

MULTI-VEHICLE SCHEDULING OF CONTAINERS IN HIGHWAY PORT UNDER NETWORK CONDITION

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Abstract

In order to improve the tractor-to-semitrailer ratio and reduce the operating cost, this study explored the scheduling problem of multi-vehicle tractor and semitrailer scheduling of containers in highway port. A multi-vehicle tractor and semitrailer scheduling model was established to minimize the network operation cost, and a two-stage heuristic algorithm based on the saving mileage method and an improved simulated annealing algorithm was designed to solve the model. Results show that, compared with the fixed transportation mode, the reduction rate of the number of container tractors and semitrailers under network transportation increased from 7.33 % to 49.88 %, the cost saving rate increased from 2.33 % to 14.14 %, and the reasonable value of the tractor-to-semitrailer ratio increased from 1:1.08 to 1:2.00. It is proved that with the increase of the working time of the tractor, the multi-vehicle tractor and semitrailer transportation shows more obvious advantages. In the meanwhile, the reasonable value of the tractor-to-semitrailer ratio and the tractor scheduling scheme under different working hours are obtained, which provides decision support for enterprise operation.

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Key Words: Highway Transportation, Tractor and Semitrailer Transportation, Highway Port, Network Condition, Multi-Vehicle

1. INTRODUCTION

The scale of freight volume is the prerequisite for tractor and semitrailer transportation. As a large logistics facility, the highway port can realize massive agglomeration of freight volume. Compared with zero load transportation, the concentration of single point freight volume of highway ports has increased several times, which can greatly decrease the operation cost. Therefore, highway ports have unique advantages of tractor and semitrailer transportation. However, to give full play to its advantages, such transportation requires a highway port network of tractors and semitrailers. Tractor and semitrailer transportation is carried out between highway ports, which is not only the operation place, but also the point of customer demands. Different from the general demand in tractor and semitrailer transportation, the demand of highway tractor and semitrailer transportation is based on semitrailers. The demand quantity may be multiple vehicles and the demand at both ends may not be equal, that is, there are multiple tractors and semitrailers crossed between two highway ports and unbalanced demands at both ends, which increases the complexity of scheduling optimization. Therefore, the study of the multi-vehicle optimization problem of highway port load scheduling under network condition tractor and semitrailer shedding presents important guiding significance for the optimization of vehicle resource allocation and enterprise operation.

In essence, the optimization of container multi-vehicle scheduling in highway port is the application of tractor and semitrailer routing problem (hereinafter referred to as TSRP) [1, 2]. In recent years, theoretical studies have focused on tractor and trailer transportation in iron and steel enterprises and ports where each customer point is served only once, and the research is carried out from the consideration of constraints such as service time window and

special needs of orders [3, 4]. However, in actual highway port tractor and semitrailer transportation network, the operation is carried out between highway ports, which are not only the tractor and semitrailer operation site, but also the customer demand point. Different from the requirements in other practical application scenarios of tractor and semitrailer transportation, the demands in highway port tractor and semitrailer transportation take semitrailers as the unit, and the number of demands may be multiple semitrailers, which increases the complexity of optimizing the tractor and semitrailer transportation scheduling.

The present study proposes the following innovations: First, the container multi-vehicle tractor and semitrailer scheduling optimization model is constructed based on tractor and semitrailer transportation under network condition, and the practical needs such as multiple parking lots, multiple and unbalanced demands, and heavy tractor pulling small semitrailer are considered. Second, the multi-stage heuristic algorithm is designed and the improved simulated annealing and particle swarm algorithms are compared with the improved ant colony algorithm to verify their effectiveness in solving large-scale scheduling optimization problems.

2. STATE OF THE ART

Scholars have focused on VRP (Vehicle Routing Problem) multiple-vehicle scheduling. Bula et al. [5] introduced the factor of multi-vehicle into the problem of single-target dangerous goods vehicle path, and proposed the improved variable neighbourhood search algorithm as the model solution. However, the algorithm is based on the “circular tractor and trailer” assumption and only considers single demand and single parking lot problems. Li et al. [6] studied 2E-VRPTW (Two-echelon Vehicle Routing Problem with Time Windows) problem with time window and mobile satellites, and designed an adaptive, large neighbourhood heuristic search algorithm, but only based on the “one-line two-point and tractor and semitrailer at both ends” mode. Bulhões et al. [7] solved the problem of supply and demand matching between customers considering goods and multiple vehicles, but the algorithm did not consider the case of “heavy tractor pulling small semitrailer.” Considering the time window and multiple models, Ghannadpour and Zarrabi [8] proposed the non-dominant ranking genetic algorithm based on tractor-and-trailer transportation under a hub-spoke network, but only considered single demand and demand balance. Bevilacqua et al. [9] studied the two-stage fixed fleet heterogeneous vehicle path and proposed a Lin-Kernighan heuristic algorithm based on local search. However, this algorithm only considered a “circular tractor and trailer” case and neglected the possibility of unbalanced demand. Most related studies also tend to use meta-heuristic algorithms to solve VRP problems under the constraint of multi-dimensional complex environment [10]. Dumez et al. [11] proposed the VRP problem of time window constraints. Srivastava et al. [12] designed the non-dominant ranking genetic, multiple neighbourhood adaptive taboo search, and elite ant group algorithms to solve the model, but did not consider the demand. Combining urban logistics, Li et al. [13] studied the two-level common distribution location-path problem and designed a mixed integer planning model and an adaptive large neighbourhood search algorithm. However, unbalanced demand was not considered. Xu et al. [14] established a delivery vehicle path model considering multiple parking lots, multiple vehicles, goods, and unmatched customer supply and demand; an iterative search local solution algorithm was then designed based on large-scale neighbourhood search, but did not consider the unbalanced demand. Cao and Wang [15] established a two-stage vehicle distribution path planning model with the target function of the minimum distribution cost. The genetic algorithm was used to analyse and solve the model, but only a single parking lot and single demand were considered. According to the characteristics of the urban living garbage classification collector mode, Liu et al. [16] used

the improved genetic algorithm to solve the vehicle scheduling problem, but did not consider the unbalanced demand. Mu et al. [17] simulated an annealing algorithm to solve two classification transportation models. However, the unbalanced demand was not considered. Zhang et al. [18] established an urban heterogeneous vehicle logistics scheduling model with the minimum total distribution scheduling cost and the maximum vehicle loading utilization rate as the optimization objectives, and designed an improved mixed whale swarm algorithm to solve the model through examples. However, this study was based on a “circular tractor and trailer” assumption and single parking lot problem. Guo et al. [19] and Wang and Huang [20] also carried out similar studies.

In summary, existing studies have focused on organizational models such as “one line and two points, tractor and trailer at both ends”, tractor-and-trailer transportation under hub-spoke network, and “circular tractor and trailer.” Few studies examine the network tractor and semitrailer transportation. In addition, most of the abovementioned studies only consider the model assumptions established from the perspective of single parking lot, single demand, and demand balance while ignoring multiple and unbalanced demands in practice. In the aspect of algorithm solution, these previous studies prove that the optimization problem of tractor and semitrailer transportation scheduling is NP-Hard [2], and meta-heuristic and heuristic algorithms are used as solutions. The studies rely on theoretical values and ignore the actual scenarios when carrying out local research.

The remainder of this study is organized as follows. Section 3 presents the model of the multi-vehicle container unloading scheduling in highway ports and a two-stage heuristic algorithm. In Section 4, a two-stage heuristic algorithm is used for example calculation, and the results are compared with those of fixed transportation mode, such as the operating costs, the number of tractors used, and the tractor and semitrailer ratio. Moreover, the effectiveness of the algorithm is verified by comparing with the improved particle swarm optimization and ant colony algorithms. Finally, Section 5 summarizes this study and draws relevant conclusions.

3. METHODOLOGY

3.1 Problem description

For tractor and semitrailer of network condition (as shown in Fig. 1), highway port tractor and semitrailer transportation enterprises have multiple highway ports in different geographical locations and unbalanced demands. This problem needs to clarify the tractor model, towing capacity, and semitrailer load. A tractor with high capacity to tow a smaller or equal semitrailer must be established to minimize the network operation cost and maximize profit.

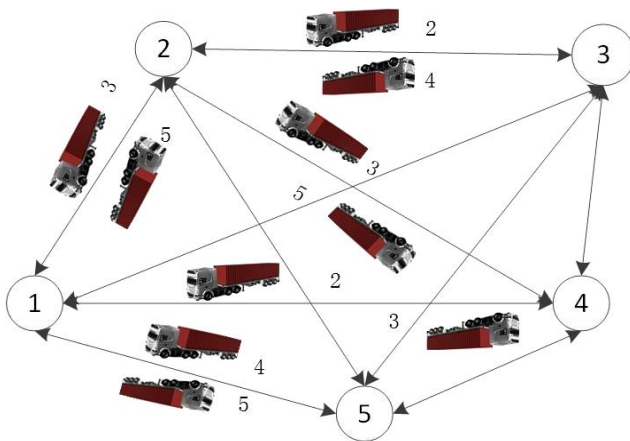


Figure 1: Schematic diagram of the network-type multi-vehicle container dispatching in highway port.

3.2 Problem hypothesis

According to the characteristics of highway port semitrailer transportation, the following hypotheses are proposed:

- (a) All tractor and semitrailer in the network belong to recommended but inconsistent models for highway tractor and semitrailer transportation. Tractor can only tow semitrailer with maximum mass not greater than their own.
- (b) Given enough semitrailer, tractor does not need to wait for semitrailer loading and unloading operations.
- (c) Distance and time between the two highway ports are the same.
- (d) Enterprises can arrange scheduling according to actual demand, and all demands must be met.

3.3 Symbol definitions

Parameter definition:

N – collection of all highway ports, with a total of n highway ports, $N = \{1, 2, \dots, n\}$,

i, j, l – number of highway ports, $i, j, l \in N$,

M – collection of tractor types,

m – type of tractor, $m \in M$,

K – collection of tractor, $K = \{1, 2, \dots, k\}$,

k – number of tractor, $k \in K$,

m_k – m -type tractor k , $k \in K$,

e_{m_k} – standard load mass of the m -type tractor,

d_{ij} – distance between highway ports i and j , in (km),

q_{ijm} – transportation demand of the m -type tractor from the highway port i to j , with cargo tonnage for ordinary tractor and semitrailer. Given that demand is not necessarily balanced, q_{ijm} is not necessarily equal to q_{jim} ,

C_{ijm_k}, c_{ijm_k} – cost of loading and idling of m -type tractor from highway port i to j , in (USD/km),

c_{m_k} – fixed cost of m -type tractor k per unit time, including vehicle depreciation and employee salary, in (USD),

T – continuous working hours of tractor, all of which are stipulated to have equal continuous working hours each day,

v_{m1}, v_{m2} – speed of m -type tractor when towing heavy semitrailer and idling, in (km/h).

Decision variable:

k_1, k_2 – states of the tractor towing heavy semitrailer or idling,

$$x_{ijm_{k_1}} = \begin{cases} 1 & \text{The tractor tows heavy trailer from highway port } i \text{ to } j \\ 0 & \text{Other} \end{cases},$$

$$x_{ijm_{k_2}} = \begin{cases} 1 & \text{The tractor is idle from highway port } i \text{ to } j \\ 0 & \text{Other} \end{cases},$$

$a_{ijm_{k_1}}, a_{ijm_{k_2}}$ – number of trips of the m -type tractor k towing heavy semitrailer or idle from highway port i to highway port j .

3.4 Modelling

According to the actual operation of highway ports, the cost of network operation is the lowest for tractor and semitrailer transportation enterprises.

Objective function

The network operation cost is composed of heavy semitrailer driving, idle driving, fixed, and penalty costs. The goal of minimizing the network operating cost is expressed as follows:

$$\begin{aligned} \min Z_1 = & \sum_{i=1}^n \sum_{j=1}^n \sum_{m \in M} \sum_{k \in K} a_{ijm_{k_1}} d_{ij} C_{ijm_k} x_{ijm_{k_1}} + \sum_{i=1}^n \sum_{j=1}^n \sum_{m \in M} \sum_{k \in K} a_{ijm_{k_2}} d_{ij} C_{ijm_k} x_{ijm_{k_2}} + \sum_{m \in M} \sum_{k \in K} c_{m_k} \\ & + \sum_{i=1}^n \sum_{j=1}^n \sum_{m \in M} \sum_{k \in K} P_{ijm_k} \end{aligned} \quad (1)$$

Constraint condition:

The tractor and semitrailer demand is met:

$$\sum_{k \in K} a_{ijm_{k_1}} x_{ijm_{k_1}} = q_{ijm} \quad (2)$$

Continuous working time limit of tractor:

$$\frac{\sum_{i=1}^n \sum_{j=1}^n d_{ij} x_{ijm_{k_1}}}{V_1} + \frac{\sum_{i=1}^n \sum_{j=1}^n d_{ij} x_{ijm_{k_2}}}{V_2} \leq T \quad (3)$$

Number of tractor in road network:

$$K_Z = \sum_{m \in M} \sum_{k \in K} m_k \quad (4)$$

Penalty cost:

$$P_{ijm_k} = \begin{cases} (\gamma - 1)d_{ij}C_{ijm_k}, & \gamma \text{ is the penalty coefficient of towing low-quality trailer with high-quality tractor,} \\ & \text{and Cost range coefficient of tractors with different traction qualities, } \gamma > 1; \\ +\infty, & \text{indicating all demands are met} \end{cases} \quad (5)$$

3.5 Algorithm design

According to the characteristics of container tractor and semitrailer transportation under the network mode, if the intelligent heuristic algorithm is used to optimize the two decisions, the whole problem becomes highly complicated and obtaining a satisfactory solution in a short time becomes difficult. Therefore, scheduling tasks are reasonably spliced by mileage saving method to reduce the number of solution spaces and obtain better initial solutions. Finally, the improved simulated annealing algorithm (SA) is applied for optimization.

4. RESULT ANALYSIS AND DISCUSSION

4.1 Data acquisition

Tractor and semitrailer transportation enterprises have highway ports in 30 cities. How to arrange vehicle scheduling in the network to minimize the operating cost of the entire network is a technical problem for enterprise managers. According to the three batches of road tractor and semitrailer transportation recommended models published by the Ministry of Transport, the enterprise can integrate tractor vehicles and heavy- and empty-hanging driving costs and fixed costs, as shown in Table I. Assuming the speed of heavy and empty driving is 50 km/h and 70 km/h. The continuous working time per day is $T = 16$ h. The radiant function in Matlab 2010a software is used to generate container tractor and semitrailer transportation tasks between 30 highway ports in [0, 5].

Table I: Business models of tractor and semitrailer transportation enterprise L.

Model number	Container tractor			
	Type	Heavy semitrailer driving cost (USD/km)	Idling driving cost (USD/km)	Fixed cost (USD)
1	Three-axle 40-foot container semitrailer	0.1437	0.7185	93.405
2	Two-axle 40-foot container semitrailer	0.1293	0.0575	86.22

4.2 Analysis of example results

Fig. 2 shows the result of the algorithm operation, which shows the change of the overall operating cost of the system with the increase of iterative algebra. As shown in the figure, after nearly 600 iterations, the extreme value is optimal. The simulation results of specific vehicle driving paths are shown in Fig. 3. A total of 4020 tractor are used in this tractor and semitrailer scheme. To ensure the clarity of the simulation diagram, we illustrate the driving paths of two tractors.

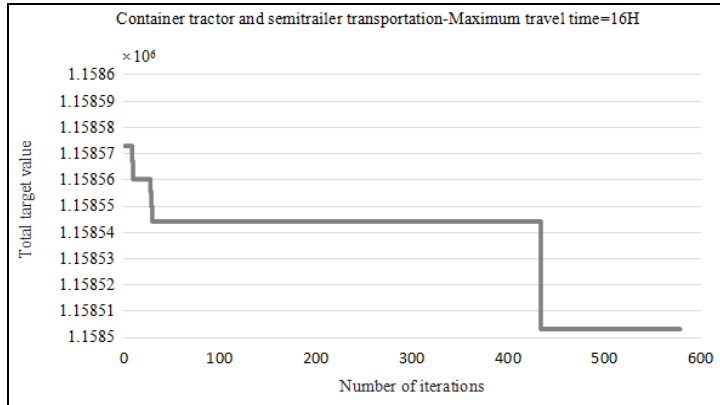


Figure 2: Iterative curve of total operating cost of container tractor and semitrailer transportation.



Figure 3: Simulation results of container tractor and semitrailer transportation.

As seen in Table II, the container tractor and semitrailer transportation tractor-to-semitrailer ratio of this enterprise is obtained as 1:1.08, which is slightly higher than that of China in 2021 (1:1.04). The results show that, compared with the traditional mode, the number of container tractor and semitrailer drops by 7.33 % and the cost is saved by 2.33 %. In tractor and semitrailer transportation, the tractor is allowed to tow multiple trailers if possible, and thus the number of tractors used is bound to decrease.

To further verify the model performance and the algorithm, this study compares three algorithms, ACS (Ant Colony System), PSO (Particle Swarm Optimization), and SA, which adopt the same local search strategy. The maximum objective functions of the three algorithms run for 30 times, as shown in Table III.

Table II: Comparison of calculation results.

Project	Fixed transportation	Multi-vehicle tractor and semitrailer transportation
Tractor K	4338	4020
Fixed cost (USD)	389492	361003
Heavy load cost (USD)	796608	796657
Idle cost (USD)	0	109
Penalty cost (USD)	0	734
Total cost (USD)	1186100	1158503
Reduction ratio of tractor number (%)	7.33	
Reduction ratio of total cost (%)	2.33	
Tractor-to-semitrailer ratio	1:1.00	1:1.08

Table III: Comparison of calculation results of algorithm indicators.

Project	ACS	PSO	SA
Average objective function value (USD)	1220777	1275274	1232118
Lowest objective function value (USD)	1306197	1347119	1314501
Optimal objective function value (USD)	1161752	1232121	1158503
Average running time (s)	8472	8678	7874

As shown in Table III, the average target value of container tractor and semitrailer transportation based on ACS algorithm is smaller than PSO and SA, which are 4.27 % and 0.92 % lower, respectively, and the running time is 5.28 % lower than PSO and 51.8 % higher than SA. By comparison, the average total operating cost of ACS algorithm is slightly better than that of SA algorithm, but the running time is much longer. The optimal value of SA algorithm is superior to those of the other algorithms. Therefore, the improved SA two-stage heuristic algorithm is proven better than the other algorithms, and finding the optimal solution when dealing with large-scale problems is explained.

4.3 Sensitivity analysis

This study considers the influence of different tractor working hours on vehicle scheduling scheme that is more in line with the actual enterprise operation. The working time of the tractor in the example is increased and three test examples are generated. The working time is increased in turn: 32, 48, and 72 hours, respectively [21].

Fig. 4 shows the algorithm operation results, comprising the change of the overall operating cost of the system with the increase of iterative algebra. As can be seen from the figure, after nearly 600 iterations, the extreme value is optimal.

Comparison of calculation results is given in Table IV. Tractor working times of 32, 48, and 72 hours are considered. For the same conditions the comparison of the change of tractor-to-semitrailer ratio is shown in Fig. 5 and the comparison of the total cost saving rate of container transportation and the reduction rate of tractor number in Fig. 6.

When the tractor working hours differ, the reduction rate of container tractor increases from 7.33 % to 49.88 %, the cost saving rate increases from 2.33 % to 14.14 %, and the reasonable value of container tractor-to-semitrailer ratio increases from 1:1.08 to 1:2.00.

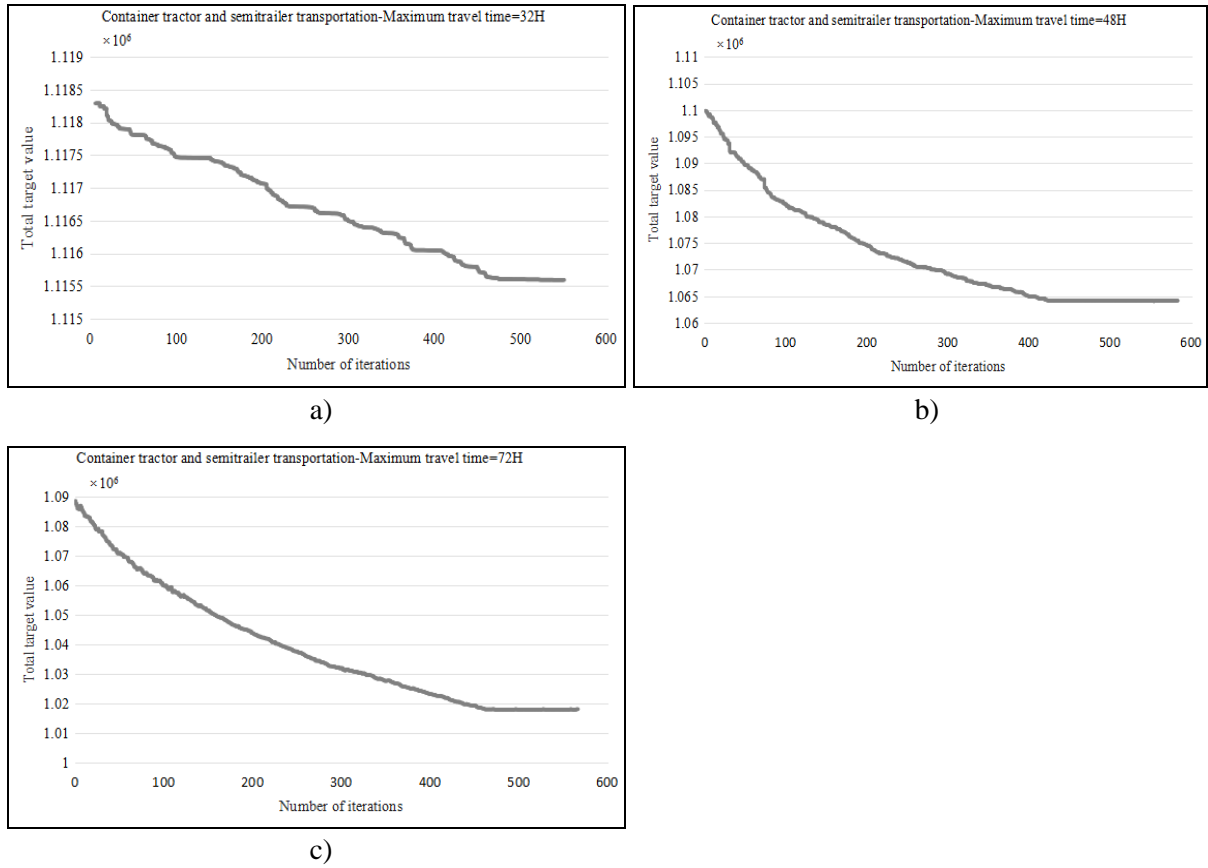


Figure 4: Iterative curve of total operating cost of container tractor and semitrailer transportation; a) $T = 32$ h, b) $T = 48$ h, c) $T = 72$ h.

Table IV: Comparison of calculation results.

Project	$T = 32$ h		$T = 48$ h		$T = 72$ h	
	Fixed transportation	Multi-vehicle tractor and semitrailer transportation	Fixed transportation	Multi-vehicle tractor and semitrailer transportation	Fixed transportation	Multi-vehicle tractor and semitrailer transportation
Tractor K	4338	3549	4338	2895	4338	2174
Fixed cost (USD)	389492	318798	389492	260004	389492	195224
Heavy load cost (USD)	796608	796608	796608	796608	796608	796612
Idle cost (USD)	0	199	0	7629	0	26440
Penalty cost (USD)	0	0	0	0	0	64
Total cost (USD)	1186100	1115605	1186100	1064240	1186100	1018340
Reduction ratio of tractor number (%)	18.19		33.26		49.88	
Reduction ratio of total cost (%)	5.94		10.27		14.14	
Tractor-to-semitrailer ratio	1:1.00	1:1.22	1:1.00	1:1.50	1:1.00	1:2.00
Running time (s)	4962		6741		6924	

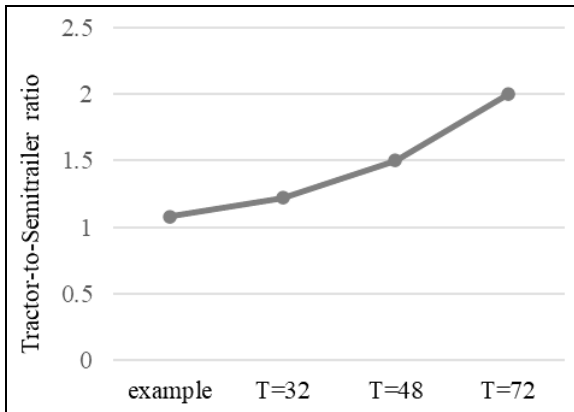


Figure 5: Comparison of the change of tractor-to-semitrailer ratio with tractor working hours.

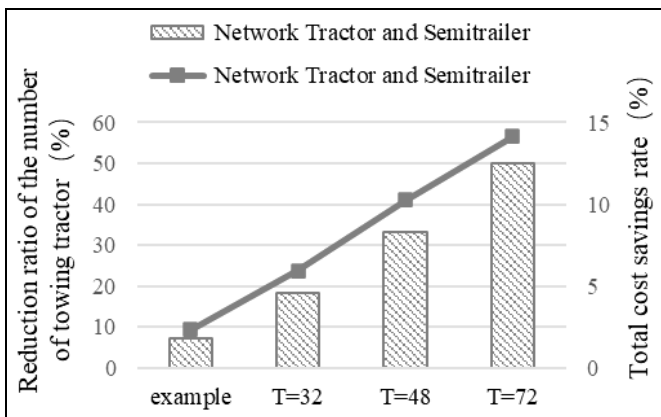


Figure 6: Comparison of the total cost saving rate of container transportation and the reduction rate of tractor number with the working hours of tractors.

The increase of tractor working hours also increases the advantages of the multi-vehicle tractor and semitrailer transportation. Meanwhile, the reasonable values of the rejection ratio and tractor scheduling scheme under different working hours are obtained, which provides decision support for enterprise operation.

Simulation results of tractor scheduling scheme: The number, transportation time and running route of each tractor are calculated. A tractor starts from the highway port of its city. It traverses its own tasks in the table and stays at the highway port. The simulation results of specific vehicle driving paths are shown in Fig. 7. When the running time is 32 hours, a total of 3,549 tractors are used in the tractor and semitrailer scheduling scheme, 2,895 tractors are used when the running time is 48 hours, and 2,316 tractors are used when the running time is 72 hours. To ensure the clarity of the simulation diagram, the driving paths of two tractors are illustrated as an example. Green and purple represent the running routes of two tractors. In Fig. 7, as the tractor running time increases, the number of tasks completed by each tractor also increases.

5. CONCLUSION

In this study, the highway port is considered to be both a tractor and semitrailer operation site and a customer demand point. From the perspective of multiple parking lots, multiple demands, unbalanced demands and large trucks towing small semitrailers, a multi-vehicle container tractor and semitrailer scheduling model for highway ports based on unbalanced demand was established under multi-vehicle tractor and semitrailer scheduling. A two-stage heuristic algorithm was designed for empirical analysis.



Figure 7: Comparison of simulation results of container tractor and semitrailer transportation under different running times.

The results verified that the multi-vehicle tractor and semitrailer was better than the fixed transportation mode in terms of operating cost and tractor number, and provided decision support for highway port semitrailer transportation enterprises. The following conclusions could be drawn:

(1) Based on the proposed solution, the operating cost of multi-vehicle tractor and semitrailer transportation is lower than that of single vehicle tractor and semitrailer transportation. Thus, the multi-vehicle tractor and semitrailer transportation can more appropriately arrange and make the best use of transportation capacity.

(2) For multi-vehicle tractor and semitrailer transportation, the calculation results show that when the tractor works for 16 hours, the reasonable semitrailer ratio is 1:1.08. With the increase of the tractor working hours, the tractor-to-trailer ratio of container tractor and semitrailer transportation increases from 1:1.08 to 1:2.00. The proposed model algorithm can effectively reduce the total operating cost consumed by fixed transportation mode and provide decision support for enterprises.

(3) In order to further verify the performance of the model and algorithm, it is compared with PSO and ACS. The results verify the effectiveness of the improved SA algorithm and illustrate the superiority of finding the optimal solution when dealing with large-scale problems.

This study gives full consideration to the situations of unbalanced demands, multiple demands, and heavy tractor towing small semitrailer in highway port. The whole network vehicle scheduling optimization is proposed for the highway port network, which is beneficial to the economic benefits of the tractor and semitrailer transportation enterprises. We assume that highway ports have enough semitrailer, that is, semitrailer scheduling is full, which still differs from the actual operation. Therefore, these details can be considered in future research based on the current study results.

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