of drivers increases, then the optimal price, optimal special hygiene level, and the respective ODR platform's profit, drivers' profit, and consumer surplus will all go up. We have also uncovered that if the effective demand arrival rate increases, then the optimal price, optimal special hygiene level, and the respective ODR platform's profit, drivers' profit, and consumer surplus will all go down. More importantly, we highlight the fact that if the number of drivers is relatively large or the effective demand arrival rate is low, an all-win situation by blockchain adoption will be easier to be achieved. As this situation well reflects the situation under COVID-19, we urge car-hailing platforms to adopt blockchain under the epidemic.

In the extended models, we have considered various important extensions and conducted the corresponding analyses. In the first extended model in which the drivers determine the special hygiene level themselves (Model DVD), we have explored the respective mixed-leadership game. We have found that if blockchain is absent, compared to the basic models in which the ODR platform decides the special hygiene level, both the optimal service price and special hygiene level will become lower under Model DVD. This finding shows that "who decides the special hygiene level" does matter; while surprisingly, if the drivers are in charge, the special hygiene level will in fact get worse for the case without using blockchain. For the case when blockchain is present, comparing to the basic models in which the ODR platform decides the special hygiene level, we have proven that the optimal service price is lower under Model DVD if the unit blockchain operations cost is sufficiently high with respect to a threshold, and the optimal special hygiene level is lower under Model DVD if the unit blockchain operations cost is sufficiently high with respect to another critical threshold. Moreover, we have analytically revealed that under Model DVD, blockchain adoption increases both the optimal service price and special hygiene level. For robustness checking, we have also demonstrated that under Model DVD, the ODR platform, drivers and consumers will all be benefited by the implementation of blockchain if and only if the consumers' inherent worry of infection is sufficiently high. It means the findings under the basic models remain valid even if the special hygiene level decision is made by the drivers, rather than the ODR platform.

Finally, in the second extended model, we have considered the case when the customers are risk averse (i.e., Model RA). Under Model RA, we have uncovered that no matter whether blockchain is present or absent, for the case in which consumers are risk averse, the optimal service price, special hygiene level, profits of the ODR platform and drivers and consumer welfare are lower compared to the respective case in which consumers are risk neutral. In addition, irrespective of whether the customers are risk neutral or risk averse, adopting blockchain will always yield higher optimal selling price and special hygiene level. Thus, the risk attitude of consumers does not affect this result. Last but not least, we have proven that for the case in which consumers are risk averse, the values of blockchain for the ODR platform, drivers, and consumers are reduced compared to the case in which the consumers are risk neutral.

B. Future Research

Similar to other analytical modeling studies, we admit limitations. In the current study, viewing blockchain implementation as a tool to cope with the CoV outbreak, we show that the technological tool may achieve an all-win situation under certain conditions or with the government sponsor. In the future, the specific value of government sponsorship deserves deeper explorations. For example, it is interesting to examine how government sponsorship to the ODR platform can lower the infection rate and hence would reduce the social costs in treating the inflection and the sponsorship may become more significant with blockchain adoption (as the technological tool further reduces inflection leading to savings in medical treatment, which can cover the sponsorship in return). Moreover, after the CoV outbreak, during the normal operations of ride-hailing platforms, no matter with hired drivers or contractors, how blockchain technology can play a role is another interesting topic, which provides a promising future research direction. Under the CoV outbreak, we argue that safety is the top priority. Just like in many cities, there are tracing devices for travelers (e.g., Singapore, Hong Kong, etc). However, using blockchain would hurt privacy, which is important. We propose to explore this issue in future research. Furthermore, we assume that the effective arrival rate is exogenous for neat results. More research efforts can also be put on the scenarios where the effective arrival rate is affected by consumers' decisions and the pricing and special hygiene decisions made by the platforms. Finally, in the current models, the perceived hygiene level by consumers and consumers' worry of being infected are fixed and known. However, in the real world, it may be random (due to the lack of transparency). It will hence be very interesting to study how the presence of blockchain can help reduce the uncertainty. It is also a promising future research direction to consider the case in which variables like consumers' worry of getting infected are random and follow some probability distributions (for both the cases with and without blockchain implementation). Further analyses can be conducted to explore their impacts.

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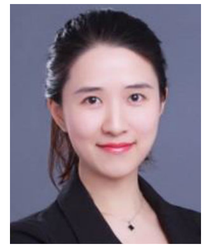

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