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Online Car-Hailing System Performance Analysis Based on Bayesian Network

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ABSTRACT The concept of the sharing economy has attracted wide attention due to its huge impact on transforming traditional industries. Online car-hailing, combining the sharing economy and ICT technologies, shapes a new landscape, which can greatly shorten the traveler's waiting time and reduce the empty-run rate of cars (such as Uber and DiDi). However, a few comprehensive studies have been conducted on the sustainable development of online car-hailing considering both the user experience and the operational cost. To address this issue, this paper systematically studies the influencing factors, their relations, and their impacts on online car-hailing in an empirical way. First, an index system in four key aspects, namely service, price, safety, and traveling time, is established to evaluate the user experience. Second, the Bayesian network theory is employed to model the complexity of each factor and the extent of its influence on the online car-hailing system with expert scores. The two most important influence paths affecting the passengers' choices of online car-hailing are determined. Third, we further construct an investment allocation model with the aim of minimizing the economic cost of the online car-hailing system while maintaining the system performance, considering the limiting factors, such as the complexity and cost. Finally, we perform a simulation experiment, which generates some practical suggestions for improving the online car-hailing system.

INDEX TERMS Online services, Bayesian methods, simulation, computational complexity.

I. INTRODUCTION

Originating from collaborative consumption, the sharing economy is a new business model that emerges from the Internet, where consumers can share products and services in a collaborative manner without shifting ownership [1]. The sharing economy is defined as "peer-to-peer-based activity of obtaining, giving, or sharing the access to goods and services, which is coordinated through a community-based online service" [2], [3]. Online car-hailing originated from combining ICT technology and a digitized taxi operation and is a typical case of sharing economy. It transforms the traditional way of car-hailing (waiting at the roadside and knowing nothing about the available cars) and can effectively deal with two evident problems in traditional car-hailing. Due to the high consumption frequency and large number of consumers, the taxi vacancy rate is still very high, even in some large cities [4]. In Beijing, 34% of passengers have to wait more than 20 minutes, and only 32.2% of passengers can hail a taxi within 10 minutes [5]. At the same time, the taxi empty rate is above 25% in the daytime. In other words, passengers and empty cars know little about each other and cannot find each other in an effective way. The emergence of online car-hailing was promoted by the development of the Internet, especially the rapid upgrading of mobile Internet technology, and has greatly eased the problem of passengers not finding a taxi while many taxis run empty [6]. Based on the Mobile Internet Technology, the online car-hailing platform optimizes the matching of vehicles and passengers through algorithms [7]. It will share the passengers' information with car driver who can meet the traveling requirements, and the online car-hailing platform provides the best suggestions, which will facilitate immediate communication between the passenger and car driver to achieve the best matching of supply and demand.

Thus, online car-hailing has promoted the efficient use of social resources and profoundly changed people's traveling habits. Sustainability, the customers' feedback and their

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willingness to continue to use online car-hailing have attracted much attention. The customer is one of the main players in the online car-hailing system. The customers' choice to use the system is an important issue in the sustainable development of online car-hailing systems. Generally, factors such as queuing time, price, service and security will affect the customers' willingness. Identifying the key factors that affect customers' willingness is the focus of this study. Second, the complexity of each factor and its degree of influence on the sustainability of the online car-hailing system are different. Degerming how to comprehensively measure the importance of each factor for the sustainability of online car-hailing systems is another innovation of this study. Therefore, this paper conducts research on the influencing factors of consumers' choices and constructs a reliability allocation model to identify the influence path of customers' behavior. Accordingly, the sustainability of online car-hailing systems can also be improved. The main contributions are as follows:

(1) An index system in four key aspects, namely, service, price, safety and traveling time, is established to evaluate the user experience, according to the operation mechanism of the online car-hailing system. Then empirical research on the user experience of online car-hailing systems is carried out from the perspective of the customers.

(2) To identify the key influencing factors for the sustainability of online car-hailing systems, this paper establishes a Bayesian network model based on the factors in the index system to study the sustainable development of online car-hailing systems. Through the triangle fuzzy matrix, the fuzzy rating data can be transformed into accurate prior probabilities. The Bayesian network is used to simulate the system complexity of each factor and the influencing degree of the car-hailing the network. It was concluded that the price and safety are the two main factors. The results show that the model can reflect the interaction between various factors and provide a new approach to solve the problems.

(3) This paper proposes a new approach to identify the reliability distribution of online car-hailing systems, considering the complexity and cost factors. Based on logistics management theory, system reliability theory and the reliability allocation optimization method, this paper considers the influencing factors of the network car system and proposes reliability distribution methods that involve reliability, complexity and cost. This model can be used to meet the requirements for the reliability system, maximize the efficiency with the lowest cost and provide practical advice to online car-hailing operators.

The paper is organized as follows: Section 2 reviews the related literature; Section 3 analyses the operation mechanism of the online car-hailing service and identifies the factors that affect the user experience in the online car-hailing system; Section 4 conducts a Bayesian network based empirical study on the degree of factors' influence; Section 5 presents a reliability allocation model based on a generalized cost function; and Section 6 concludes the paper.

II. LITERATURE REVIEW

A. ONLINE CAR-HAILING

The sharing platform includes several primary subdivisions, including bicycle-sharing, car-sharing, and house-sharing. The sharing market mainly involves the demand-side, supply-side and sharing economic platform for the goods or services [8]. Online car-sharing represents a typical outcome of "Internet +" and "sharing economy". It not only exerts a great impact on the traditional taxi market but also changes urban lives. For example, from the perspective of building a sustainable city, vehicles used for car-sharing are often fuel-efficient and have a positive impact on reducing urban emissions and urban congestion [9]. Therefore, the question arises, "How to develop the online car-hailing system of the future?"; this has become a global discussion topic that is continuously contemplated. Increasingly more scholars have begun to turn their research interest to the operation of online car-hailing systems. From the perspective of an operator, Ouyang and Zeng [10] divide the online taxi-hailing into tailored taxi services and carpooling services. Meanwhile, carpooling is similar to ridesharing [11]. From the perspective of the user-experience, the online car-hailing experience is composed of three phases. They are the anticipatory, experiential, and reflective stages. Plans are made [12] in the anticipatory phase, and users recall their previous travelling experience and think about their future travel within this context. The gathering of travel information also begins in this phase. During the experiment, factors including the passenger's perceived service, risk, time and price are run through the entire process of the network car experience. Finally, in the reflective phase, users evaluate their completed trip and the lessons they learned for their next trip.

In terms of the operation of online car-hailing systems, scholars have carried out many studies from different aspects. Cervero *et al.* [13] study the usage of taxi in the US and identify the reasons and characteristics of the passenger' choices. They also find that online car-hailing has a substitutional effect on public transportation and private cars. It has both positive and negative influences on urban traffic, and it is difficult to determine their choices based on existing data. Wang *et al.* [14] analyze the impact of the pricing strategy on the traditional taxi market based on bilateral market theory and the equilibrium model. They proposed a mutually stable equilibrium pricing model between the traditional taxi market and online car-hailing market with their focus on the car market system. Jiang and Zhang [15] analyze the impact of double-apping on the online car-hailing system. The results show that the platform itself is in a prisoner's dilemma and cannot serve both sides at the same time. The action taken by one party, which allows the driver to apply for dual application, will not bring any benefits to the platform. Stiglic *et al.* [16] find that a modest increase in the passenger and driver time flexibility can significantly increase the expected matching rate. Xu *et al.* [17] determine the factors affecting the taxi driver's response to the service requests of online car-hailing from the perspective of the taxi driver. In addition, some scholars have focused mainly on the development of the online car-hailing platform, the rise of the online car-hailing platform [18], [19], its operational characteristics [20], environmental protection [21], government supervision [22], bilateral matching algorithm [23], [24] and other aspects.

B. INFLUENCING FACTORS FOR THE ONLINE CAR-HAILING SYSTEM

There are many studies that consider the factors that influence consumers to choose sharing economy services and products. Kim *et al.* [25] strengthen the analysis of publicly perceived usefulness, perceived ease of use and personal norms based on the theory of planned behavior, technology acceptance theory and normative activation theory. In addition, Shaheen *et al*. [26] study the influence of the traveler's personal and family features on their traveling intentions based on statistical OLS and correlation analyses. Tussyadiah [27] indicates that guest satisfaction with using P2P accommodation was influenced by factors including enjoyment, monetary benefits (value), and accommodation amenities. Wu *et al.* [28] discuss the factors that influence Chinese travelers' behavioral intentions towards room-sharing platforms in the sharing economy, and the results indicate that although the intensity varies, utilitarian motivation, hedonic motivation and perceived trust do have positive effects on tourists' behavioral intentions.

Currently, there is a growing number of studies that recognize the importance of online car-hailing service quality, price, safety and travel time. Cheng *et al.* [29] study the factors affecting online and offline service quality concerning the car-hailing industry driven by the sharing economy, further validating the relationship between the quality of service, satisfaction and loyalty in the sharing economy-driven business context. Zuo *et al.* [30] conclude that continuous improvement of the service quality is a key factor for the sustainable growth of online car-hailing and the sharing economy. Yang *et al.* [31] believe that dynamic pricing can strike a balance between supply and demand and improve the utilization efficiency of taxi resources, which is necessary for market regulation. However, higher fares also have the potential risk of pricing low-income people out of the market. Lee and Cheng [32] study the influence of modern information technology on driving safety. Zhang *et al.* [33] propose a block chain-based network and privacy protection mechanism based on the de-centralization, permanence and auditability of the block chain. Time is an important factor affecting the user's riding behavior. Wong *et al.* [34] formulate nested logit models to show that the perceived walking time, waiting time at the pick-up point and the travel time are the factors influencing car-hailing. Long *et al.* [35] proposed a bilateral online car-hailing matching model based on the passengers' value of time (VOT) and traveling time uncertainty.

C. BAYESIAN NETWORK AND RELIABILITY DISTRIBUTION

The Bayesian network, which is also called belief network, is applied to reduce the uncertainty and address incompleteness. The Bayesian method [36] has been widely applied by scholars and industry since it was proposed by Pearl in 1988. The Bayesian network is based on Bayes' theorem, and it can describe the probabilities of the relationships among the variables in the graphic model [37]. The graphic model presents a probabilistic connection between different variables. The structure figure in the Bayesian method can give an intuitive macro description of the non-representational problems. The Bayesian network model is used to create a more complex process, and it needs experts' participation to determine the network nodes to solve problems related to field knowledge through repeated research and constantly improving the Bayesian network structure. Byun *et al.* [38] propose a matrix-based Bayesian network (MBN) that facilitates efficient modeling based on joint probability, mass functions and flexible inference. In addition, the Bayesian network analysis also appears in supply chain management [39], risk management [40], project decision-making [41]and environmental simulation [42].

Reliability and redundancy allocation [43] are commonly seen problems when designing a system. The Bayesian network can only analyses only the key factors affecting the system stability. It is necessary to rely on the reliability distribution model. This commonly used method aims to distribute the reliability of each subsystem equally. However, different factors that affect the reliability distribution should not be given the same weight, nor should the same level of reliability be assigned. To solve this problem, Chang *et al.* [44] propose a maximum entropy order weighted average method, which effectively overcomes the shortcomings of the average weight distribution method. Elegbede *et al.* [45] propose the principle of cost minimization and applied the ECAY algorithm to study the reliability allocation of parallel systems. Attiya and Hamam [46] present the reliability allocation model of a heterogeneous distribution system based on a cost function, and then present a heuristic algorithm based on simulated annealing technology. Yalaoui *et al.* [47] propose a non-polynomial dynamic programming algorithm for the reliability allocation of serial-parallel systems, and an example shows that its convergence effect is ideal. In conclusion, most reliability allocation models take cost as the objective function to seek the optimal reliability allocation scheme [48].

It can be seen from the above literature, on the one hand, the research on the relevant online car-hailing system mainly focuses on the pricing strategy of the car-hailing platform, bilateral matching strategy, and platform supervision. In fact, the network car system is a complex system, whose reliability is affected by many uncertain factors that are correlated with each other. The existing literature lacks a systematic analysis of the key factors. At the same time, due to a series of uncertain factors affecting the sustainability of the existing theoretical framework, decision models such as the grey evaluation and fuzzy comprehensive evaluation are used, most of which are deterministic models. The Bayesian network model and reliability allocation model can address the uncertainties and provide an analysis. This combination serves as a new approach to study the factors of online car-hailing systems. However, the relevant studies mainly focus on engineering applications, and an effective reliability allocation algorithm has already been developed. The paper proposes a reliability model with consideration of the importance coefficient, complexity and cost. The result better fits the characteristics of the online car-hailing system.

III. IMPACT FACTORS OF USER EXPERIENCE

A. CHARACTERISTICS OF ONLINE CAR-HAILING

In recent years, with the evolution and development of metropolises and an increasing population, residents in first-tier cities such as Beijing, Shanghai and Guangzhou, have encountered difficulties in finding a taxi. However, the increase of taxis and expansion of their operational scale should be approved by the government. The taxi's starting price has been strictly set. In addition, there are a variety of factors resulting in the slow increase in the number of the taxis. Online car-hailing attracts many taxis to enter the market, given that there exists a convenient registration system and efficient operation, which fills the vacancy of the taxis. Online car-hailing has a unique advantage in public transportation because it can provide sufficient vehicles. Online car-hailing can confirm the time, place and destination of the trip through interactive communication between the passengers and drivers. It provides targeted services for business people and people in a hurry to improve the traveling efficiency and reduce transportation costs.

There are three main elements involved in online car-hailing: the driver, passenger, and platform. After deciding to travel, the passenger selects the type of vehicle and sends the destination of the trip to the platform. The online car-hailing platform will give the passenger an estimated price, while the passenger can also choose to give the driver a tip for a better service. After the passenger confirms the order, the platform will send the passenger's travel information to the driver who is near the passenger. Then, the driver receives the order information. If the driver thinks that the income of this service matches his expectations, he will accept the order and then contact the passenger to give him a ride. After the trip, the passenger pays the fee to the online car-hailing platform, and the platform will transfer the fee to the driver after extracting a certain percentage for the commission. According to the operating characteristics of the online car-hailing service, this paper proposes four key factors affecting the online car-hailing system. (a) Traveling time: Passengers can use mobile phones or iPads to obtain information about the car and drivers. The information shared by the online platform saves the waiting time. (b) Price of an online taxi: The intervention of the online payment platforms such as WeChat payment, Alipay and UnionPay makes credit card payment possible, which allows people to pay after consumption. The cost of online car-hailing is also relatively lower since there are various allowances and subsidies, such as coupons, red envelopes and discounts. (c) Services level: The online car-hailing company can provide passengers with high quality services with its sound scoring system and complaint feedback mechanism, which also depends on the sharing of credit information. For example, an online car-hailing driver can borrow money on a financial platform to provide services, and the DiDi Platform may limit the driver's order allocation based on the driver's repayment history and other credit rating criteria. (d)Safety: Gradually improved laws and regulations guarantee online car-hailing safety. Online car-hailing operators can use software to track the driving time and route in real time, and passengers can also share their real-time location to relatives to avoid incidents.

B. MEANING OF EACH NODE IN THE BAYESIAN NETWORKS

1) SERVICE LEVEL (B1)

The development of the online credit platform has made it possible to further improve customer service. The order delivery mechanism is based on a service assessment accumulated by the drivers' historical order records and is used to prioritize the delivery of orders to particular drivers. Meanwhile, the credit rating is also an important measure for order delivery. After receiving a loan, the driver must repay it on time to accumulate credits and earn a higher order priority to improve the service level. This cycle forms a positive feedback loop, and a collaborative feedback link will promote the healthy development of the supply chain. The following indicators will reflect this feedback.

a: PRE-SALES SERVICE (C_1)

Pre-sale service can provide sufficient information to consumers, and it also obtains information about consumers and competitors for product design and uses it to meet market requirements. For online car-hailing systems, pre-sales service means providing accurate positioning services, a timely and reliable order matching strategy, and communication mechanisms for drivers and users. These pre-sale services include the user will being able to enter their location and query destination on the network car platform before calling a taxi online and having a relatively accurate positioning service.

b: ON-PURCHASE SERVICE (C_2)

The goal of the on-purchase service is to provide customers with the most cost-effective solution, which can provide user feedback such as the driver's attitude, whether the car is comfortable and the driving skills.

c: AFTER-SALES SERVICE (C_3)

After-sales service is to provide service when the journey is finished, which is also a marketing tool. The sales staff can use various cooperative methods to enhance the reputation of the enterprise, expand the market and improve the efficiency and profits of sales through the after-sales service. For an online car-hailing system, the after-sale service provides timely feedback for users' experiences/complaints. For example, timely assistance to help passengers find their lost items.

d: SERVICE RESPONSE SPEED (D_1)

It refers to the time that feedback takes from an enterprise according to the customer's request when the service response system is stimulated by external forces, and it is also known as the customer's request. Streamlined services can improve the service quality and response speed to events. The company makes careful consideration and analyses for the users and develops a standard and efficient service process management approach. Online car-hailing uses a whole customer satisfaction evaluation system, making it a fast and response platform that provides 24 hours of service for customers.

e: POSITIONING ACCURACY (D_2)

Positioning accuracy refers to the difference between the location information and the real location. The error refers to the coincidence degree between the average value and the true value under certain experimental conditions. Mobile positioning is one of the characterizing businesses of mobile communication systems. Operators use their mobile network, short message service, GPS and other geographic information service systems to provide comprehensive services, which mainly include tracking business services, personalized information services, navigation services, etc.

f: ARRIVAL TIME (D_3)

The arrival time reflects the rapid arrival of the online hailed taxi to the designated place where the passenger is located. One of the reasons why passengers use online car-hailing is that it avoids unproductive car-hailing, thus saving time and cutting travelling cost. Once the online-hailing taxi reaches the passenger, it will undoubtedly shorten the time of the passenger's taxi hailing and enhance the probability of the passenger choosing an online car.

g: ONLINE CAR-HAILING EXPERIENCE (D_4)

The experience of online car-hailing mainly reflects the passenger's psychological perceptions or emotional experience during the trip. In the process, several factors affecting the passengers' experience such as the vehicle condition, driver's driving skills, and driver's attitudes and utterances. If customers find that cabs hailed online are less comfortable, they are less likely to use online-hailing platforms when they need a ride.

h: THE SERVICE OF THE DRIVER (D_5)

The driver service requirements mainly include that the drivers should arrive at the designated place in advance according to the appointment with the passengers and contact the passengers actively. The driver needs to take a reasonable route to ensure that the passengers will arrive at the destinations on time. The driver should always be polite and ensure the safe driving. They should be equipped with safe driving skills and obey the traffic rules, which will facilitate the future financing processes and gain a higher order priority.

i: ACCIDENT MANAGEMENT SERVICES (D_6)

Accident management services refers to a company sending assistance to the site of an accident immediately after receiving an accident report. The driver in the accident should report to traffic police and an executive of the online car-hailing company. The driver of online-hailing taxi should perform rescue work and secure the site of accident.

j: FARE CALCULATION SERVICE (D_7)

With the promulgation of the Management of the Mobile Phone and Calling-up Service regulation in Beijing, the mobile phone call service has officially entered into the taxi service industry. Several car-hailing apps offer packages of benefits and allowances, which would benefit both the passengers and taxi drivers.

2) PRICE OF AN ONLINE TAXI (B2)

The development of payment platforms such as WeChat Pay, Alipay and UnionPay has made it possible for consumers to use credit payments. A credit payment is a post-consumer payment, and there is a delay period. During this period, the consumers do not have to pay any fees for the occupation of funds, which provides a price subsidy to a certain extent. The good consumption record of consumers, in turn, gives the consumer more subsidies, such as red envelopes and vouchers during the promotional periods. In this way, a positive feedback cycle is formed to further promote the consumer behavior while using the online car-hailing service, which attracts people's interest in the sharing of credit information in the supply chain. This cycle will also be reflected in the following indicators.

a: STARTING PRICE (C_4)

A reasonable taxi rating system can enhance the competitiveness of the industry and promote benign development, which plays an important role. Therefore, the regulation of tariff provisions is very important since there are varieties of factors affecting the price of freight transport. The price is mainly determined by the competition between transportation supply and demand parties and competition between various modes of transportation. As the threshold of the mobile Internet technology is gradually lowered, the competition among platforms is reflected in fighting for users' resources, and various platforms have invested a large amount of capital into this arena.

b: ALLOWANCES (C_5)

Online car-hailing has given people a new way of travelling. The online car-hailing platform allows a large number of vehicles to engage in the platform, including private cars, to provide taxi services with high allowances that can help companies compete for market share. The passengers' ordering behavior in DiDi will accumulate the original credit history. Subsidies such as vouchers, cash red envelopes, etc. will be distributed during promotions according to one's credit history. Now passengers can use a credit payment, and shared credit payment information will be added to the original credit history. Based on the credit information, each passenger will be assessed for a credit rating and then subsidized accordingly. Therefore, passengers will try to make their credit rating as high as possible to obtain the corresponding price allowance. At the same time, the lag period of the credit payment as described above is also a kind of subsidy. In a sense, sharing finances will affect the entire supply chain.

c: AVERAGE PRICE PER MILE (C_6)

Price is one of the most important factors in determining the passengers' transport mode choices. The lower the average price is of online car-hailing per kilometer, the more likely the passengers are to choose an online vehicle.

3) SAFETY (B3)

a: PAYMENT SECURITY (C_7)

One of the features of online car-hailing is the convenience of payment, which integrates booking, riding, payment and other services. Passengers can load credit card information on the platform, using Alipay, WeChat payment and other mobile payment methods to conduct online payments, which allows passengers to avoid cumbersome cash transactions and caters to the payment habits of today's people. Payment security is one of the key factors, and safe methods should be applied to prevent the leakage of information.

b: SAFETY OF TRAVEL (C_8)

People mainly use electronic devices such as mobile phones to hail a taxi online. In reality, many drivers place multiple phones around the steering wheel, and use different ride-hailing apps to pick up customers. The Regulation on the Implementation of the Law of the People's Republic of China on Road Traffic Safety clearly stipulates that there should not be behaviors that would affect the driving and threaten the safety of the drivers. While driving, the driver's attention might be distracted by the online car-hailing notifications, which will undoubtedly bring hidden dangers.

c: TRAVEL DATA CONFIDENTIALITY (C_9)

The information generated in the service process, such as the traveling time, bus fare, bus routes and other geographic information, not only concerns the individual, but also is an integral part of the systematic function. The data of a single user will not generate business value, but a large number of users' data can provide support for platform optimization. Passenger data confidentiality means that the platform should strictly protect the passengers' personal information and traveling data. The platform should not use the personal information for commercial purposes or illegal benefits. In terms of the transport data, the enterprise should establish a data analysis firewall system.

d: THE SPEED OF ONLINE CAR-HAILING (D_8)

The speed of online car-hailing refers to the maximum speed of driving that is safe and comfortable when the weather is good, and the traffic density is normal. The traffic speed of the online car-hailing vehicle is closely linked with the safety of the customers, and the drivers of the online car-hailing should strictly abide by the traffic regulations and control the speed of the vehicles.

e: PERSONAL SAFETY (D_9)

A broad concept of personal safety includes human life, health, freedom of movement, personality and reputation. The core concept of transport quality is safety, which means that passengers should not encounter accidents that threaten their safety or property.

f: REGULAR SECURITY CHECKS AND VEHICLE MAINTENANCE (D_{10})

Regular security checks and vehicle maintenance refers to the regular overhaul maintenance and preventive protection of the vehicles to ensure the security and reliable operation of the vehicle and keep the cars in good technical condition. The online ride-hailing platform provides a 24-hour service. It tracks the location through the Internet and GPS technology and monitors the service and driving route of the car-hailing service.

4) TRAVELING TIME (B4)

a: RUSH HOUR (C_{10})

Online car-hailing provides car services based on the online platform. With the development of information technology, passengers can use software on their phones to choose from different types of cars, various types of services and enjoy the best transport routes, which solves the difficulty of taking the taxis during rush hours.

b: USAGE OF CARS LATE AT NIGHT (C_{11})

In the late night, the car-hailing platform has a relatively small number of vehicles, which could affect the speed of driving, thus lowering the passenger's level of satisfaction. The taxi driver evaluation system and the real-time positioning tracking system have positive effects on disclosing the drivers' identity information and monitoring drivers' service. These advantages allow the ride-hailing service platform to be clear about the conditions of the driver and the operation of the vehicle, thus increasing the safety of the trips.

c: HOLIDAY AND FESTIVALS (C_{12})

The number of people traveling on holidays and festivals is larger than normal, and it is not convenient to take a traditional taxi during vacation time. The online car-hailing service can save travel time and avoid conflicts during the trip.

d: WEATHER CONDITIONS (C_{13})

When it rains heavily, the average charge of online car-hailing platform is twice or even more than four times that of the regular time. The online car-hailing service can save the traveling time and make it more convenient to take taxis.

IV. BAYESIAN NETWORK-BASED MODEL OF USER EXPERIENCE

A. BAYESIAN PRINCIPLES

1) JOINT PROBABILITY FORMULA

The concurrence probability of events A and B,

$$P(AB_i) = P(A|B_i)P(B_i) = P(B_i|A)P(A);$$

$P(B_i|A) = \frac{P(A|B_i)P(B_i)}{P(A)}$. When the events are independent of each other, $P(AB_i) = P(A)P(B_i)$;$P(B_i|A) = P(B_i)$, that is, event A's non-occurrence does not influence event B's occurrence probability.

For a distribution function, F (x, y), of a two-dimensional random variable (X, Y), if there exists such a non-negative function, $f(x, y)$, any x, y can accord with $F(x, y) = \int_{-\infty}^{y}\int_{-\infty}^{x} f(u, v)dudv\,(x, y)$ and is a continuous two-dimensional random variable, the function $f(x, y)$ is the probability density of the two-dimensional random variable (X, Y), or the joint probability density of the random variables, X and Y.

2) CONDITIONAL PROBABILITY

The occurrence probability of event A under the condition that another event, B, has already occurred is $P(A|B)$, which is expressed as "A's occurrence probability given B occurred". If there are only two events A, B, then $P(A|B) = \frac{P(AB)}{P(B)}$, and the probability of event B changes with event A's occurrence. Suppose that E is the random test, Ω is the sample space, and A and B are two random events. Assuming that $P(A) > 0$, $P(A|B) = \frac{P(AB)}{P(B)}$ is B's conditional probability when A occurs. By the definition of the conditional probability, $P(AB) = P(A|B)P(B)$ the above multiplication formula can be applied to any infinite event. Assume $A_1, A_2, \cdots, A_n$ are n events,

$$n \geq 2, P(A_1, A_2, \ldots, A_n)$$
$$P(A_1, A_2, \ldots, A_n) = P(A_1)P(A_2|A_1)\ldots P(A_n|A_1, A_2, \ldots, A_{n-1})$$

For two independent events A and B, if A and B are independent of each other, the conditional probability of A under the premise of B is the probability of A itself. Similarly, the conditional probability of B at A is B's self-probability. The conditional probability P(B|A) also has three basic probability properties. The first is non-negativity. The second is normative, and the third is conformable addition.

3) TOTAL PROBABILITY FORMULA

If events B1, B2, form a complete event group and they all have positive probabilities, then any event A complies with the following formula:

$$P(A) = P(AB_1) + P(AB_2) + \cdots + P(AB_n)$$
$$= P(A|B_1)P(B_1) + P(A|B_2)P(B_2) + \cdots + P(A|B_n)P(B_n)$$

Assume that the sample space of test E is S, and $B_1, B_2, \ldots, B_n$ is a partition of S, and then $P(B_i) > 0\ (i = 1, 2, \cdots n)$. For any event A in the sample space, $P(A) = \sum_{i=1}^{n} P(B_i)P(A|B_i)$ constantly exists.

4) BAYESIAN FORMULA

Assume $A_1, A_2, \ldots, A_n$ is a partition of the sample space, B is the random time in Ω, and $P(B) > 0$, then

$$P(A_i|B) = \sum_{i=1}^{n} P(B_i)\frac{P(A_i)P(B|A_i)}{\sum_{i=1}^{n} P(A_i)P(B|A_i)}$$

constantly exists, i = 1, 2, ..., n.

In the Bayesian formula, $P(A_i)$ and $P(A_i|B)$ are known as the prior probability and posterior probability of the cause. $P(A_i)(i = 1, 2, \cdots n)$ is a person's perception of the incident's occurrence probability when there is no further information. With new information obtained and when B happened, a new estimate of the incident's occurrence probability would be made. The Bayesian formula is a deduction from reasons to the results. In contrast, the total probability formula is from the results to the reasons. The Bayesian formula's significance lies in that if event A has occurred, the reason behind needs to be determined, if there are n probable causes of A, B_1, B_2, ..., B_n, and any two causes are mutually incompatible, the probability of any Bi needs to be known, that is the conditional probability $P(B_i|A)$, then Bi is the most likely cause for event A's occurrence. $P(B_i)$ is called the prior probability, which is the summary of past experience and a conclusion of the possibility of occurrence for various reasons. Before the occurrence of event A, it is known, $P(A|B_i)$ is the probability of occurrence of A under various reasons, which can be obtained from technical means, $P(B_i|A)$ is posterior probability, which is the new knowledge on the occurrence possibility of various causes when A occurred.

B. EMPIRICAL STUDY OF THE BAYESIAN NETWORK

1) BAYESIAN NETWORK MODEL BASED ON THE INFLUENCING FACTORS OF ONLINE VEHICLE-HAILING

As shown in Fig.1, the Bayesian network structure was first established based on experts' knowledge, and then the network model was obtained through analysis and update of the database.

2) DETERMINING THE VALUE RANGE OF THE NODES

The value range of A is {0,1} showing whether the consumers choose online vehicle-hailing service; 0 means not and 1 means yes.

The value range of B_1, B_2, B_3, B_4 are {0,1}, which shows if the service, price, safety or traveling time of online cars affect

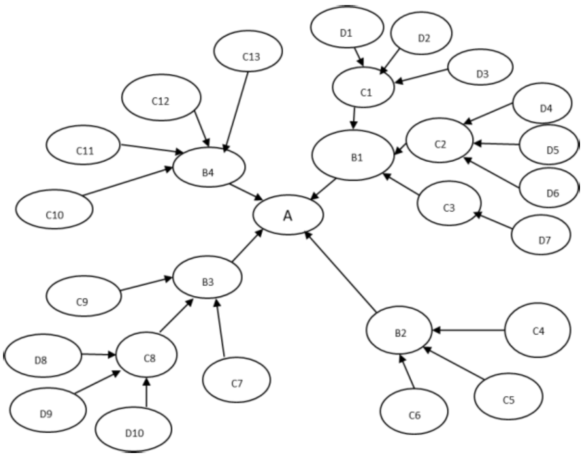

FIGURE 1. Bayesian network structure.

online vehicle-hailing; 0 means no influence and 1 means there is influence.

The value range of C_1, C_2, C_3 is {0,1}, which indicates whether the pre-sales service, on-purchase service and after-sales service influence the online car-hailing. 0 means no influence, and 1 means there is influence.

The value range of C_4, C_5, C_6 is {0,1}, respectively showing whether starting fee, subsides, average fee per kilometer have influence on online vehicle-hailing. 1 means there is influence and 0 means there is not.

The value range of C_7, C_8, C_9 is {0,1}, which respectively shows whether payment security, rides safety and user travel data confidentiality have influence on online vehicle-hailing. 1 means there is influence and 0 means no.

The value range of C_{10}, C_{11}, C_{12}, C_{13} is {0,1}, which respectively shows whether peak hours, car-hailing late at night, holidays and weather conditions have influence on safety. 1 means there is influence and 0 means no.

The value range of D_1, D_2, D_3 is {0,1}, which respectively shows whether response speed, accurate positioning and timely arrival have influence on pre-sales service, 1 means there is influence and 0 means no.

The value range of D_4, D_5, D_6 is {0, 1}, which shows whether riding experience, driver's service and accidents' handling have influence on the on-purchase service. 1 means there is influence and 0 means no.

The value range of D_7 is {0, 1}, which shows whether car fare billing service has influence on after-sales service. 1 means there is influence and 0 means no.

The value range of D_8, D_9, D_{10} is {0,1}, which respectively shows whether driving speed, safety and have influence on pre-sales service and regular vehicle maintenance have influence on riding safety, 1 means there is influence and 0 means no influence.

3) FUZZY PROBABILITY BASED ON THE TRIANGLE FUZZY MATRIX

When the exact probability cannot be obtained, the estimate was made by group decision based on experience of experts.

TABLE 1. Semantic meaning of incident probability and corresponding triangular fuzzy number.

Probability range	Triangular fuzzy matrix	Expressions
<1%	(0.0,0.0,0.1)	extremely low
1%-10%	(0.0,0.1,0.3)	low
10%-33%	(0.1,0.3,0.5)	slightly low
33%-66%	(0.3,0.5,0.7)	medium
66%-90%	(0.5,0.7,0.9)	slightly high
90%-99%	(0.7,0.9,1.0)	high
>99%	(0.9,1.0,1.0)	extremely high

The calculation of the conditional probability requires a large amount of sample data to assign different values to each node. In this paper, questionnaires were distributed to obtain the experts' estimates of the conditional probability of nodes, and the triangular fuzzy number method [49] was applied to carry out the related data processing.

The triangular fuzzy number can be signified by three parameters *a, m* and *b,* marked as(*a, m, b*).

For two sets of triangular fuzzy numbers: $\tilde{A} = (a_1, m_1, b_1)$, $\tilde{B} = (a_2, m_2, b_2)$, the following algorithms were used:

A plus B,

$$\widetilde{A} + \widetilde{B} = (a_1 + a_2, m_1 + m_2, b_1 + b_2)$$

A multiplies B,

$$\widetilde{A} * \widetilde{B} = (a_1 * a_2, m_1 * m_2, b_1 * b_2),$$

A divides B,

$$\widetilde{A} \div \widetilde{B} = (a_1 \div a_2, m_1 \div m_2, b_1 \div b_2),$$

It there exists exact number k, then,

$$\widetilde{A} \div k = (a_1 \div \mathrm{k}, m_1 \div k, b_1 \div k),$$

Many of the event states' probabilities are difficult to directly and accurately calculate, thus, the probability was obtained and estimated by a group estimate based the experience of experts. As shown in Table1, to convert the fuzzy number into an event probability estimate, levels 1-7 are set, which represent "extremely low", "low", "slightly lower", "medium", "high", "slightly higher", "very high". In this way, the experts' opinions can be transformed into a fuzzy probability represented by triangular fuzzy numbers.

The conditional probability table of the nodes is obtained by means of a questionnaire. If the number of experts is q, the linguistic value of the probability of the node X_i in state j given by expert k can be converted into a triangular fuzzy number, $\widetilde{P}_{ij}^k = (a_{ij}^k, m_{ij}^k, b_{ij}^k)(k = 1, 2, \ldots, q)$ according to Table 2, and then the average exact probability can be obtained from the mean area method. The exact probability of node X_i in state j is:

$$P_{ij}^{'} = \frac{a_{ij}^{'} + 2m_{ij}^{'} + b_{ij}^{'}}{4}.$$

TABLE 2. Conditional probability table of pre-sales service, C1.

Condition		Triangular fuzzy number		Probability	
State0	State1	State0	State1	State0	State1
D_1、D_2、D_3	——	(0.16,0.36,0.44)	(0.54,0.69,0.76)	0.33	0.67
D_1、D_2	D_3	(0.22,0.24,0.46)	(0.64,0.7,0.80)	0.29	0.71
D_1、D_3	D_2	(0.29,0.32,0.43)	(0.44,0.72,0.76)	0.34	0.66
D_1	D_2、D_3	(0.14,0.2,0.26)	(0.72,0.8,0.88)	0.2	0.8
D_2、D_3	D_1	(0.13,0.27,0.33)	(0.65,0.74,0.87)	0.25	0.75
D_2	D_1、D_3	(0.16,0.4,0.62)	(0.44,0.57,0.82)	0.4	0.6
D_3	D_1、D_2	(0.41,0.64,0.79)	(0.19,0.4,0.53)	0.62	0.38
——	D_1、D_2、D_3	(0.14,0.21,0.36)	(0.54,0.83,0.88)	0.23	0.77

TABLE 3. Conditional probability table of Node C1.

	D_1	State0			
	D_2	State0		State1	
	D_3	State0	State1	State0	State1
C_1	State0	0.33	0.29	0.34	0.2
	State1	0.67	0.71	0.66	0.8
	D_1	State1			
	D_2	State0		State1	
	D_3	State0	State1	State0	State1
C_1	State0	0.25	0.4	0.62	0.23
	State1	0.75	0.6	0.38	0.77

The node's conditional probability after the normalizing processing is:

$$P = \frac{P_{ij}^{'}}{\sum P_{ij}^{'}}$$

4) PRIOR PROBABILITY

The network topology and the parameters in the model form a complete Bayesian network model. Among them, the probability distribution for each node represents the parameters of each node. After constructing the network structure, the probabilistic relationships among the nodes are figured, which is the basis of Bayesian network reasoning. The conditional probability table for each node was calculated. Table 2 is the conditional probability table of one node for illustration.

Through the conditional probability table, the probability of occurrence of node C_1 in two states can be clearly seen under the condition of the father nodes D_1, D_2 and D_3 as shown in Table 3. For example, if D_1, D_2, and D_3 do not occur, the probability that C1 does not occur is 33%. If D1 occurs, and D_2 and D_3 do not occur, the probability of B3's occurring is 75%.

The probability value of Node B_3 can be obtained by the formula:

$$P(B) = \sum\nolimits_{i=1}^{n} P(B|A_i)P(A_i)$$

Let:

$$\begin{aligned}
&a = P(D_1 = State0)P(D_2 = State0)P(D_3 = State0)\\
&P(C_1 = State0|D_1 = State0, D_2 = State0,\\
&D_3 = State0)\\
&b = P(D_1 = State0)P(D_2 = State0)P(D_3 = State1)\\
&P(C_1 = State0|D_1 = State0, D_2 = State0,\\
&D_3 = State1)\\
&c = P(D_1 = State0)P(D_2 = State1)P(D_3 = State0)\\
&P(C_1 = State0|D_1 = State0, D_2 = State1,\\
&D_3 = State0)\\
&d = P(D_1 = State0)P(D_2 = State1)P(D_3 = State1)\\
&P(C_1 = State0|D_1 = State0, D_2 = State1,\\
&D_3 = State1)\\
&e = P(D_1 = State1)P(D_2 = State0)P(D_3 = State0)\\
&P(C_1 = State0|D_1 = State1, D_2 = State0,\\
&D_3 = State0)\\
&f = P(D_1 = State1)P(D_2 = State0)P(D_3 = State1)\\
&P(C_1 = State0|D_1 = State1, D_2 = State0,\\
&D_3 = State1)\\
&g = P(D_1 = State1)P(D_2 = State1)P(D_3 = State0)\\
&P(C_1 = State0|D_1 = State1, D_2 = State1,\\
&D_3 = State0)\\
&h = P(D_1 = State1)P(D_2 = State1)P(D_3 = State1)\\
&P(C_1 = State0|D_1 = State1, D_2 = State1,\\
&D_3 = State1)
\end{aligned}$$

and $P(C_1 = State0) = a+b+c+d+e+f+g+h = 0.2903$

Among these:

$$\begin{aligned}
P(D_1 = State0) &= 0.2\\
P(D_1 = State1) &= 0.8\\
P(D_2 = State0) &= 0.25\\
P(D_1 = State1) &= 0.75\\
P(D_3 = state0) &= 0.1\\
P(D_3 = State1) &= 0.9
\end{aligned}$$

Similarly:

$$P\{C_1 = State1\} = 0.71$$

5) POSTERIOR PROBABILITY

According to the reverse reasoning of the Bayesian network, when the child node's probability of occurrence is known, the probability of the parent node in a certain state caused by the child node in that state can be calculated by a Bayesian formula. Suppose the influence of C_1 (pre-sales service) exists, that is $P\{C_1 = State1\} = 1$, from the posterior probability formula of the Bayesian network:

$$\begin{aligned}
P(D_1 = State1, C_1 = State1) \\
&= P(D_3 = State0, D_2 = State0, D_1 = State1) \\
&\quad \times P(B_3 = State1|D_3 = State0, D_2 = State0, \\
&\quad D_1 = State1) \\
&\quad + P(D_3 = State1, D_2 = State0, D_1 = State1) \\
&\quad \times P(B_3 = State1|D_3 = State1, D_2 = State0, \\
&\quad D_1 = State1) \\
&\quad + P(D_3 = State0, D_2 = State1, D_1 = State1) \\
&\quad \times P(B_3 = State1|D_3 = State0, D_2 = State1, \\
&\quad D_1 = State1) \\
&\quad + P(D_3 = State1, D_2 = State1, D_1 = State1) \\
&\quad \times P(B_3 = State1|D_3 = State1, D_2 = State1, \\
&\quad D_1 = State1)
\end{aligned}$$

$$\begin{aligned}
&P(D_3 = \mathrm{State}0, D_2 = \mathrm{State}0, D_1 = State1) * \\
&P(C_1 = State1|D_3 = State0, D_2 = State0, D_1 = State1) \\
&\quad = 0.8 * 0.25 * 0.1 * 0.75 = 0.015 \\
&P(D_3 = \mathrm{State}1, D_2 = \mathrm{State}0, D_1 = State1) * \\
&P(C_1 = State1|D_3 = State1, D_2 = State0, D_1 = State1) \\
&\quad = 0.8 * 0.25 * 0.9 * 0.6 = 0.108 \\
&P(D_3 = \mathrm{State}0, D_2 = \mathrm{State}1, D_1 = State1) * \\
&P(C_1 = State1|D_3 = State0, D_2 = State1, D_1 = State1) \\
&\quad = 0.8 * 0.75 * 0.1 * 0.38 = 0.0228 \\
&P(D_3 = \mathrm{State}1, D_2 = \mathrm{State}1, D_1 = State1) * \\
&P(C_1 = State1|D_3 = State1, D_2 = State1, D_1 = State1) \\
&\quad = 0.8 * 0.75 * 0.9 * 0.77 = 0.4158
\end{aligned}$$

Among which:

$$\begin{aligned}
P(D_1 = State0) &= 0.2 \\
P(D_1 = State1) &= 0.8 \\
P(D_2 = State0) &= 0.25 \\
P(D_1 = State1) &= 0.75 \\
P(D_3 = state0) &= 0.1 \\
P(D_3 = State1) &= 0.9 \\
P(C_1 = State0) &= 0.29 \\
P(C_1 = State1) &= 0.71
\end{aligned}$$

$$P(D_1 = State1|C_1 = State1) = \frac{P(D_1 = State1, C_1 = State1)}{P(C_1 = State1)} = \frac{0.5616}{0.71} = 0.79098592$$

6) IMPLICATIONS

a: DATA ACQUISITION

To identify the influencing factors of online car-hailing and obtain objective and reasonable evaluation results, this study carefully selected the influencing factors and constructed a questionnaire based on the existing research and expert advice. Thirty experts in the logistics industry are selected to design the questionnaire survey, and they all hold a Ph.D. The institutions and titles information of 30 experts who assess the scores are shown in the Appendix B(Table of the information of the experts). There are three steps when we establish the questionnaire: First, data for ISM come mainly from professional opinions. It assesses the interaction between factors (if there is any) with number "1" or "0". If there is a connection between two factors, it would be marked as "1". Otherwise it would be "0". Second, what the experts assess are the probabilities of influence among different factors. The assessing result is neither 1 nor 0, and it is the quantified triangle fuzzy number. The experts give the professional options about fuzzy numbers: extremely high; high; slightly high; medium; slightly low; low; extremely low. The triangular fuzzy matrix will turn the fuzzy numbers into the accurate probability. On occasions where accurate probability is hard to be obtained, the results are often achieved by group decision of experts' experience. Third, the calculation of conditional probability requires large amount of sample data to meet various value requirements. Therefore, if accurate probability cannot be calculated, the group decision is applied. The experience of experts is cited to make decisions. Questionnaires are sent out to collect professional opinions on the conditional probability of nodes. And triangle fuzzy matrix is used to deal with related data. After the questionnaires' results are processed, the semantic value of the influence degree is converted into the probability value. Then, the probability value of each factor contributing to the coordinated development of logistics and economy is obtained, and the numerical value of the probability represents the upper level indicator's influence on the lower level indicator. The questionnaire is composed of two parts. The first part is for the basic information of the respondents, focusing on the respondent's occupational and educational background; the second part uses triangular fuzzy numbers to establish the conditional probability table of the influencing factors for online vehicle-hailing. The probabilities of each factor's range are (0,1), and each node is independent.

b: RESULT ANALYSIS

According to the probability of node A in the Bayesian network, the higher the probability is, the stronger the coordination is. By analyzing and sorting the questionnaire data, and inputting the data into GeNIe Bayesian simulation software, the probability value of each node is obtained where "State 0" indicates that the online vehicle-hailing system does not exist, "State 1" means it exists, as shown in Fig 2.

According to the Bayesian network reverse reasoning, when online car-hailing occurs, that is, $P(A = State1) = 1$, safety, and car prices have a greater influence on the passenger's choice, and the most direct influencing factors are safety, prices, services, and traveling time. These four factors determine the occurrence probability of online car-hailing.

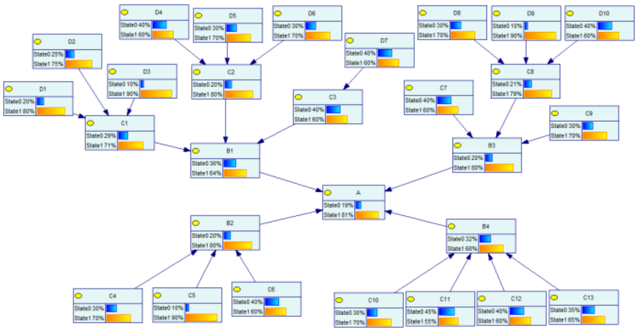

FIGURE 2. Probability of each node for passenger online car-hailing.

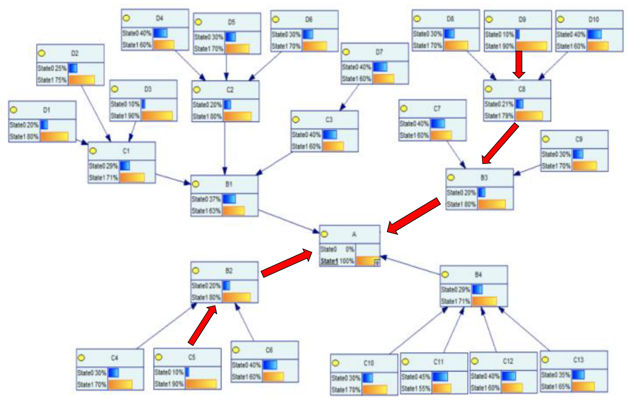

FIGURE 3. Posterior probability of passengers' online car-hailing.

According to the GeNIe software's simulation and inference of the Bayesian network, when the passengers select online car-hailing, the corresponding probability values of the four factors, namely, service, price, safety and traveling time are 63%, 80%, 80%, 71%, indicating that the price of online car and safety level have a notable influence on the online car-hailing service. A higher posterior probability of the nodes indicates greater impact of the node on the target node. As shown by the red arrows in Fig. 3, two key paths that influence the consumer's choice of online car-hailing are given. They are: {personal safety—ride safety—safety—online car-hailing} and {subsidies—price—online car-hailing}. This result is in line with previous expectations. Undoubtedly, passengers will say that the safety of travel is within their own consideration. It requires the entire supply chain to put the passengers' safety first. From the perspective of DiDi, it is necessary to establish a rigorous driver assessment system and provide drivers with safe driving skills training. From the drivers ' point of view, they should pay attention to safe driving and conscientiously abide by the corresponding rules and regulations.

Another factor that affects the consumers' choice of online car-hailing behavior is price. Due to the sharing of funds, information and other resources in the entire supply chain, online car-hailing is cheaper than a traditional car rental. As a provider of supply chain finance, DiDi will establish a closed-loop supply chain. A credit rating mechanism is estimated by lending to drivers and passengers in this way. For the driver,

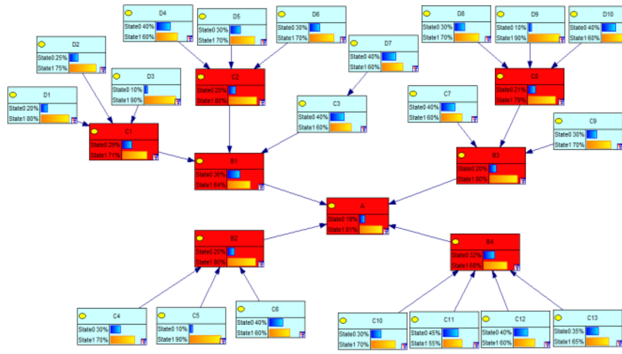

FIGURE 4. Sensitivity analysis of online car-hailing.

better service and safer trips are delivered through the order delivery mechanism. For passengers, a good credit record will help them obtain better price subsidies. Therefore, the sound development of the entire supply chain can be promoted.

c: SENSITIVITY ANALYSIS

The sensitivity analysis helps to verify the parameter probability of the Bayesian network, and the sensitivity or probability parameters of higher influence have a more effective impact on the Bayesian network inference results. The online car-hailing system's service, prices, safety and traveling time play an important role in the passengers' online car bookings. The high sensitivity of a probability parameter indicates that it has a more obvious impact on the Bayesian network reasoning, which requires more attention to improve the performance of the Bayesian network. The online car-hailing sensitivity analysis is shown in Fig.4.

7) COMPONENT IMPORTANCE AND COMPLEXITY

Each node in the Bayesian network has a certain degree of influence on the entire car-hailing network. To quantify the degree of influence ω_i, this paper makes $\omega_i = \frac{M_i}{\sum_{i=1}^{n} M_i}$, where M_i is the degree of correlation of each node relative to its parent node. According to the conclusion of key causal chain, probabilistic reasoning, sensitivity analysis, and the correlation degree of the nodes obtained by GeNIe, the analysis results show that the correlations M_i of nodes $B_1, B_2, B_3, and\ B_4$ with respect to A are respectively: $M_1 = 0.04157, M_2 = 0.08218, M_3 = 0.09382, M_4 = 0.06315$,

Therefore:

$$\omega_{B1} = 0.148083, \omega_{B2} = 0.292747,$$
$$\omega_{B3} = 0.334212, \omega_{B4} = 0.224957$$

Generally, a system consists of multiple interconnected subsystems. The more complex the subsystem is, the higher the cost of increasing the reliability of the subsystem nonlinearly is, while the feasibility will decrease. To quantify the complexity of the subsystem, this paper uses the ratio of the number of subsystem units to that of the whole system, $u_i = \frac{N_i}{\sum_{i=1}^{n} N_i}$, to represent the unit complexity , u_i, as shown in (Table 5).

TABLE 4. Correlation degree of each node.

Node	Mutual Info
A	0.34375
D_3	0.12698
D_9	0.11367
C_5	0.09874
B_3	0.09382
B_2	0.08218
C_2	0.08137
D_1	0.07946
C_8	0.07762
D_2	0.07368
C_1	0.07123
B_4	0.06315
D_5	0.06187
D_6	0.05974
C_4	0.05731
C_{10}	0.05214
C_9	0.04981
D_8	0.04534
C_{13}	0.04346
B_1	0.04157
D_4	0.01956
D_{10}	0.01489
D_7	0.00091
C_3	0.00083
C_7	0.00075
C_6	0.00061
C_{12}	0.00035
C_{11}	0.00009

TABLE 5. Unit complexity and degree of influencing degree.

Number	Unit	M_i	ω_i	N_i	u_i
1	Service(B_1)	0.04157	0.148083	7	0.3684
2	Price(B_2)	0.08218	0.292747	3	0.1579
3	Safety(B_3)	0.09382	0.334212	5	0.2632
4	Traveling time(B_4)	0.06315	0.224957	4	0.2105

V. RATIONAL INVESTMENT FOR A BETTER USER EXPERIENCE

A. RELIABILITY ALLOCATION MODEL FOR USER EXPERIENCE IMPROVEMENT

Reliability and cost are relatively abstract concepts. The cost includes the human, material and financial resources needed to improve the reliability per unit. Therefore, it is difficult to obtain the statistics on the relationship between the cost and reliability. To solve this problem, this paper applies the generalized cost function to describe the reliability and cost function. The generalized cost function is based on the feasibility, *fi*, the unit minimum reliability, *Ri,min,* and the unit maximum reliability, *Ri,max* [50]. The generalized cost function is the nonlinear growth function of the cost per unit. Achieve the maximum reliability costs a considerable amount of expense in theory. In contrast, the cost of achieving a low reliability is very small, consistent with the reality that the cost increases with reliability. The characteristics of the generalized cost function provide the basis for the integration of various factors in the system for reliability allocation. Therefore, based on the generalized cost function, this paper constructs the reliability model of the online car-hailing system that includes the importance and complexity of the system. The general cost function is as follows:

$$c(R_i, f_i, R_{i,\min}, R_{i,\max}) = e^{\left[\frac{(1-f_i)(R_i - R_{i,\min})}{R_{i,\max} - R_i}\right]} \tag{1}$$

R_i is the reliability of unit *i*.

f_i is the feasibility, and the value range is from 0 to 1.

$u_i = 1 - f_i$ is an improved coefficient of unit complexity.

$R_{i,min}$ is the initial (current) reliability value of the i_{th} component obtained from the failure distribution of that component for the specified time.

$R_{i,max}$ is the maximum achievable reliability of the i_{th} component.

The value range of f_i is {0,1}. The larger the value is, the more feasible the whole system is, and the lower the generalized cost is.

The cost coefficient to enlarge or reduce the generalized cost is introduced [51]. The reliability cost can be distributed to different units. The cost factor is expressed by the reciprocal of the importance coefficient ω_i, which ranges from 0 to 1. The greater the importance coefficient is, the lower the cost coefficient is. The actual investment is increased to make the units with a higher degree of significance consume greater reliability costs and achieve higher system reliability. Therefore, the generalized cost function can be further expressed as:

$$C_i(R_i) = \frac{1}{\omega_i} c(R_i) = \frac{1}{\omega_i} c(R_i) = \frac{1}{\omega_i} e^{\frac{u_i(R_i - R_{i,\min})}{R_{i,\max} - R_i}} \tag{2}$$

The final generalized cost function is as follows:

$$C = \sum_{i=1}^{n} C_i(R_i) \tag{3}$$

The objective function of the reliability allocation model is as follows:

$$\begin{aligned} &\min\ C = \sum_{i=1}^{n} C_i(R_i) \\ &s.t.\ R_S > R_G \\ &\quad R_{i,\min} \le R_i \le R_{i,\max}, \quad i = 1, 2, \ldots, n. \end{aligned} \tag{4}$$

R_G is the expected reliability degree the system aims to reach, R_S is the reliability degree of the system. Since each

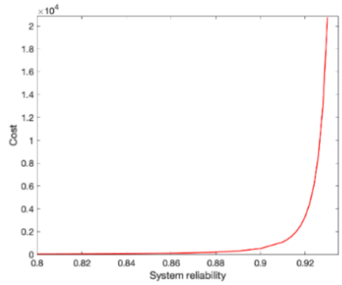

FIGURE 5. The relationship between system reliability and cost.

TABLE 6. Essential parameters for the reliability of online car-hailing.

ESSENTIAL PARAMETERS FOR THE RELIABILITY OF ONLINE CAR-HAILING

Number	Unit	ω_i	u_i	$R_{i,min}$	$R_{i,max}$
1	Service(B_1)	0.148083	0.3684	0.75	0.99
2	Price(B_2)	0.292747	0.1579	0.75	0.99
3	Safety(B_3)	0.334212	0.2632	0.75	0.99
4	Traveling time(B_4)	0.224957	0.2105	0.75	0.99

influencing factor may cause problems or failures, and affect the reliability of the entire system, they are connected in series; therefore,

$$R_S = \prod_{i=1}^{n} R_i.$$

B. EXAMPLE ANALYSIS

Assuming that the related data of online car-hailing is as shown in Table 6, as a change of each factor will change the reliability of online vehicles, the factors are connected in series. Four factors, service, price, traveling time and safety of online hailed cars, are listed as units. The minimum reliability of each cell is set to 0.75, and the maximum reliability of each cell is set to 0.99.

The nonlinear programming of the model meets all the requirements. The cost change caused by an increase in the system reliability is shown in Fig. 5. As the figure shows, with an increase in reliability, the marginal cost shows a gradual upward trend. When the system reliability reaches [0.92, 0.99), the slope of the curve increases sharply, and the cost is close to infinity.

The change in cost with different levels of reliability is consistent with the actual situation [52]. When the reliability reaches a certain level, a further increase of the reliability requires a large input of manpower, material resources and financial resources. The marginal cost tends to be infinite, which is economically infeasible. Therefore, on the assumption that $R_G = 0.90$, this paper reached the reliability distribution results according to the reliability distribution model. It is shown inTable 7.

Model ① is about the reliability allocation model and involves the complexity and degree of influence; Model ② is about the reliability allocation model, taking into account only the complexity, which means, that the degree of influence of each factor is the same, $\omega_i = 0.25$; Model ③ is an equal distribution model, which does not include the complexity and degree of influence, $R_i = \sqrt[n]{R_G}$. It can be seen from Table 7 that the system reliability drawn by the three models is close to the required reliability of 0.9. The reliability from the equal distribution method is 0.9740, with the highest cost in the three models, up to 583.5308. Compared with the equal distribution method, the reliability of the two relatively complicated factors in the distribution result, namely, service and safety, are reduced by 0.0058 and 0.0008, respectively, taking only complexity into consideration. The cost is also reduced.

TABLE 7. Reliability distribution results under three models.

Unit	①	②	③
Service(B_1)	0.9666	0.9682	0.9740
Price(B_2)	0.9793	0.9787	0.9740
Safety(B_3)	0.9743	0.9732	0.9740
Traveling time(B_4)	0.9759	0.9759	0.9740
System reliability	0.90004	0.89996	0.89999
Cost	561.8771	558.3858	583.5308

In the allocation result that considers the complexity and influencing degree, the reliability of the service is even lower. Although safety has the largest impact on the system, it is more complex than price and traveling time. Thus, the reliability of safety is slightly lower than that of price and traveling time, considering the complexity, comprehensive impact and cost. In addition, Model ① has the highest level of reliability and moderate cost, which further proves the effectiveness of this model.

C. IMPLICATIONS

According to the results of the reliability distribution in Table 7, when the other parameters remain the same, the distribution of the reliability is different due to the differences in the significance of each unit. The price has the largest reliability allocation result ($R_2 = 0.9793$), and it has large cost changes as reliability increases. Therefore, when the maximum and minimum reliability and complexity were not considered,, it is a priority to increase the unit with the higher reliability allocation results such as the unit price and unit traveling time, to improve the reliability of the entire system. Measures such as giving subsidies and promoting credit payments should be continued to keep the online car-hailing system's price advantages, and a reasonable interest distribution mechanism should be established to maintain a stable price. At the same time, the bilateral matching strategy should be optimized to improve the reliability of traveling time, and the user matching waiting time should be reduced. Services such as comprehensive evaluations of the distance and road conditions for the best driving path should be provided. Moreover, although the reliabilities of security and service are relatively low, 0.9743 and 0.9666, respectively, it is also crucial to the stability of the online car-hailing system. To offer safe trips through an online car-hailing system, the qualification of the driver and the vehicles' conditions should be evaluated, and safety training for drivers is necessary. At the same time, the online car-hailing platform should establish a sound customer privacy protection mechanism, attaching more importance to data security. To improve the quality of online car-hailing service, drivers should be more cautious serving their customers. Rewards and penalty mechanism can be established according to the users' feedback.

It is noteworthy that increased unit reliability will increase the system's reliability and cost. When the degree of reliability increases to a certain extent, a continued increase will greatly increase the cost, resulting in a significant increase in the cost of the system with increasing unit reliability. In this case, the cost variation due to the increase of various factors and the system reliability should be considered, and the reliability allocation of all units should be assigned.

VI. DISCUSSIONS AND CONCLUDING REMARKS

This study focused on the internal logical analysis of online car-hailing, and systematically identified the influencing factors from four aspects: service, price, safety and traveling time. By constructing the Bayesian network model, the study determined the significance of each of the influencing factors. This passage constructed a reliability allocation model of a sustainable online car-hailing system with a broad cost function, considering complexity and significance of each factor. The study:

(1) Identifies the four factors that influence online car-hailing system. The services include the pre-sales service, on-purchase service, after-sales service, response speed, accurate positioning, timely arrival, riding experience, driver's service, accident handling and fare billing. The price include the starting price, subsidies, and average price per kilometer. The safety includes the payment security, ride safety, user travel data confidentiality, speed, personal safety, regular vehicle maintenance and security checks. The traveling time includes the rush hour, late night trips, holidays and weather conditions.

(2) The Bayesian network is used to identify the key influencing factors and the key influencing paths of the online car-hailing system. The key influencing factors, B1, B2, B3, B4, C1, C2 and C6 are identified through a Bayesian network sensitivity analysis. At the same time, this paper identifies the two influence paths that drive online car-hailing through a causal chain analysis: {personal safety–ride safety—-online car-hailing} and {subsidies–price–online car-hailing}. The credit accumulation obtained through the supply chain finance has an important influence on the consumers' choice of online car-hailing due to the sharing of information resources in the supply chain.

(3) This study constructed a reliability allocation model of a sustainable online car-hailing system with a broad cost function, considering the complexity and significance of each factor. A sample analysis is also applied to examine the influence of the service, prices, traveling time and safety have on the stability of online car-hailing system. The results show that with the consideration of the complexity, influencing degree and cost, high reliability should be given to the price, followed by the traveling time, safety and service.

Although some achievements have been made in this study on online car-hailing, there are still some limitations. First, the data collected in this study mainly comes from investigation. Future research can use quasi-experiments or field experiment to further improve the accuracy of the conclusions. Second, this study assumes that the lowest reliability of each factor is 0.75, but in reality, the lowest reliability of the subsystems often changes. Future research can analyze online car-hailing in different areas, and time periods to explore the topic, with the variation in time-space, to further determine the maximum level of reliability of each subsystem for different online car-hailing systems.

APPENDIX A
TABLE OF CONDITIONAL PROBABILITY

Conditional probability of D_1	
State0	0.2
State1	0.8

Conditional probability of D_2	
State0	0.25
State1	0.75

Conditional probability of D_3	
State0	0.1
State1	0.9

Conditional probability of D_4	
State0	0.4
State1	0.6

Conditional probability of D_5	
State0	0.3
State1	0.7

Conditional probability of D_6	
State0	0.3
State1	0.7

Conditional probability of D_7	
State0	0.3
State1	0.7

Conditional probability of D_8	
State0	0.3
State1	0.7

Conditional probability of D_9	
State0	0.1
State1	0.9

Conditional probability of D_{10}	
State0	0.4
State1	0.6

Conditional probability of C_1

D_1		State0				State1			
D_2		State0		State1		State0		State1	
D_3		State0	State1	State0	State1	State0	State1	State0	State1
C_1	State0	0.33	0.29	0.34	0.2	0.25	0.4	0.62	0.23
	State1	0.67	0.71	0.66	0.8	0.75	0.6	0.38	0.77

Conditional probability of C_2

D_4		State0				State1			
D_5		State0		State1		State0		State1	
D_6		State0	State1	State0	State1	State0	State1	State0	State1
C_2	State0	0.4	0.3	0.3	0.3	0.2	0.1	0.2	0.1
	State1	0.6	0.7	0.7	0.7	0.8	0.9	0.8	0.9

Conditional probability of C_3

D_7	0	1
State0	0.4	0.4
State1	0.6	0.6

Conditional probability of C_4

State0	0.3
State1	0.7

Conditional probability of C_5

State0	0.1
State1	0.9

Conditional probability of C_6

State0	0.4
State1	0.6

Conditional probability of C_7

State0	0.4
State1	0.6

Conditional probability of C_8

D_8		State0				State1			
D_9		State0		State1		State0		State1	
D_{10}		State0	State1	State0	State1	State0	State1	State0	State1
C_8	State0	0.1	0.2	0.2	0.3	0.2	0.1	0.2	0.2
	State1	0.9	0.8	0.8	0.7	0.8	0.9	0.8	0.8

Conditional probability of C_9

State0	0.3
State1	0.7

Conditional probability of C_{10}

State0	0.3
State1	0.7

Conditional probability of C_{11}

State0	0.45
State1	0.55

Conditional probability of C_{12}

State0	0.4
State1	0.6

Conditional probability of C_{13}

State0	0.35
State1	0.65

Conditional probability of B_1

C_1		State0				State1			
C_2		State0		State1		State0		State1	
C_3		State0	State1	State0	State1	State0	State1	State0	State1
B_1	State0	0.3	0.4	0.3	0.4	0.2	0.3	0.5	0.3
	State1	0.7	0.6	0.7	0.6	0.8	0.7	0.5	0.7

Conditional probability of B_2

C_4		State0				State1			
C_5		State0		State1		State0		State1	
C_6		State0	State1	State0	State1	State0	State1	State0	State1
B_2	State0	0.2	0.1	0.2	0.3	0.3	0.3	0.1	0.2
	State1	0.8	0.9	0.8	0.7	0.7	0.7	0.9	0.8

Conditional probability of B_4

C_{10}		State0							
C_{11}		State0				State1			
C_{12}		State0		State1		State0		State1	
C_{13}		State0	State1	State0	State1	State0	State1	State0	State1
B_4	State0	0.4	0.3	0.4	0.4	0.4	0.3	0.3	0.8
	State1	0.6	0.7	0.6	0.6	0.6	0.7	0.7	0.2
C_{10}		State1							
C_{11}		State0				State1			
C_{12}		State0		State1		State0		State1	
C_{13}		State0	State1	State0	State1	State0	State1	State0	State1
B_4	State0	0.3	0.2	0.3	0.2	0.2	0.3	0.3	0.3
	State1	0.7	0.8	0.7	0.8	0.8	0.7	0.7	0.7

Conditional probability of A

	C_{10}	State0							
	C_{11}	State0				State1			
	C_{12}	State0		State1		State0		State1	
	C_{13}	State0	State1	State0	State1	State0	State1	State0	State1
A	State0	0.3	0.2	0.3	0.2	0.3	0.1	0.1	0.1
	State1	0.7	0.8	0.7	0.8	0.7	0.9	0.9	0.9
	C_{10}	State1							
	C_{11}	State0				State1			
	C_{12}	State0		State1		State0		State1	
	C_{13}	State0	State1	State0	State1	State0	State1	State0	State1
A	State0	0.2	0.1	0.2	0.1	0.3	0.2	0.3	0.2
	State1	0.8	0.9	0.8	0.9	0.7	0.9	0.7	0.8

APPENDIX B
TABLE OF THE INFORMATION OF THE EXPERTS

NO.	Personal information
1	China Travel Service Co., Ltd., Director, Ph.D.
2	National Local Joint Engineering Laboratory for IoT in Manufacturing, Director, Ph.D.
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4	Hoifu Energy Group Limited, Justice of the Peace, Ph.D.
5	Reward Group, Chairman, Ph.D.
6	Shuntiantong Real Estate Development Group Co., Ltd, General Manager, Senior Engineer, Ph.D.
7	Deputy General Manager of CNPC Finance Co., Ltd., Director of the Institute of Finance and Accounting, Ph.D.
8	iSoftStone Information Technology (Group) Co., Ltd., Vice President, Ph.D.
9	Huawei Technology Co., Ltd. R & D department expert, Ph.D.
10	CTS International Logistics Corporation Limited, Vice president, Ph.D.
11	Computer simulation and computer integrated manufacturing expert, academician of Chinese Academy of Engineering, Ph.D.
12	Department of Emergency Management, China National School of Administration, Professor, Ph.D.
13	Department of Industrial Engineering and Engineering Management / EMBA/MBA, National Tsinghua University, Chair Professor, Ph.D.
14	Operations Management, University of Nottingham, Ningbo, China, Professor, Ph.D.
15	Business Engagement and Innovation Services, Business School, University of Nottingham, Dean, Ph.D.
16	Department of Management and Economics, Dalian University of Technology, Professor; Director of Modern Industry Research Center; Ph.D.
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18	Department of Economics and Finance, Department of Management Science, City University of Hong Kong, Chief Professor, Ph.D.,
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20	School of Communication, Hong Kong Baptist University, Chair Professor, Dean, Ph.D.
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25	Business School, Beijing Technology and Business University, Professor, Ph.D.
26	Department of Logistics Management, Business School, Beijing Technology and Business University, Associate Professor, Ph.D.
27	School of Electrical Information, Jinan University, Dean, Professor, Ph.D.
28	School of Environment, Tsinghua University, Associate Professor, Ph.D.
29	Michigan Institute of Natural Resources and Environment, Associate Professor, Ph.D.
30	School of Science and Engineering, Liaoning University of Petroleum and Chemical Technology, Associate Dean, Professor, Ph.D.

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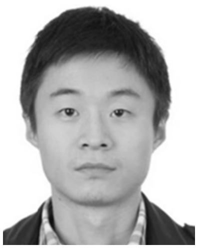

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