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The coal origin-destination matrix analysis and multimodal transportation cost modelling in the Yangtze River region, China

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ABSTRACT

The railway-road-inland waterway (IWW) transportation network in the Yangtze River basin was extracted using ArcGIS software and the triangular mesh covered the simulated region was generated using GIS software. The population density and gross domestic product were chosen as the characteristic economic variables, which were interpolated spatially into the mesh to analyse the origin-destination (OD) matrix of the coal transport network. Then, the multimodal transportation cost model was developed considering the detailed cost functions of railway, road and IWW. Finally, the coal transportation cost under different transportation allocation scenarios was calculated and compared to investigate the advantages and potential of the multimodal transportation mode in the Yangtze River basin. The cost analysis about the multimodal transportation system showed that the IWW mode has great potential to decrease the transportation cost of the coal within the OD matrix although the railway mode took at least 80% of the total transportation load.

1. Introduction

The turnover amount of freight transport increased quickly with the multi-year averaged increasing rate being 10.4% from 1998 to 2013, which was higher than the multi-year averaged increasing rate of 9.7% in China's economic development. The freight transportation plays an important role in the economic development, mainly depending on the trade and investment in China. Meanwhile, the multimodal transportation has developed quickly in North America and Europe over the past 20 years due to the low cost and low service efficiency. However, it's entirely different in China, especially in the logistics of the goods of the manufacturing industry. The reasons include many aspects such as the transportation demand for certain goods, the laws, the transportation price standards, and the flexibility of the services customers need.

The physical networks of railway, road and IWW in the Yangtze River region were extracted using ArcGIS software, and the cities or provinces were used as the origins and destinations for goods waiting to be transported, including transportation, loading, unloading and transshipment, as shown in Figure 1. The IWW transportation always plays an important role in the goods supply chain, providing loading, unloading, transshipment service for

goods and passengers between different countries and regions. Recently, IWW transportation has attracted the attention of the government because it is one of the eco-friendly and economical transportation modes to alleviate road congestion and costs. In China, the percentage of waterway transportation in total freight transportation has increased by three times from approximately 10% in 1990 to over 30% in 2010. China's 12th Five-Year Plan continuously boosts the transportation via IWW. The country shows more efforts to make further development of high-grade waterway channels on the Yangtze River as well. The Deep-water Channels Renovation Project at the Yangtze River has been successively completed and further launched to construct 12.5m deep IWW on the lower reaches of Nanjing section and 4.5m deep IWW on the Wuhan section. Other projects during the planning period include the maintenance of IWW of Jingjiang River and the capacity expansion of branch shipping lanes of Xijiang River (Tan, Li, & Zhang, 2015). It is expected that the total length of the high-grade IWW will amount to 13,000 km by the end of 2015. The shipment capacity in the IWW is spatially distributed along the Yangtze River in China, as shown in Figure 1. The ships with 30,000–50,000 tons can navigate between the Yangtze River mouth (Shanghai port) and Nanjing

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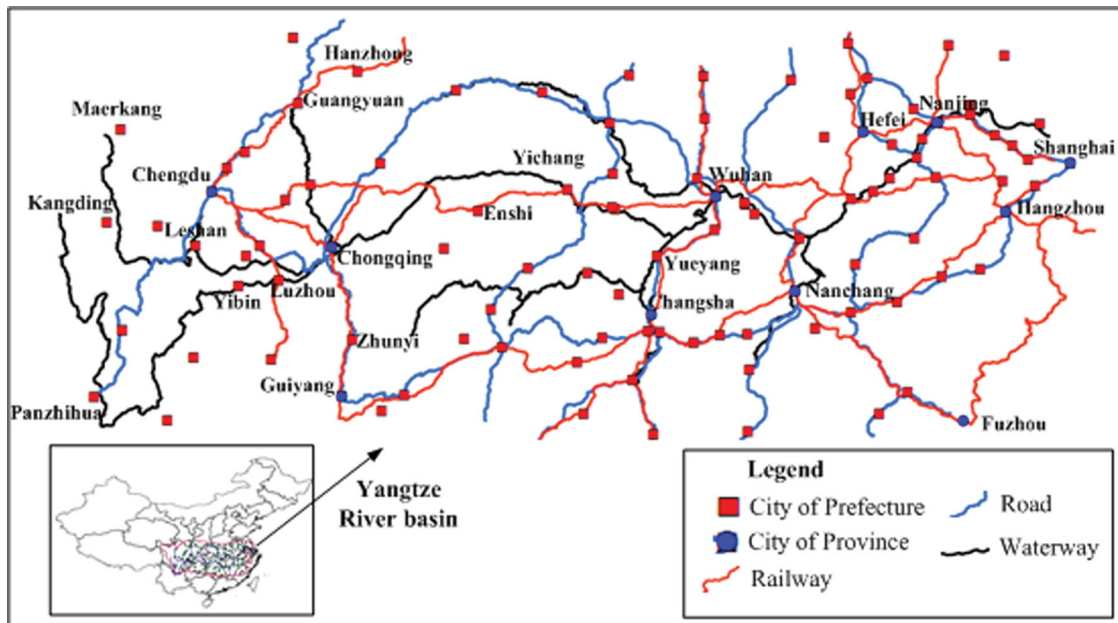
Figure 1. Railway-road-IWW multimodal transportation network in the Yangtze River basin of China.

port, approximately 390 km. However, the capacity of ships decreases to 3000 tons between Wuhan and Nanjing with 750 km length. The ship capacity continues to decrease to 1000 and 500 tons, respectively, when navigating upstream to Yichang and Yibin. The heterogeneity of the navigational condition along the river existed and the ship capacity becomes smaller and smaller from the downstream to the upstream of the Yangtze River (Tan et al., 2015). Meanwhile, the railway and road develop quickly in recent years, which lead to the change of the cost balance among the 3 transportation modes.

The multimodal transportation cost analysis involved a complex and comprehensive understanding of the many factors that affect multimodal transport costs. In recent years, many researchers put the emphasis on cost assessment to tap the potential of multimodal transportation. For example, Chen and Harker (1990) proposed to create a virtual link with a specific cost for specific-purpose infrastructure. Jourquin and Beuthe (1996) developed the method of virtual network using NOUDS software, which created a virtual network corresponding to the different operations that are feasible on each link or node of a real network. Müller and Benassi (2014) developed a multimodal transportation cost model to analyse the railway and road transportation costs in Argentina. Xie et al., (2017) developed a multi-objective programming model based on comprehensive cost, transport time and carbon emissions, and solved it by Step by step method. There are many other experts who study multimodal transport from the shortest route of transport. Angelica Lozano and Storchi (2001) studied the shortest feasible path problem in multimodal transport and solved it by sequential

algorithm. Kwasnica and Stavrulaki (2010) developed a two-stage game where firms set capacities and then locations, and showed that three types of subgame perfect equilibria were possible. The above-mentioned models systematically study the shortest feasible path and transportation cost of multimodal transport, but neither consider the detailed physical transportation network including the land and waterways transportation modes nor comprehensively assessing the advantages of multimodal transportation comparing the separated mode. Therefore, a multimodal transportation cost model was developed and applied to study the coal transportation cost under a railway-road-IWW system in the Yangtze River basin of China.

2. Methodology

2.1. The model structure

The transportation network can be represented as the linking of the railway, road and IWW lines with the topology information, which will be symbolized as the origin-destination (OD) matrix. The detailed cost functions can be analysed according to the available data and the characteristics of the specific transportation model, which are integrated into the cost model based on the OD matrix from the economic data analysis. Some parameters are used to describe the cost components and control the cost calculation algorithm, which are defined by the user as the input files. Then, the transportation cost in different modes can be calculated and the multimodal transportation cost will also be calculated considering

different allocation scenarios. Finally, the Dijkstra shortest path algorithm (1959) and North-West-Corner algorithm (Hillier & Leiberman, 1990) are used to minimize the total transportation distance and cost, respectively. The flow chart is shown in Figure 2.

A multimodal transport network consists of connection infrastructures, such as terminals or logistics platforms, where goods are loaded, unloaded, transshipped or processed in different ways. To analyse transport operations on the network, costs or weights must be attached to these geographical links of the transported goods as well as the connection points for handling the goods. However, most of these infrastructures can be used in different ways and at different costs. For example, boats of different sizes and operating costs can use the same waterway, and at a terminal, a truck's load can be transshipped on a train or a ship bundled with some others on a boat or simply unloaded as it reached its destination. Normally, the costs of these alternative operations should be different. The geographic network should provide the detailed transport operations where the same infrastructure is used in different ways.

2.2. Origin-destination (OD) matrix

Generally, the creation of the OD matrix of typical goods transportation can follow the 3 steps:

(1) Re-aggregation of available data using a characteristic variable such as population density (PD) or gross domestic product (GDP) to proportionally redistribute the goods in the simulated region;
(2) Cargo from zone A to zone B is usually transported through the shortest path as seen in Figure 3;
(3) Once a certain amount of the cargo (for one specific product) waiting for transportation that should arrive at the destination zones (for example zone B and zone D) has been built and normalized, then the total amount of the cargo should be forced to match with the departing (origin) zones (for example zone A and zone C) as shown in Figure 3. Therefore, building the OD pairs will be an optimization problem, in which the total tons-kilometers should be minimized in the OD matrix through a linear programming algorithm.

Subsequently, the detailed calculation can be following as:

(1) When the information of the goods production (origin) for bigger region than the size of the traffic zones in the simulated area is obtained, a characteristic variable can be used to distribute it proportionally in the traffic zones, for example, if zone A produces 80%
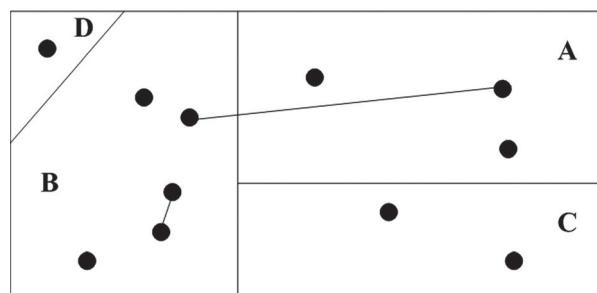

Figure 3. Zones of the goods at origin and destination points.

economic unit and zone C produces 20% economic unit, it's likely that zone A is the origin of the 80% goods, while zone B is the origin of the other 20% goods.
(2) When the information of the goods consumption (destination) is obtained, the same calculation can be conducted by the population proportion among the zones. In this paper, the characteristic variables including population density (PD), the Gross Domestic Product (GDP), and the areas of the zone surfaces are proportionally distributed in the simulated region.
(3) After building the OD matrix including the information of the link distance, production, and consumption of the goods based on the shortest path algorithm, OD pairs should be corrected manually when we have the additional information to consider that's not the real shortest path going from zone A to zone B.

Additionally, it should be noted that the optimization approach assumes that product in zone A should be consumed by the most nearby zone B, rather than the zone D far away. This works well with a certain kind of products, and not very well with others, in which the distance is not really an important thing.

2.3. Cost functions of the multimodal transportation

To calculate the cost of operating the multimodal transport network, each link of the networks (road, railway and IWW) is represented, on which the cost algorithms are applied. The railway-road-IWW multimodal cost model is programmed by the Python language considering the framework of the bimodal land transportation cost model developed by Müller and Benassi (2014), which can be downloaded from the website www.github.com/abenassi/freight_transport_network

(1) Railway and road transportation cost calculation
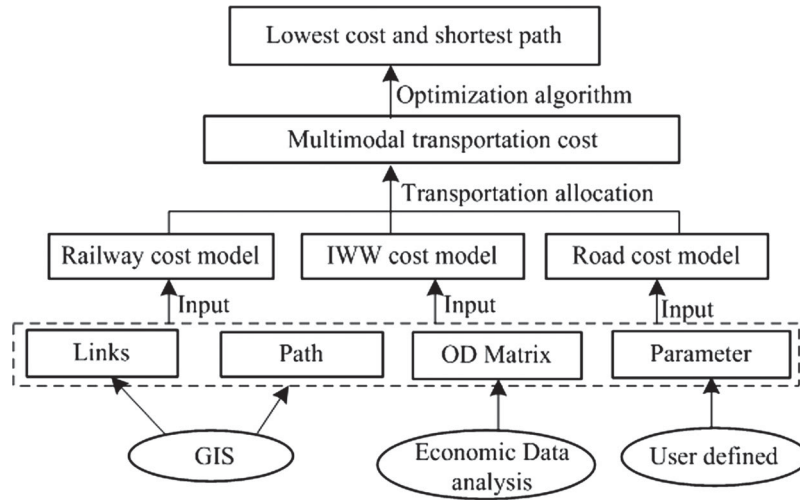
Figure 2. Flowchart of the multimodal transportation cost model.

Once the representation of the railway network is built, methods should be implemented to calculate the cost of each rail transport required for all OD pairs, with the load circulating through a set of authorized railway links. The costs of operating the railway network are divided into three parts: (1) Mobility Costs: These mainly depend on the train formations (the rolling stock) as well as the personnel needed to operate them, the fuel, the opportunity cost of rolling stock investment and maintenance. (2) Infrastructure costs: These mainly depend on the use of the infrastructure such as the opportunity cost of the investment in the railway, the crossing diversions, and the necessary maintenance. (3) Other costs: This part includes the secondary costs, which are related to the value of the immobilized load during the transportation, the cost of deposit of the cargo in origin and destination, and the short freight cost.

The cost calculation method for the road transportation mode is relatively simpler than that for railway transportation mode. The road transportation cost model only considers the mobility and infrastructure costs calculated from the available economic data. The methods and formulations for calculating railway and road transportation costs can be found in the following literature: (Kovács, 2017), (Bykadorov, 2017), (Müller & Benassi, 2014). In this paper, the simple formulas from Müller and Benassi's paper are used (Müller & Benassi, 2014).

A. Road transportation cost function

$$MC_R = mcp * ttk * APR$$

$$IC_R = B * L^A * D * APR$$

$$C_R = MC_R + IC_R \tag{1}$$

where C_R is the transportation cost of road; MC_R is the mobility cost of road; mcp is the mobility cost per ton-km; ttk is the total tons-kilometers; IC_R is the infrastructure cost of road; A, B and APR are parameters; L is the loads through a section of the road network (ton); D is the distance of a section of the road network (km).

B. Railway transportation cost function

$$MCL_{RW} = ppl * pt * lot * APR$$

$$MCF_{RW} = cpk * mt * rs * APR$$

$$MCLB_{RW} = rlc * MCF_{RW} * APR$$

$$MCLW_{RW} = up * CPF * RU * APR$$

$$MC_{LW} = muc * cplw$$

$$MC_{RW} = MCL_{RW} + MCF_{RW} + MCLB_{RW}$$
$$+ MCLW_{RW} + MC_{LW} \tag{2}$$

where MC_{RW} is the total mobility cost of railway; MCL_{RW} is the labor force cost; MCF_{RW} is the fuel cost; $MCLB_{RW}$ is the lubricant cost; $MCLW_{RW}$ is the mobility cost of the locomotives and the wagons; MC_{LW} is the maintenance cost.

$$IC_{AT} = rph * CPF * L * APR$$

$$IC_{ST} = rpl * CPF * L * (gd/mingd) * APR$$

$$IC_{CD} = NCD * ywt + rph * APR$$

$$IMC = MCT + MCRI * APR$$

$$IC_{RW} = IC_{AT} + IC_{ST} + IC_{CD} + IMC \tag{3}$$

where IC_{RW} is the total infrastructure cost; IC_{AT} is the infrastructure cost of the artery railway; IC_{ST} is the infrastructure cost of the side railway; IC_{CD} is the infrastructure

cost of the crossing detours; IMC is the maintenance cost of the infrastructure.

$$CSIC = CIC * T * ST + TD * APR$$

$$TDC = T * ST * DCP * APR$$

$$CSF = cpt * T * APR$$

$$OC_{RW} = CSIC + TDC + CSF \qquad (4)$$

where OC_{RW} is the total other cost; $CSIC$ is the cost of storing the immobilized cargos; TDC is the total deposit cost; CSF is the cost of short freight.

Then, the transportation cost of railway C_{RW} is:

$$C_{RW} = MC_{RW} + IC_{RW} + OC_{RW} \qquad (5)$$

(2) IWW transportation cost calculation

The waterway transportation cost model can be found in Enezy's paper (Enezy, Hassel, Sys, & Vanelslander, 2017) and Tan's (Tan et al., 2015) paper. In this paper, the simple formulas from Tan's paper is used, which considers the spatial heterogeneity along the navigational channel. As following:

$$C_W = 864x^2 + 1056x + 940 \qquad (6)$$

where x is the normalize distance to the Yangtze River mouth (Shanghai port), which is in [0–1]; C_W is the cost using IWW transportation mode.

Considering the transshipment cost between IWW and the other 2 modes, the model formulas are as follows:

$$C_R(x, x_1) = C_R^0 |x - x_1| + C_R^1$$

$$C_D(\mu, \lambda) = \frac{\gamma}{\mu - \lambda}, \gamma > 0, \mu > \lambda$$

$$\lambda = \int_{x \in Z} l(x) \mathrm{d}x$$

$$U_1(x | x_1, \tau, \mu) = C_R(x, x_1) + C_W(x_1) + C_D(\mu, \lambda) + \tau \quad (7)$$

where C_R is the transportation cost from x to x_1 via the road system; C_D is the service charge at the port for handling and packaging service, p_1, and the service time delay in monetary unit due to the port capacity of handling cargo; C_W is the transportation cost from port x_1 to the junction port by waterway; $U_1(x \mid x_1, \tau, \mu)$ is the generalized cost of transshipment service for the customers at location x; C_R^0 is the marginal transportation cost via road system and C_R^1 is the fixed cost of transportation via road system; μ is the service rate of the inland river port and λ is the cargo arrival rate and γ is the parameter converting the time unit to monetary unit; τ is the service charge.

3. Multimodal transportation cost calculation

3.1. Data source

The digitized geographic network about the transportation and the positions of the cities in China were downloaded from the website of National Geometrics Center of China (www.ngcc.cn). This group of city centroids was defined as the regional centres of gravity, which was considered as points of origin and destination of the goods. In this paper, coal was selected as the typical goods to present the case of a transportation cost study. The production and consumption of the coal in some provinces in 2015 located in the Yangtze River basin were taken from the literature (Lin, 2015) as seen in Figure 4, and the coal production and consumption points contained the geographical information including the latitude and longitude, the coal production, and consumption amounts. However, the data available did not give any indication about the specific points or regions of origin and destinations. The PD and GDP data in 2015 were extracted from (Lin, 2015), which showed the linear relationship between PD and GDP as seen in Figure 5.

3.2. OD matrix analysis

The OD matrix should include the information about the goods transit, the link distance between origin and destination, position of the OD points and so on as
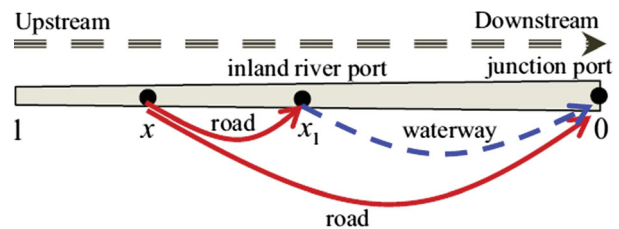

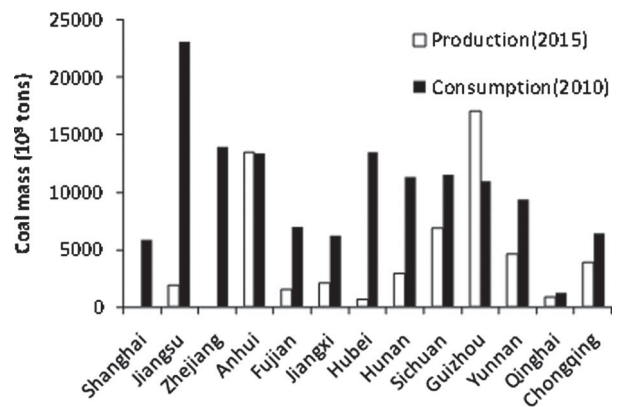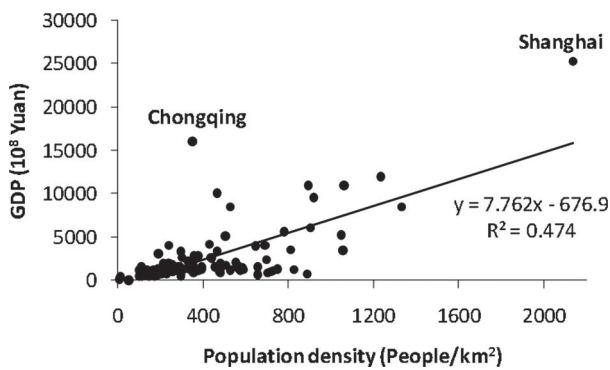**Figure 4.** The graphical explanation of the transport process.

Figure 5. Production and consumption mass of coal in the cities located in the Yangtze River basin.

Figure 6. Correlation between population density and GDP in some cities located in the Yangtze River basin.

the input files to the multimodal transportation cost model. Firstly, the transportation network was preprocessed using the Pennsylvania State University Integrated Hydrologic Model (PIHM) developed based on the open source geographical information system (GIS) software Quantum-GIS (Qu, 2004), which can be downloaded from the website http://www.pihm.psu.edu/pihm_gis Then, the spatial distribution of the PD, GDP, the coal supply and consumption capacity, the census of some economic values and the goods source zone area, which affected the logistics transportation, were interpolated to the triangular mesh by an inverse distance weight method. Finally, the OD matrix was generated following the calculation algorithm and the steps described in Section 2.2.

4. The cost analysis about the multimodal transportation system

At this stage, given the OD matrix and all cost functions for various operations, the total cost of the transportation tasks can be minimized by choosing the cheapest combinations of modes, means and routes and to compute the market shares predicted by the network model. Besides, the type of goods or products being transported can affect the usage of the transportation modes and means. In the cost model, the products transported are divided into 5 general categories (Müller & Benassi, 2014): (1) Bulk goods; (2) Non-granular primary product; (3) Semi-manufactured product; (4) Manufactured goods; (5) Unknown product. The objective of the cost model of the transport network developed here is to obtain the total cost of the transportation system for different scenarios of derivation of traffic among the road, railway and waterway modes. The coal as the product to preliminarily test the cost model developed here, all the parameters and economic state variables were inquired and calibrated from the related department of rail, road and inland river navigational bureau. The results of deriving the greatest possible load and cost according to the derivation criteria

Table 1. Multimodal transportation cost calculation results (unit: USD/ton-km).

Items	Railway		Highway		Waterway	
Time (year)	2005	2014	2005	2014	2005	2014
Mobility costs	0.017	0.008	0.060	0.065	0.011	0.010
Infrastructure costs	0.026	0.017	0.006	0.007	0.002	0.003
Other costs	0.008	0.002	0.001	0.001	0.001	0.002
Total cost	0.051	0.027	0.067	0.073	0.013	0.015

discussed above were listed in Table 1. All the costs were transferred from Chinese Yuan to US dollars as the monetary unit. As seen in Table 1, the waterway transportation cost showed advantages over the rail and road transportation, but the railway mode still took the most part of the transportation load, which reached over 80% such as the situation in the year 2005. Then, the percentage of coal transportation through railway decreased to 70% such as the situation in the year 2014 (Zhang & Zhao, 2017), the total transportation cost of railway decreased to 0.027 USD/ton-km comparing with the cost of 0.051 USD/ton-km in 2005. Meanwhile, the transportation cost of highway and waterway increased slightly in 2014 because of the transportation percentage increased caused the mobility cost, infrastructure cost and other cost increase. However, the total cost considering the multimodal transportation cost through railway, highway and waterway decreased from 0.131 USD/ton-km in 2005 to 0.115 USD/ton-km in 2014 through the network analysis and the multimodal transportation capacity improved followed the infrastructure construction.

5. Conclusions

The transportation system including the railway, road and IWW modes has developed quickly in China with the development of the economy in recent years. A multimodal transportation cost model was developed, which can be used to comprehensively assess the different goods transport mode and means choice scenarios and the total cost. Then, the coal as the typical product was used to preliminarily assess the multimodal transportation cost using the developed model. The data analysis showed that the coal production is closely related with the geographic locations, while the consumption of coal is closely related with GDP and population density. The coal transportation cost can be decreased through multimodal transportation considering the low cost of the IWW mode, the great load of the railway model and the elasticity of the road mode. The total coal transportation cost with the 70% of railway transportation will decrease obviously comparing with the 80% of railway transportation after considering

the multimodal transportation mode within the railway-highway-waterway transportation system.

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