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Design of Transport Organization Schemes for River Shipping Towing Transport

Shiyu Wang[1], Hanyang Wen[1], Linghan Tao[1], Ruyi Li[2]

[1]Chongqing No.2 Foreign Language School, China
[2]Chongqing University of Posts and Telecommunications, China

Abstract: To improve the economic efficiency of ship transportation in the Jialing River section, this paper conducts an in-depth analysis of the factors affecting tugboat and barge operations during cornering and lockage. Based on a detailed analysis of existing problems, this study proposes the re-adoption of electric tugboat solutions as a keyway to enhance the economic efficiency and transport capacity of Jialing River shipping. By establishing a mathematical model and comparing the cost levels of electric-powered vessels with traditional oil-driven ones, the study further suggests strategies for applying electric-powered tugs to increase the average tonnage per lockage pass and achieve optimization of ship transport organization, including careful adjustment of ship types and lockage vessel combinations. The research results show that under current conditions, the optimal fleet organization scheme is a combination of A motorized ships and B barges with a specific carrying weight (each barge with a load of t), which can significantly enhance the economic efficiency level of Jialing River fleets under specific premises, while also increasing transport volume and reducing costs by approximately.

Keywords: Barge, push boat and barge fleet, transport organization, scheme design.

1. Introduction

The Jialing River has a total area of about 160,000 km² and a total length of about 1,120 km. It is the largest tributary on the left bank of the upper reaches of the Yangtze River and one of the high-grade waterways in the National Layout Plan for Inland Waterways and Ports[1]. The upper stream, above Guangyuan, is about 380 km long; the middle stream, from Guangyuan to Hechuan, stretches about 645 km; and the lower stream, from Hechuan to the river mouth, is about 95 km long. The environment of the entire upper basin is relatively poor, making navigation difficult; the middle stream is wider, with widths ranging between 70 to 400 meters, and has a flatter terrain, forming the Sichuan Basin together with the middle and lower reaches of the Qujiang and Fujiang rivers, which creates favorable conditions for navigation. The lower stream flows through the parallel ridge valley region east of the basin, forming a canyon section where the river is relatively wide, with water surface widths between 150 to 400 meters. Due to the meandering nature of the upstream river, the narrow valleys, and the abundance of shoals and reefs, navigation is not favorable. Therefore, the main navigable section of the Jialing River trunk stream is the middle and lower reaches from Guangyuan to Chongqing, with a navigable mileage of 728 km. Currently, the Jialing River waterway is divided into five sections according to the waterway grades: from Guangyuan to Zhaohua, from Zhaohua to Jianxi Mouth, from Jianxi Mouth to Tongzihao, from Tongzihao to Hechuan, and from Hechuan to Chongqing.

The main ports within the Jialing River navigation section include Guangyuan Port, Nanchong Port, Guang'an Port, and Chongqing Hechuan Port. After joining the Yangtze River in Chongqing, it can radiate to the entire Yangtze River basin. There are a total of 4 container operation areas within the channel, with berths capable of accommodating 500-ton class vessels and also suitable for 1000-ton class vessels, and an annual operational capacity of 830,000 TEUs (twenty-foot equivalent units).

Along the main channel of the Jialing River from Guangyuan to Chongqing, a total of 16 hydroelectric hubs have been constructed, each equipped with ship-passing structures[2]. The ship-passing structure at Tingzikou Hub is a ship lift, while the other 15 hubs downstream from Tingzikou all have ship locks. Currently, the scenario of single-ship self-navigation for transportation shows characteristics of limited carrying capacity, high energy consumption, and poor economic efficiency[3]. Under these circumstances, no suitable barge-towing fleet transport vessel types have yet emerged, and there is also a lack of related technical data. The limitations of the waterway and locks affect the flat dimensions of the ships, leading to restricted loading capacities for individual ships, thereby impairing economic efficiency. Furthermore, since the standard vessel types suitable for the route have not yet been determined, the economic viability of single-ship transportation faces further challenges. Therefore, transport capacity should be upgraded[4].

To improve transport capacity, Company A plans to adopt new vessel designs and introduce new fleet formations for transportation. However, determining the appropriate fleet size and transport capacity is a current challenge that needs addressing. Therefore, this article aims to assist Company A from an economic perspective by predicting transport times, volumes, and fleet size to actively promote the standardization of Jialing River vessel types. This initiative will help overcome the challenges faced by the current single-vessel self-navigation method, enhance the economic efficiency of ship transport, and provide more suitable and efficient vessel options for fleet operations.

2. Formation Design

2.1. Formation principle

This text focuses on the Guangyuan to Chongqing navigation section, and by utilizing the standardized barge types and tugboats (towboats) that have been developed and introduced, it establishes alternative formation plans for different navigation sections while fully considering limitations such as channel depth, width, bend radius, tugboat pulling power, and lock dimensions.

The principles of formation include the following:

(1) Uniformity of Vessel Types: When determining the composition of a tug and barge fleet, it is important to consider the number of various barge types available and to keep the types consistent within the same fleet. This is conducive to the assembly of the fleet and can significantly reduce operational resistance, improve maneuverability, and shorten voyage time.

(2) Economic Principle: Starting from the economic perspective of transportation costs and the total load weight of the barges themselves, larger-tonnage barges should be selected for routes with high loading and unloading efficiency and longer distances, provided that channel conditions, water conservancy facilities, and the frequency of cargo dispatch allow.

(3) Efficient Use of Tugboats: Larger barge fleets should be matched with high-power tugboats (towboats), generally utilizing over 80% of the main engine's effective power. The selected tugboats should operate at their rated power under a given speed to ensure that the main engine operates normally under good conditions.

2.2. Formation determination

Currently, the navigation depth from Guangyuan to Chongqing is below 1.4 meters, allowing for the passage of barge models of 1500 tons and below. Company A has designed the power of tugboats and the types of barges as shown in Tables 1 , 2 and 3, respectively.

Table 1. Main Standard Parameters of Tugboats

Number	Tugboat Power (kw)	Length (m)	Width (m)	Draft (m)
1	198	24.8	4.3	1.1
2	272	27	7	1.9
3	368	30	7.2	2

Table 2. Standard Barge Parameters

Number	Length (m)	Width (m)	Draft (m)	Deadweight (t)
1	40.0	8.2	0.8~1.1	300
2	53.0	11.0	1.6~1.9	1000
3	70.0	13.8	2.2~2.4	1500

Table 3. Key Unmanned Barge Parameters of the Enterprise

Number	Length (m)	Width (m)	Draft (m)	Deadweight (t)	Deadweight（t）
1	70.0	13.8	2.2	1500	1500
2	43.0	11.0	2.0	700	700
3	50.0	11.0	2.0	800	800
4	43.0	13.8	2.0	950	950

This study utilizes the existing tugboat power of 271 kW and preliminary barge data from the enterprise as samples. Calculating with the matching power size of tugboats (towboats) at 8 tons/kW, we can list the suitable tug and barge formations for the Jialing River channel, as shown in Table 4.

Table 4. Tug and Barge Formation (1)

Number	Tugboat Power (kw)	Barge Model (t)	Barge Quantity	Total Deadweight (t)	Barge Formation (columns*rows)
1	198	300	2	600	1×2； 2×1
2	198	300	3	900	1×3； 3×1
3	198	300	4	1200	1×4； 2×2； 1×2+2； 1+2+1
4	198	300	5	1500	1+2×2； 1×3+2； 2+1×3
5	272	1000	2	2000	1×2； 2×1
6	368	1000	3	4500	1×3； 3×1
7	368	1500	2	3000	1×2； 2×1

This report, based on the preliminary ship type options provided by the company's materials, derives a similar tugboat power of 272 kW. In conjunction with the number of unmanned barges initially designed by the enterprise and calculated with the matching power size of tugboats (towboats) at 8 tons/kW, we can list the suitable tug and barge formations for the Jialing River channel, as shown in Table 5.

Table 5. Tug and Barge Formation (2)

Number	Tugboat Power (kw)	Barge Model (t)	Barge Quantity	Total Deadweight (t)	Barge Formation (columns*rows)
1	272	700	2	1400	1×2；2×1
2	272	700	3	2100	1×3；3×1
3	272	800	2	1600	1×2；2×1
4	272	800	3	2400	1×3；3×1
5	272	950	2	1900	1×2；2×1

3. Transportation Organization Method

Company A is currently reorganizing the fleet transportation in the Jialing River. It has been noted that there are more than a dozen locks along the Jialing River waterway, and to accelerate the lockage process, Company A wishes to allocate corresponding feeder ships at each lock to assist the main fleet in quickly passing through. The issue at hand is determining the optimal allocation of feeder ships at each lock. This section will employ mathematical modeling to solve for the required number of feeder ships and construct mathematical models for single fleet trip time, annual transport volume, and trip transportation costs to help Company A better assess whether the transportation organization plan is rational.

3.1. Model Construction

(1) Voyage Time Calculation Model

A voyage refers to the production cycle of fleet transportation (unit: days), which is a complete process of transportation production, including loading, transporting, and unloading. It involves not only the transportation of goods from the port of origin to the final destination but also entering one or more ports along the way for cargo handling. The voyage time consists of three parts: navigation time, berthing time, and other times (time through sharp bends and lockage time). The fleet's single trip transportation time model is based on ideal conditions; hence, complex real-world situations are not currently considered. The basic assumptions in the model are as follows:

(1) In the same river section, the time taken by the fleet to navigate through sharp bends requires the same time for assembly and disassembly of barges;

(2) In the same lock, the time for barges to pass through the lock is the same.

The specific model construction is as follows:

$$T_{ci} = 2\times 3\times\left(\frac{L_{AB}}{v}+\sum_{k=1}^{n}t_k+\sum_{i=1}^{m}\left\lfloor\frac{x}{y}\right\rfloor T_p+nt_d\right)/24 \quad (1)$$

T_{ci} : Fleet voyage time; L_{AB} : Distance from port A to port B; v : Tugboat speed; t_k : Port berthing time; T_p : Time for barges to pass through the lock, $i=1,2,3\cdots\cdots,m$; x : Total number of barges included in the fleet; y : Number of barges that can pass through the lock in a single operation; n : Total number of sharp bends in the waterway; t_d : Time taken to navigate through sharp bends and for assembly and disassembly of barges.

(2) Tugboat Allocation Calculation Model

The number of tugboats (unit: vessels) refers to the optimal number of tugboats that need to be operated on the route within the navigation section to maintain the set departure interval. It is calculated based on the relationship between the total round-trip time of the tugboat in that navigation section and the set departure interval. The round-trip time of the tugboat includes transportation time and the time for assembly and disassembly of barges.

The actual situation of fleet transportation is complex, but to simplify the calculation, the following basic assumptions are made:

(1) The round-trip time of the tugboat is only related to the length of the waterway, boat speed, and the time for assembly and disassembly of barges, not affected by other factors.

(2) To meet practical requirements, the number of tugboats is rounded up to the nearest integer.

(3) The round-trip time of the tugboat conforms to the turnover frequency of the fleet, and there is no empty waiting time.

The model construction is as follows:

$$M=\frac{T_{\text{wf}}}{T_{\text{g}}}=2\left(\frac{L_i}{V}+\sum_{k=1}^{n}t_k+nt_d\right)\Big/T_g \quad (2)$$

T_{wf} : Round-trip time of the tugboat between two locks; L_i : Round-trip distance of the ith navigation section; v : Tugboat speed; t_k : Port berthing time; n : Total number of sharp bends in the waterway; t_d : Time taken to navigate through sharp bends and for assembly and disassembly of barges; T_{g} : Tugboat departure interval.

(3) Fleet Transport Capacity Calculation Model

The fleet transport capacity (in ten thousand tons per year) refers to the total annual transportation volume of the fleet, calculated through the effective annual transportation time, tugboat departure interval, and barge loading capacity. Under ideal conditions, we assume:

(1) The effective transportation time of the fleet is constant and is not affected by changes in cargo volume, etc.

(2) The fleet is always fully loaded, and the transportation from the port of origin to the destination port constitutes a single trip's transport volume, without involving temporary loading or unloading of goods midway.

The model construction is as follows:

$$Q=2q\frac{T\times\eta}{T_{\text{g}}}\omega \quad (3)$$

Q : Annual total transport volume; T : Annual total working hours; η : Operation rate (the ratio of the actual operating time of the vessels to the annual total working hours); T_g : Departure interval; ω : Production rate of a single fleet; q : Total loading capacity of a single fleet.

(4) Trip Transportation Cost Calculation Model

Trip transportation cost refers to the total annual transportation cost of the fleet, which is calculated by summing the fixed costs and transportation costs for each navigation section. The fixed costs mainly include:

(1) Fixed expenses for the departure and transportation of the tugboat;

(2) Lockage fees;

(3) Port cargo turnover fees.

$$C = \sum_{i=1}^{13} C_i + C_s + C_m + C_r + f \times P + c \times L \quad (4)$$

C : Total transportation cost; C_i : Lockage fees; C_s : Crew wages; C_m : Cost of a single repair; C_r : Cost of a single operation (including management fees, insurance fees, depreciation expenses); f : Number of ports; P : Port cargo turnover fees; c : Unit distance; L : Total distance for a fleet's single trip.

3.2. Result Calculation

Based on the analysis above, Company A employs a tugboat fleet with a configuration of one tug and three barges. Taking the Cangxi to Shipantuo navigation section as an example, we will calculate the model results and conduct an economic feasibility study. Below, Table 6 provides the mileage data for each navigation section.

Table 6. Waterway Data

Waterway Data			
Lock and Natural Navigation Sections	**Waterway Mileage (km)**	**Lock and Natural Navigation Sections**	**Waterway Mileage (km)**
Cangxi - Shaxi	33.5	Xiaoloumen - Qingju	23
Shaxi - Jinyintai	22	Qingju - Dongxiguan	56
Jinyintai - Red Rock	32	Dongxiguan - Tongzihao	46
Red Rock – Xinzheng	38	Tongzihao - Lize	29
Xinzheng - Jinxi	42	Lize - Caojie	72
Jinxi -- Mahui	26		
Mahui - Fengyi	23		
Fengyi - Xiaoloumen	17.5		
total		460km	

(1) Calculation Results of Voyage Time

The total time within the calculation period is the product of navigation time and working hours. That is, working 8 hours per day, which equals 365 days × 8 hours/day = 2920 hours. The fleet transportation does not currently consider night navigation. The time for a single lock passage is calculated as 1.5 hours (including the time for assembly and disassembly). The average speed of the fleet in calm water is set at 9 km/h. Both the outbound and return trips are considered fully loaded without involving the temporary loading of goods midway. The calculation results are shown in the table below. The results from the table above show that the fleet requires 22.5 days to complete a voyage.

Table 7. Voyage Time Calculation

Calculation of Voyage Time						
Navigation Channel Section i	**Number of Ships/Vessels**	**Number of Barges Passable per Lockage Operation**	**Time Required for Lockage /h**	**Distance/ Km**	**Travel Speed km/h**	**Voyage Time /Day**
Cangxi - Shaxi	4	2	1.5	33.5		
Shaxi - Jinyintai	4	2	1.5	22		
Jinyintai - Red Rock	4	2	1.5	32		
Red Rock – Xinzheng	4	2	1.5	38		
Xinzheng - Jinxi	4	2	1.5	42		
Jinxi -- Mahui	4	2	1.5	26		
Mahui - Fengyi	4	2	1.5	23		
Fengyi - Xiaoloumen	4	2	1.5	17.5	9	22.5
Xiaoloumen - Qingju	4	2	1.5	23		
Qingju - Dongxiguan	4	2	1.5	56		
Dongxiguan - Tongzihao	4	2	1.5	46		
Tongzihao - Lize	4	2	1.5	29		
Lize - Caojie	4	2	1.5	72		

(2) Calculation Results for Tugboat Allocation

Based on the tugboat allocation model calculation, where the port berthing time is set to zero, we can determine the number of tugboats required for each navigation channel section, as well as the number of fleets under different departure intervals (8h, 4h, 2h). When the departure interval is 8 hours, there are 18 pusher boats and 54 barges; when the departure interval is 4 hours, there are 32 pusher boats and 96 barges; when the departure interval is 2 hours, there are 57 pusher boats and 171 barges.

Table 8. Calculation of Tugboat Allocation (8-hour interval)

Navigation Channel Section i	Distance of the Navigation Section/km	Port Berthing Time	Tugboat Operating Speed /km/h	Total Number of Tugboats
Cangxi - Shaxi	33.5	0	9	1
Shaxi - Jinyintai	22	0	9	1
Jinyintai - Red Rock	32	0	9	1
Red Rock – Xinzheng	38	0	9	2
Xinzheng - Jinxi	42	0	9	2
Jinxi -- Mahui	26	0	9	1
Mahui - Fengyi	23	0	9	1
Fengyi - Xiaoloumen	17.5	0	9	1
Xiaoloumen - Qingju	23	0	9	1
Qingju - Dongxiguan	56	0	9	2
Dongxiguan - Tongzihao	46	0	9	2
Tongzihao - Lize	29	0	9	1
Lize - Caojie	72	0	9	2
Fleet Size 1	18 pusher boats and 54 barges			

Table 9. Calculation of Tugboat Allocation (4-hour interval)

Navigation Channel Section i	Distance of the Navigation Section/km	Port Berthing Time	Tugboat Operating Speed /km/h	Total Number of Tugboats
Cangxi - Shaxi	33.5	0	9	2
Shaxi - Jinyintai	22	0	9	2
Jinyintai - Red Rock	32	0	9	2
Red Rock – Xinzheng	38	0	9	3
Xinzheng - Jinxi	42	0	9	3
Jinxi -- Mahui	26	0	9	2
Mahui - Fengyi	23	0	9	2
Fengyi - Xiaoloumen	17.5	0	9	1
Xiaoloumen - Qingju	23	0	9	2
Qingju - Dongxiguan	56	0	9	4
Dongxiguan - Tongzihao	46	0	9	3
Tongzihao - Lize	29	0	9	2
Lize - Caojie	72	0	9	4
Fleet Size 2	32 pusher boats and 96 barges			

Table 10. Calculation of Tugboat Allocation (8-hour interval)

Navigation Channel Section i	Distance of the Navigation Section/km	Port Berthing Time	Tugboat Operating Speed /km/h	Total Number of Tugboats
Cangxi - Shaxi	33.5	0	9	4
Shaxi - Jinyintai	22	0	9	3
Jinyintai - Red Rock	32	0	9	4
Red Rock – Xinzheng	38	0	9	5
Xinzheng - Jinxi	42	0	9	5
Jinxi -- Mahui	26	0	9	3
Mahui - Fengyi	23	0	9	3
Fengyi - Xiaoloumen	17.5	0	9	2
Xiaoloumen - Qingju	23	0	9	3
Qingju - Dongxiguan	56	0	9	7
Dongxiguan - Tongzihao	46	0	9	6
Tongzihao - Lize	29	0	9	4
Lize - Caojie	72	0	9	8
Fleet Size 3	57 pusher boats and 171 barges			

(3) Calculation Results of Fleet Capacity

The fleet consists of a tugboat and three barges, with one motorized barge (cargo capacity of 750t) and three unpowered conventional barges (cargo capacity of 2400t). The specific results are shown in Table 11 below. Under the three departure intervals of 8h, 4h, and 2h, the annual transport capacity of the fleet is 2 million, 4 million, and 9 million tons respectively.

Table 11. Fleet Capacity (million tons per year)

Total Time Within the Calculation Period /h	Departure Interval/h	η Operating Rate	ω Net Productivity of a Single Fleet	Total Loading Capacity of the Fleet /t	Fleet Capacity/(million tons per year)
2920	8	1	1	3150	200
2920	4	1	1	3150	400
2920	2	1	1	3150	900

(4) Calculation Results of Voyage Transportation Costs

Assuming the employment of 4 crew members: one second-class captain with a salary (including social security) of 316 yuan/day; one second-class chief engineer with a salary (including social security) of 284 yuan/day; one helmsman (pilot) with a salary (including social security) of 265 yuan/day; and one refueler (cook) with a salary (including social security) of 232 yuan/day. The wages, maintenance costs, and operating expenses are calculated based on one voyage cycle. The specific results are shown in Table 12 below, indicating that the cost required for the tug and barge fleet to complete a voyage is 109,500 yuan.

Table 12. Calculation Results of Voyage Transportation Costs

Navigation Channel Section i	Cs Crew Salaries	Cm Maintenance Costs	Cr Operating Expenses	Ci Lockage Fees	c Unit Electricity Cost	Transportation Costs/Ten Thousand Yuan
Cangxi - Shaxi	1097	6250	24450	1575	80	10.95
Shaxi - Jinyintai				1575		
Jinyintai - Red Rock				1575		
Red Rock – Xinzheng				1575		
Xinzheng - Jinxi				1575		
Jinxi -- Mahui				1575		
Mahui - Fengyi				1575		
Fengyi - Xiaoloumen				1575		
Xiaoloumen - Qingju				1575		
Qingju - Dongxiguan				1575		
Dongxiguan - Tongzihao				1575		
Tongzihao - Lize				1575		
Lize - Caojie				1575		

4. Summary

This paper begins by using the existing ship type data from Company A to design the formation of the tug and barge fleet, determining the number of different barge models and the formation style when the tug power is at 271 kW. Following that, based on the tug and barge fleet formation provided by Company A, production and operation commonly used rhythm numbers are employed to construct models for voyage time, tug allocation numbers, annual transport volume, and transportation costs. Finally, using the data provided by Company A, calculations were made for the anticipated voyage time, tug allocation numbers, annual transport volume, and transportation costs of the envisioned tug and barge fleet, offering references for Company A in setting fleet scale and quantity.

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