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Transportation Service Procurement Auctions in Cyber-Physical Internet

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Abstract: This study is the first to propose auction models for transportation service procurement (TSP) in Cyber-Physical Internet (CPI). In the TSP problem, shippers are the service buyers who generate a large number of orders, and carriers are the service sellers who can deliver these orders. CPI is a novel concept aiming to completely alter freight transportation to develop a new generation of global logistics network (GLN). The introduction of CPI prompts the rethinking of several TSP basic issues, such as route planning, service mode selection, and real-time pricing based on spatial-temporal information sharing in CPI. Therefore, we first detail two key components of CPI, i.e., *the router* and *the routing table* and then describe the GLN in CPI through a typical example. We further establish a one-sided Vickrey-Clarke-Groves (O-VCG) online reverse auction mechanism to maximize social welfare. This auction mechanism is built to make decisions according to multidimensional information provided by the routing table about the transport services. Moreover, we further analyze the four important attributes of the auction mechanism, including *allocative efficiency*, *incentive compatibility*, *individual rationality* and *budget balance*. We finally conclude with critical challenges and future research directions, including potential TSP auctions in CPI and the applicability of the underlying model to general logistics systems based on spatial-temporal considerations.

Keywords: Cyber-Physical Internet; Transportation service procurement; Router; Routing table; Auctions.

1. INTRODUCTION

Cyber-Physical Internet (CPI) is a novel notion that modernizes and revolutionizes the global logistics system. It was proposed, defined and described by Huang (2022), based on the vision of Physical Internet (PI) (Montreuil, 2011; Montreuil, Meller and Ballot, 2012), in which sending and receiving goods is like sending and receiving email messages. In the past, the focus of PI was on seeking a physical solution to develop logistics networks by borrowing the concept of the Internet (Montreuil, Meller and Ballot, 2013). In recent years, the importance of digital interoperability in PI has been uncovered since digitization is critical to interconnect logistics and supply networks (Sternberg and Norrman, 2017; Pan et al., 2021). Therefore, CPI is proposed as a potential solution to improve the digital interoperability of physical logistics networks.

CPI incorporates a reflection on cyber-physical visibility and spatial-temporal traceability. CPI aims to strengthen the resilience of the global logistics network (GLN) and improve the efficiency of transportation networks under the ravages of the Covid-19 pandemic (Choi, 2021). It is expected to improve the sustainability of the way physical objects are moved, stored, realized, supplied, and used around the world in a comprehensive manner from the perspective of economic, environmental, and social efficiency (Crainic and Montreuil, 2016). If realized, the way logistics services are provided and consumed will change dramatically, just as email has changed the role of the post office and the way people use postal services (Huang, 2022).

The vision of CPI is to send and receive goods just like sending and receiving messages within chat groups using an instant messaging platform. In a GLN, goods are entrusted by shippers to carriers and will be shipped from origin to destination (Bowersox and Calantone, 1998). The role of CPI in the GLN is to facilitate the transportation process and enable shippers to enjoy the on-demand synchronmodal logistics services. For example, consider a warehouse in which a large number of goods need to be transported to a cross-border factory. In this warehouse, goods are usually segmented and loaded onto trucks. The trucks travel through a network of highways, roads, and intersections to reach the next logistics hub. In this hub, the goods are then encapsulated into containers to reach the factory via ships. Following the key components and settings of the Internet, in CPI, segments could be analogous to trucks or ships, communication links are analogous to highways and roads, and data packets are similar to containers. Just as a truck takes a path through GLN, a data packet has a path through CPI (Kurose, 2005).

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Transportation service procurement (TSP) is a crucial part of the GLN that cannot be ignored. This is because carriers usually expect to provide shippers with a high level of transportation services at minimal costs. TSP refers to a process of determining transportation and exchange relationships across the GLN (Huang and Xu, 2013). Specifically, when shippers with goods need to procure transportation services from third-party logistics companies, they typically ask potential carriers for a quote on a unique set of delivery routes. They then sign a short-term or long-term contract based on their negotiated transportation cost (Song and Regan, 2003). In the past, the systematic literature review methodology has been widely used to explore research opportunities in the TSP problem (Basu et al, 2015; Jothi et al., 2015; Lafkihi et al., 2019). Based on the literature review, the main research stream is the applications of operations research methods to optimize transport operations, e.g., distribution network design, vehicle routing, and transport planning. Besides, since the transaction process between two carriers and shippers resembles a simple sealed-bid auction, many researchers have used auctions to study the TSP problem, including one-sided auctions, double auctions, and combinatorial auctions. For example, Xu and Huang (2013) propose two truthful double auctions for TSP, which are optimal to run a long auction cycle when maximizing social welfare. Based on this study, multi-unit Vickery auctions, and one-sided combinatorial auctions are proposed to address logistics resource sharing problems in logistics product service systems (Kang et al., 2019; Kang et al., 2021).

Hence CPI and TSP, as two major concepts, aim to completely alter freight transportation and logistics for developing a new generation of the GLN. The introduction of CPI prompts the rethinking of several TSP basic issues, such as route planning, service mode selection, and service pricing based on spatial-temporal information sharing in CPI (Yao et al., 2019; Pivoto et al., 2021). Based on the literature, we know that auctions ask and answer who should be served at what prices (McAfee and McMillan, 1987), and have been widely adopted to solve various problems in many fields (Lafkihi et al., 2020; Tan et al., 2019; Tan et al., 2021; Kang et al., 2022). This shows the great potential of auctions to establish TSP equilibrium solutions in CPI. We therefore first detail key components of CPI, including *the router* and *routing table*, and then describe GLN in CPI through a typical example. Three key fields are introduced in detail to address the TSP problem based on the auction mechanism.

Subsequently, we establish a one-sided Vickrey-Clarke-Groves (O-VCG) online reverse auction mechanism to maximize social welfare. The carrier acts as the bidder. A router is regarded as an auction center. There are multiple auction centers in a GLN. According to the multidimensional information provided in the routing table about the transport services, decisions can be made based on the proposed auction mechanism. We further analyze the four important attributes of the auction mechanism, including *allocative efficiency*, *incentive compatibility*, *individual rationality* and *budget balance*.

The rest of this paper is organized as follows. Section 2 introduces the router and the routing table, and presents the GLN in CPI. Section 3 proposes O-VCG online reverse auction mechanism for TSP in CPI and shows its properties. Section 4 discusses critical challenges and future research directions.

2. GLN IN CPI

2.1 Routers and routing tables

To build the GLN in CPI, two key elements of CPI must be described, namely *the router* and *the routing table*. The router has two functions: *forwarding* and *routing*. In the Internet, forwarding is the local action of a router that forwards data packets from an input link interface to the appropriate output link interface. Routing refers to the router selecting the path of data packets from the source to the end according to the routing algorithm. In CPI, consider the goods mentioned in the previous section that are transported across borders from the warehouse to the factories by trucks and ships. Goods are transported by truck between multiple logistics hubs before reaching the outbound logistics hub. We think of *forwarding* as a process through a single logistics hub: the truck enters the logistics hub from a road connected to the hub and decides which road it should take to leave the hub. In addition, *routing* can be thought of as the process of planning a cross-border shipping route for a ship: before departure, the carrier has consulted the router of CPI and chosen one of several possible routes.

Similar to the routing table in the Internet network, a critical element in every router of CPI is the routing table. In CPI, a router forwards goods by the routing table. The routing table contains nine important fields: destination, mask, protocol, pre, cost, next hop, interface, metric, transportation, and reserve, as shown in Table 1. Here, we only explain several fields related to making routing plans.

- Destination represents the logical addresses of routers and hosts to which goods are delivered in CPI. This destination is encapsulated using Physical Internet Protocol (PIP) which uses 32bit binary numbers to form a unique address for a router or host. The router creates and updates the rows of the routing table based on the protocol. In Table 1, for example, 10.2.0.0 and 255.255.0.0 are the addresses generated by PIP.
- Mask is usually used to divide the logical hierarchy of addresses and is also generated using PIP.
- Protocol is a guideline for the routing table to generate and update routing information. In CPI, classical Internet protocols can be used to build routing tables and determine the forwarding address, such as OSPF (Open Shortest Path First Protocol) and STATIC (Static Routing Protocol). The routing plan can be generated based on the information provided by the routing table. In this research, an

auction mechanism is designed for making routing plans.

- Next hop refers to the next stop PIP address for goods sent to the destination.
- Interface is defined as the router's entrance and exit. Each router has a number of interfaces to allow goods to get in and out of the router.
- Metric is used to measure the performance of routing paths whose destination PIP is the value in field destination, in terms of such as transportation time and cost. In the CPI, the smaller the metric, the better the routing.
- Transportation is the means of transporting goods, such as air transport and maritime transport.
- Reserve is utilized to cope with future or more complex needs in logistics networks.

To be specific, for the same destination, there may be multiple potential next hops accompanied by different transportation modes. The sizes of metric and reserve are 64bit, the sizes of destination, mask, and metric are 32bit, and the sizes of protocol, pre, interface, and transportation are 8bit. Moreover, the routers are classified according to the location of a logistics hub, as shown in Fig. 1. Triangle mark routers in ports, diamond mark routers in airports, and square mark routers in the land. Besides, to distinguish the transportation modes, we use different line patterns to indicate the different modes. The solid line represents the route generated by trucks on the road, the dash line represents the route generated by ships on the waterway, the round dot line represents the route generated by airplanes on the airway, and the long dash dot line represents the route generated by trains on the railroad.

Table 1 Routing table

Destination (32bit)	**Mask (32bit)**	**Protocol (8bit)**	**Pre (8bit)**	**Cost (16bit)**	**Next hop (32bit)**	**Interface (8bit)**	**Metric (64bit)**	**Transportation (8bit)**	**Reserve (64bit)**
10.2.0.0	255.255.0.0	OSPF	80	100	10.0.1.5	Ethernet0/0	453	Ship-B	/
10.2.0.0	255.255.0.0	STATIC	0	0	10.0.0.1	Ethernet0/1	0	Car-A	/

2.2 A typical GLN in CPI

We use a typical GLN with the Greater Bay Area (GBA) as the logistics hub to illustrate GLN in CPI. GBA, as a megalopolis, is the world's factory, and its economy has been mainly dominated by export manufacturing activities. In this regard, the origin of raw material imports and the destination of product exports are mostly in overseas markets. GBA has been able to create a stable connection between the two ends through multiple transportation modes and cost-effective logistics hubs. However, an unexpected Covid-19 pandemic has caused the global manufacturing industry to undergo a major reconfiguration recently. Logistics operations are disrupted on a large scale due to the social quarantine measures advocated by epidemic prevention. People were forced to work from home and shop online, resulting in a surge in demand for high-quality e-commerce logistics services. In fact, port operations are frequently disrupted, the passenger flights' circuit breaker mechanisms are often triggered, and goods arrivals and departures are severely delayed. Severe logistics capacity shortages caused severe operational congestion and gridlock at terminals and ports. The world container index has more than quintupled, and the air freight index has more than doubled in the last two years (Notteboom et al., 2021). GBA has also had to transform to meet domestic and global demand. CPI contributes to establishing post-pandemic "new norms" (Huang, 2022).

As shown in Fig. 1, GBA serves as a logistics hub connecting several logistics hubs around the world, 8 of them are described as examples, and they are located in Russia, Australia, Mexico, etc. Recall that logistics hubs are similar to routers, and data packets are similar to containers. Each of the nine warehouses/factories A-I on the map is connected to a router. Router 1, which is located in GBA, is connected to all the other 8 routers. This means that data packets can be forwarded between routers and goods can be transported between logistics hubs. In order to introduce the routing table in GLN, three fields destination, next hop, and transportation are selected as examples to illustrate in detail. The design of the auction mechanism in the next section also depends on these three fields. The destination refers to the final destination of goods delivery, the next hop is the next location to forward from the current location, and transportation is the mode of transportation used to the next hop. For example, there are goods in A to be transported to I. Router 1 uses forwarding and routing functions. Router 1 provides two possible solutions. For the same destination I, one feasible solution is to reach the next hop router 9 by train, and the other is to reach the next hop router 2 by airplane. Besides, for router 9, there are goods at I to be transported to H. At this point, there is only one routing available, so router 9's routing table shows the next hop as router 8 and chooses out traffic as the truck. Other routers are similar in that they all generate their own routing tables.

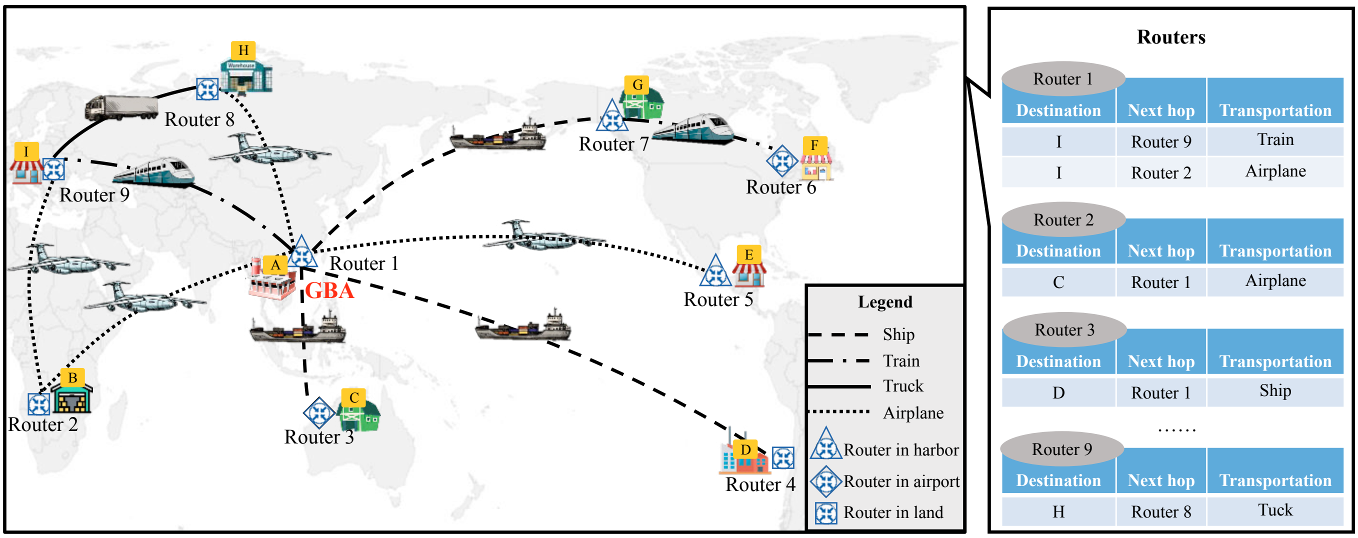

Fig. 1. A typical GLN in CPI

3. O-VCG AUCTION MECHANISM

3.1 Model setting

The shipper refers to the party that has the need to transport the goods from an origin to a destination, and the shipper is the buyer of the transportation service. The carrier is the party that provides the transportation service and is also the bidder. According to auction language, sellers bid to sell their goods and services at the price they are willing to sell them for. This mechanism is called a reverse auction and is applicable to this study (Krishna, 2009). In this paper, we consider a shipper and I carriers. The shipper wants to procure D units of transportation services for the potential routes given in the routing table with certain requirements for on-time performance. t_L is the maximum transportation time acceptable to the shipper. The shipper sets a reserved price for unit transportation services, recorded as R. When the carrier's bid is higher than R, the shipper will not purchase the transportation service.

The auction format is conducted in an online manner in auction centers. A router is an auction center. There are multiple auction centers in a GLN. Online auctions are conducted as sealed-price auctions in a finite, discrete time period $T=\{0,1,\cdots t\}$. The capacity limitations for carrier i to provide transportation services in T is k_i. A carrier can only participate in one auction center at a time. We assume that each carrier $i \in I$ is risk neutral. The bid proposal of each carrier i is denoted by $\boldsymbol{b}_i=(a_i,d_i,c_i,t_i,m_i)\in\Omega$, which is a five-dimensional vector, where a_i and d_i are the arrival and departure time of carrier i at the auction center, respectively. The maximum waiting time for carrier i at an auction center is w_i, $d_i \le a_i + w_i$ (Kong et al., 2021). c_i and t_i are the carrier's transportation time and transportation mode, respectively. Since the mode of transportation will affect the transportation time, we write $t_i = t(m_i)$. We denote $\boldsymbol{b}=(\boldsymbol{b}_1,\boldsymbol{b}_2,\cdots,\boldsymbol{b}_I)\in\Omega,\ i\in I$ as the set of all the biding proposal. And Ω is the set of all bidding proposals. For ease of reference, we summarize the variables and corresponding definition in Table 2.

Table 2 Notation and definition

Variables	Definition
i	The index of carriers.
I	The set of carriers, $i \in I$.
D	The units number of transportation service shipper procure.
t	The discrete auction time.
T	The auction period, $T=\{0,1,\cdots t\}$.
t_L	The maximum transportation time acceptable to the shipper.
R	The reserved price for unit transportation services.
a_i	The arrival time of carrier i at the auction center.
d_i	The departure time of carrier i at the auction center.
w_i	The maximum waiting time for carrier i at an auction center, $d_i \le a_i + w_i$.
m_i	The mode of transport services carrier i offers.
t_i	The transportation time of carrier i for the shipper, $t_i = t(m_i)$.
k_i	The capacity limitations for carrier i to provide transportation services throughout T.
$\boldsymbol{b}_i$	The bid proposal of carrier i, $\boldsymbol{b}_i=(a_i,d_i,c_i,t_i,m_i)$.
$\boldsymbol{b}$	The bid proposal of carrier set I, $\boldsymbol{b}=(\boldsymbol{b}_1,\boldsymbol{b}_2,\cdots,\boldsymbol{b}_I)$.
Ω	The set of all bidding proposals, $\boldsymbol{b}_i,\boldsymbol{b}\in\Omega$.
u_s	The utility of the shipper.
u_i	The utility of carrier i.
x_i^t	The number of transportation services that carrier i is assigned at t.

3.2 Auction mechanism

According to the potential next-hop choices given in routing tables. Carriers of all feasible routes can submit their bid proposals in the auction center. We propose an O-VCG online reverse auction mechanism to ensure the efficient allocation of transportation services. The objective is to maximize the social welfare, i.e., the sum of the utilities obtained by shippers and carriers. Given the information, the social welfare maximization can be formulated as the following binary integer programming (BIP) problem:

$$\text{IP}: \max \sum_{t=0}^{T} \sum_{i=1}^{I} (R - c_i) x_i^t \quad (1)$$

$$0 \le \sum_{t=0}^{T} \sum_{i=1}^{I} x_i^t \le D \quad (2)$$

$$\sum_{t=1}^{T} x_i^t \le k_i, \forall i \in I \quad (3)$$

$$t_i \le t_L, \forall i \in I \quad (4)$$

where the objective function (1) is to maximize the social welfare. Constrain (2) guarantees that supply does not exceed demand. Constrain (3) ensures that each carrier i has assigned not more than its maximum transportation capacity. Constrain (4) guarantees the transportation time of the carrier does not exceed the maximum transportation time acceptable to the shipper. The payment rules are based on a well-known VCG mechanism (Vickrey, 1961; Clarke, 1971; Groves, 1973).

The auction center solves the objective equation (1) and find the feasible solution to achieving social welfare $\pi(\boldsymbol{b})$. Denote the number of transportation services that carrier i is assigned in auction period T as $x_i = \sum_T x_i^t$, and we then have $\pi(\boldsymbol{b}) = \sum_I (R - c_i) x_i$. Using insights from VCG mechanism, we can calculate that each carrier receives a payment of $p_i = c_i - [\pi(\boldsymbol{b}) - \pi(\boldsymbol{b} \setminus \boldsymbol{b}_i)]$, where $\pi(\boldsymbol{b} \setminus \boldsymbol{b}_i)$ is the social welfare if the carrier i were excluded from the auction, and we assume other carriers submit truthful bid proposal. In such a case, the utility of carrier i is $u_i = \sum_I (R - c_i) x_i - \sum_{I \setminus i} (R - c_i) x_i \ge 0$. Due to the reservation price, the carrier's utility u_s must be greater than 0; otherwise, the carrier will not purchase the transportation services.

Obviously, the utility of both carriers and the shipper is non-negative. This implies that the proposed mechanism is *individually rational*. Also, a feasible allocation can be found in the auction period T, which indicates that the mechanism is *allocative efficiency*. O-VCG is also *incentive compatibility* for the shipper. Essentially the VCG mechanism provides a solution for any utilitarian problem with the dominant strategy (Nisan and Ronen, 1999; Xu and Huang, 2014). Besides, once the carrier fails to provide transport services as promised, including delayed shipments as well as broken contracts, the carrier will pay penalty charges. As long as the penalty fee is large enough, the auction centers could be *ex-post budget balanced* (Moulin, 2009).

4. CONCLUSION

This paper explores CPI solutions to meet the surge in demand for high-quality e-commerce logistics services. After a brief review of PI, this paper addresses the TSP problem in CPI via the auction mechanism. Three main contributions can be summarized in this research: (1) We introduce a new concept, CPI, with a vision of sending and receiving goods just like sending and receiving messages within chat groups using instant messaging platforms. (2) We detail key components of CPI, i.e., the router and the routing table, and describe a typical GLN in CPI. And (3) We establish an O-VCG online reverse auction mechanism for TSP in CPI to maximize social welfare and analyze its four key important properties.

Regarding future research, the experimental study and the simulation results will be proposed and analyzed. A one-sided forward auction mechanism where the shipper acts as the bidder and double auction mechanisms where the shipper and the carrier bid simultaneously will be considered and designed to make comparisons with this paper. Depending on the multidimensional information provided by the router, designing more precise utility functions will be of interest. We can use the classical scoring rules studied by Asker and Cantillon (2008) to establish new utility functions for the systematic analysis of the equilibrium behaviors of carriers and shippers in CPI. In addition, in the area of pricing, in order to make full use of information from routing tables and to improve transport service allocation and service efficiency. Different pricing methods such as iterative combinatorial auctions, bargaining and spatial-temporal pricing will be studied.

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