CHEMICAL ENGINEERING TRANSACTIONS
VOL. 71, 2018

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Xiantang Zhang, Songrong Qian, Jianmin Xu
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ISBN 978-88-95608-68-6; **ISSN** 2283-9216

DOI: 10.3303/CET1871017

Optimization of Truck-and-Trailer Transportation Scheduling for Hazardous Chemicals with Empty Trailer Task

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A hazardous chemicals truck-and-trailer transportation scheduling model with empty trailer task was established in an actual hazardous chemicals transportation network. The model involves two stages. In the first stage, an empty trailer scheduling plan with the shortest total distance was established. In this process, a scenario where a heavy trailer task unlocks an empty trailer was considered. In the second stage, a hazardous chemicals truck-and-trailer transportation scheduling model was established with the target to have minimum total operating cost and time consumption. Finally, a specific calculation example was established, and the programming was implemented using Microsoft Visual Studio 2013 development platform, to create hazardous chemicals truck-and-trailer transportation program. On comparing the truck-and-trailer transportation program with a program where there is no truck-and-trailer in hazardous chemicals transportation, it was seen that truck-and-trailer transportation program can reduce the number of the vehicles performing tasks by 50%, reduce total time consumption by 38% and total cost by 40.6%, which validates the effectiveness of the model and algorithm.

1. Introduction

As a kind of special goods, the special transportation and scheduling of hazardous chemicals is beneficial to the demonstration effect of drop-and-pull transportation. At present, hazardous chemical transportation has been taken seriously attention by all walks of life. This paper is of practical significance to study truck-and-trailer transportation scheduling of hazardous chemicals. Based on existing literature, Chao (2002) was the first to propose the Trailer Truck Routing Problem (TTRP). Inanli et al. (2015) considers the distribution network of a confectionary chain in Turkey. Lin et al. (2011) added the time window conditions and unlimited vehicle carrying capacity to the constraint conditions in the TTRP. In other studies in China, Cheng et al. (2010) designed the VRPSDP solution algorithm based on truck-and-trailer transportation after grouping the in-plant transport tasks in steel enterprises using temporal clustering. Yang et al. (2016) established an optimization model for truck-and-trailer transportation scheduling with the condition of indefinite empty trailer tasks in areal road network. However, these approaches do not take into account a heavy trailer task unlocking an empty trailer task. Research on hazardous goods transportation mainly focuses on the safety control at home and abroad. For example, Zheng (2017) propose an improved ant colony algorithm to study the hazardous chemical transportation route optimization. Sun (2017) analyzed dangerous chemicals transport risk points and proposed some advice for dangerous chemicals transport safety management. But the research on hazardous chemical truck-and-trailer transportation has only put forward some tentative ideas. There is a temporary gap in theoretical researches. This paper separates the empty trailer task plan and the overall scheduling plan, which is of great significance for research on truck and trailer scheduling for hazardous chemicals.

Please cite this article as: Feng M., Cheng Y., Wu X., 2018, Optimization of truck-and-trailer transportation scheduling for hazardous chemicals with empty trailer task, Chemical Engineering Transactions, 71, 97-102 DOI:10.3303/CET1871017

2. Models and Methods

2.1 Model assumptions

(1) Use the central yard as the parking lot, all trucks leave from the central yard and finally return to it.
(2) Before the scheduling period begins, all heavy trailer tasks have been cleared.
(3) The truck speed during all operating states is consistent.
(4) The models and rated loading capacity of all the trucks involved in the completion of the tasks are the same. During the entire task, the truck is in good condition, and can handle various tasks.
(5) One truck can only tow one trailer at most.

2.2 Symbol description

C_1 is the numbering set for trailer supply points, C_1={0,1,2…c_1}; C_2 is the numbering set for trailer demand points, C_2={0,1,2…c_2}; E_i is the trailer supply quantity at the trailer supply point i; F_j is the trailer demand quantity at the trailer demand point j; D_{ij} is the distance between the trailer supply point i and the trailer demand point j; Y_{ij} is the number of trailers from the trailer supply point i to the trailer demand point j; The empty trailer scheduling set is (A,B,G), wherein, A represents the departure point of the empty trailer scheduling task, B represents the arrival point of the empty trailer scheduling task, G represents the number of trailers from the departure point A of the empty trailer scheduling task to the arrival point B.
M is the total task set of heavy trailer and empty trailer. M={0,1,2…m}; Wherein, N={0,1,2…n} is the empty trailer scheduling task set, N<M; P represents the truck set. P={0,1,2…p}; $t_{i'j'}$ is the time taken by the truck to move from task i' to task j'; $f_{i'}$ is the time required to perform task I'; $W_{i'}$ is the waiting time when performing task i'; $t_{i'}$ is the time taken to arrive at the starting point of task i'; δ is the unit time cost; γ is the usage cost of each truck; R_k is the working time upper limit of the truck k within the scheduling period. $X_{i'j'k} = \begin{cases} 1 & \textit{Use the tractor } k \textit{ to perform the task } j' \textit{ after performing task } i' \\ 0 & \textit{Otherwise} \end{cases}$; $ST_{i'}^{k}$ is the starting point of task i' in the travel path of truck k, and $ET_{i'}^{k}$ is the end point of the task i' in the travel path of the truck k. ST is the starting point set of tasks, and ET is the end point set of tasks.

2.3 Penalty cost function

The time window of the heavy trailer task is set as follows: Based on different degrees of violation of the time window, the time window is set as a hybrid time window, and [$t_{i'1}$, $t_{i'2}$] is the hard time window to start performing the task i', after which, the violation will lead to high penalty cost. [$t_{i'3}$, $t_{i'4}$]is the soft time window that can be violated to some extent. However, if the violation results in a penalty cost, the penalty cost will be decided jointly by the penalty coefficient and the degree of violation.
The time window of empty trailer task is set as follows: This time window is also set as a hybrid time window, and [0 $t_{i'2}$]is the hard time window that must be met to start performing the task i'.[0 $t_{i'1}$] is the soft time window that can be violated to some extent. Formula (1) is the corresponding penalty cost function. Formula (2) is the corresponding penalty cost function.

$$F(t_{i'}) = \begin{cases} \infty & t_{i'} < t_{i'1} \\ \alpha(t_{i'3} - t_{i'}) & t_{i'1} \le t_{i'} < t_{i'3} \\ 0 & t_{i'3} \le t_{i'} < t_{i'4} \\ \beta(t_{i'} - t_{i'4}) & t_{i'4} < t_{i'} \le t_{i'2} \\ \infty & t_{i'} > t_{i'2} \end{cases} \tag{1}$$

$$F(t_{i'}) = \begin{cases} 0 & t_{i'} < t_{i'1} \\ \alpha(t_{i'} - t_{i'1}) & t_{i'1} \le t_{i'} \le t_{i'2} \\ \infty & t_{i'} > t_{i'2} \end{cases} \tag{2}$$

2.4 Optimization model for empty trailer scheduling

2.4.1 Generation of empty trailer task

Empty trailer scheduling model is established as follows:

$$\min Z = \sum_{i=1}^{c_1}\sum_{j=1}^{c_2} Y_{ij} D_{ij} \tag{3}$$

$$\sum_{i=1}^{c_1} Y_{ij} \geq F_j \qquad j \in C_2 \tag{4}$$

$$\sum_{j=1}^{c_2} Y_{ij} \leq E_i \qquad i \in C_1 \tag{5}$$

$$\sum_{i=1}^{c_1} E_i \geq \sum_{j=1}^{c_2} F_j \qquad i \in C_1, j \in C_2 \tag{6}$$

$$N = N / j' \text{ when } ET_{i'} = ET_{j'} \text{ and } t_{i'1} \leq t_{j'1} \ (i' = n+1, n+2, \ldots, m, \ j' \in N;) \tag{7}$$

The objective function formula (3) means that the empty trailer transport distance is minimum (the empty trailer transport distance in this paper refers to the road network distance covered by the tasks established to meet all empty trailer demands).Formula (4) ensures that the number of empty trailers dispatched to each customer point can meet its demand. Formula (5) ensures that the number of empty trailers dispatched from each customer point does not exceed its supply capacity. Formula (6) ensures that the supplied quantity of empty trailers in the system can meet the demand. Formula (7) means that if the end point of the heavy trailer task is the end point of the empty trailer task, and its time window is less than the time window of the empty trailer task, the empty trailer task can be ignored.

2.4.2 Solution for initial empty trailer task

Step 1: Take the customer demand point j($j \in C_2$) as the center, find the empty trailer supply point i($i \in C_1$)with the shortest distance for it. If $E_i \geq F_j$, go to Step 2; if $E_i < F_j$, go to Step 3.
Step 2: $E_i = E_i - F_j$,, record (i,j,F_j) and put in empty trailer scheduling set (A,B,G), set $F_j=0$, the demand search of point j is finished, go to Step 4.
Step 3: $F_j = F_j - E_i$,, record (i,j,E_i)and put in empty trailer scheduling set(A,B,G), set $E_i=0$, go to Step 1.
Step4: Check whether all $F_j=0$, if yes, the algorithm ends, otherwise, j=j+1, go to step 1.
Record the initial empty trailer scheduling task set as$(A,B,G)_1$.

2.4.3 Optimal solution for empty trailer scheduling

The optimal solution is solved in two stages.
First stage: The scenario that the heavy trailer unlocks empty trailer is not considered.
Step 1: Calculate the transport distance of the empty trailer task in$(A,B,G)_1$, record as Z_1.
Step 2: Take the customer demand point j($j \in C_2$) as the center, calculate the solution of empty trailer scheduling task using the steps to the solve the initial empty trailer task, and calculate the transport distance Z_j of the empty trailer task in $(A,B,G)_j$, j=j+1, go back to step 2, until all the records of Z_j with the customer point j as the center are completed.
Step 3: The empty trailer task solution set (A,B,G) corresponding to the minimum Z_j is the optimal solution set for the empty trailer task.
Step 4: Record current empty trailer task N={0,1,2…n}.
Second stage: Consider unlocking of heavy trailer, and get the optimal solution.
Step 5: Set the initial value j'= 1,
When $ET_i=ET_i$ and $t_{i'1} \leq t_{j'1}$(i'=n+1,n+2,…,m; j'=1,2,…n), record the empty trailer task j';
Step 6: New empty trailer task N'={Initial N set-newly recorded empey trailer task set}.

2.5 Optimization model for hazardous chemicals truck-and-trailer transportation scheduling

2.5.1 Model building

$$\min \sum_{k=1}^{p}\sum_{j'=1}^{m} \gamma x_{0j'k} + \sum_{k=1}^{p}\sum_{i'=1}^{m}\sum_{j'=1}^{m} (f_{i'} + w_{i'} + t_{i'j'})\delta x_{i'j'k} + \sum_{i'=1}^{m} F(t_{i'}) \tag{8}$$

Constraint conditions:

$$\sum_{k=1}^{K}\sum_{j'=1}^{m} x_{0j'k} \leq p \tag{9}$$

$$\sum_{j'=1}^{m} x_{0j'k} = \sum_{i'=1}^{m} x_{i'ok} \leq 1, k \in P \tag{10}$$

$$\sum_{k=1}^{p}\sum_{i'=0}^{m} x_{iqk} = \sum_{k=1}^{p}\sum_{j'=0}^{m} x_{qjk} = 1, q \in M \tag{11}$$

$$\sum_{i'=0}^{m}\sum_{j'=0}^{m} x_{i'j'k}(t_{i'j'} + f_{i'} + w_{i'}) \leq R_k, k \in P \tag{12}$$

$$\sum_{k=1}^{p}\sum_{i=0}^{m} x_{i'j'k}(t_{i'} + f_{i'} + w_{i'} + t_{i'j'}) \leq t_{j'}, j' \in M \tag{13}$$

If $ET_{i'}^{k} = ST_{j'}^{k}$, then $t_{i'} \leq t_{j'}$, $i' \in N, j' = n+1, n+2, \ldots, m, k \in p$ (14)

Formula (8) aims to minimize the total truck usage cost, total time delay cost and the time penalty cost. Formula (9) ensures that the number of trucks used does not exceed the upper limit of resources; Formula (10) ensures that both the starting and end points of the truck path are the drop and pull center; Formula (11) ensures that each task is performed once only by one truck; Formula (12) ensures that the working time of each truck does not exceed the work cycle time limit; Formula (13) represents the time recurrence relation when the truck performs two consecutive tasks; Formula (14) means that the empty trailer task for each truck is before the heavy trailer task.

2.5.2 Generation of initial solution

Most provinces ban hazardous chemicals from 0 to 6. Assuming that the working time of the truck drivers is calculated from 9:00 am. The time of 9:00 am is expressed as 0. The time of 10:00 am is expressed as 60. The drivers work for 8 hours each day, therefore, the time of 5:00 pm is expressed as 480. Time t is a number between 0~480.

Sequence the task M from early to late according to the smaller value of the time window, form the task set φ. The steps for specific heuristic rules are as follows:

Step 1: The set L represents the unfinished task, set the initial value L=M, task number i'=1(i'∈φ), truck number k=1(k∈P);

Step 2: Randomly select a task i' from L, determine whether the task i' added to the task sequence of the truck k can meet the time window requirements of the task. If yes, the task i' is added to the end of the task sequence of the truck k, set L=L/ i', perform Step 3; if not, set k=k+1, perform Step 2.

Step 3: Determine whether L has become an empty set, if yes, stop the calculation and output the initial solution; otherwise, set i'= i'+1, and perform Step 2.

2.5.3 Generation of initial solution

Step 1: Name the task set φ as task 1, task 2... task n; truck k starts from task i';

Step 2: When task i'meets the requirements of the task time window and the operating time of truck k, add task i' to the travel path of truck k, check whether all the tasks are completed. If yes, go to Step 4; otherwise, i'= i'+1, go back to Step 2. When the task i' does not meet the requirements of the task time window and the operating time of truck k, go to Step 3.

Step 3 :k=k+1, go to Step 2.

Step 4: Compare the cost of the truck to complete all the tasks with the cost of the initial plan. If the cost is lower than the initial cost, use the new plan to replace the initial plan.

Step 5: Go back to Step 1 to obtain a new scheduling plan, compare the cost of the new scheduling plan with the cost of the recorded initial plan, if the termination condition is met, output the current solution as the optimal solution (the termination condition is that a consecutive number of new solutions are not accepted).

3. Models and Methods

There are totally 13 nodes in the area, which are represented by the letters A, B, C, D, E, F, G, H, I, J, K, L and M, respectively. The hazardous chemicals central yard is represented by O. This paper selects 47 hazardous chemicals tasks in the area on the same day for this study.

The average speed V of the truck is 45km/h, the daily operating cycle T is 8 hours, the daily usage cost of the truck is RMB400/truck, the unit time cost is RMB60 /hour, penalty coefficients α, β are 2. The distance between the points is shown in Table 1. Heavy trailer task and time window are shown in Table 2.

Table 1: Distance between the points (unit: m)

	A	B	C	D	E	F	G	H	I	J	K	L	M
O	11385210451185124374322751342110833158702204630274115237469 8832												
A	0	13248151802342627945160082225310091114202156310091148871811 3											
B		0	1569815008156292915330929306027245 9229 107642694523236										
C			0	128342201124944178021500820528241165917 192688435									
D				0	102473679430308250472223519027141113180920648								
E					0	43125396753524222184138692087339416302 39							
F						0	180442611726703376052271871 42 21632						
G							0	9919	32775402272040711213959 1				
H								0	3453539158200791980379 70				
I									0	11489147322632426651			
J										0	197863601832137		
K											0	1845812489	
L												0	14749
M													0

Table 2: Hazardous chemicals heavy trailer task and time window

Task	(i→j)	Hard time window	Soft time window	Task	(i→j)	Hard time window	Soft time window
Task 10	M→F	[174,204]	[144,234]	Task 29	B→K	[285,315]	[255,345]
Task 11	M→F	[128,158]	[98,188]	Task 30	J→K	[116,146]	[86,176]
Task 12	M→F	[200,230]	[230,260]	Task 31	B→I	[228,258]	[198,288]
Task 13	M→J	[203,233]	[173,263]	Task 32	G→F	[47,77]	[17,107]
Task 14	F→J	[220,250]	[190,280]	Task 33	G→A	[139,169]	[109,199]
Task 15	F→G	[4,34]	[0,74]	Task 34	G→A	[159,189]	[129,219]
Task 16	F→B	[79,109]	[49,139]	Task 35	G→E	[313,343]	[283,373]
Task 17	F→B	[207,237]	[177,267]	Task 36	G→K	[257,287]	[227,317]
Task 18	J→L	[252,282]	[222,312]	Task 37	G→K	[166,196]	[136,226]
Task 19	J→F	[218,248]	[188,278]	Task 38	L→G	[416,446]	[386,476]
Task 20	J→H	[338,368]	[308,398]	Task 39	L→K	[330,360]	[300,390]
Task 21	J→A	[235,265]	[205,295]	Task 40	L→K	[306,336]	[276,366]
Task 22	J→A	[68,98]	[38,128]	Task 41	L→K	[164,194]	[134,224]
Task 23	J→A	[31,61]	[1,91]	Task 42	A→K	[107,137]	[77,167]
Task 24	C→L	[59,89]	[29,119]	Task 43	A→K	[87,117]	[57,147]
Task 25	B→D	[57,87]	[27,117]	Task 44	D→K	[56,86]	[26,116]
Task 26	B→H	[102,132]	[72,162]	Task 45	H→K	[305,335]	[275,365]
Task 27	B→A	[246,276]	[216,306]	Task 46	H→K	[403,433]	[373,463]
Task 28	B→A	[277,307]	[247,337]	Task 47	H→K	[22,52]	[0,82]

3.1 Solution for empty trailer scheduling

The supplied quantity of empty trailers at A, D, E, G, I, K, L, N, O node is 3,3,2,1,1,1,2,3,18. The demand quantity of empty trailers at B,C,F,H,J,M node is 2,1,1,2,1,2.The solution results of the first stage of empty trailer scheduling obtained through programming are as follows: (A,B,G）={ (O, M, 2), (G, H, 1), (I, B, 1), (A, H, 1), (K, B, 1), (O, C, 1), (E, J, 1), (L, F, 1)}.

Run the second stage of the empty trailer solution; the empty trailer scheduling for the tasks K→B, G→H, E→J, I→B, L→F are replaced by the empty trailers generated by other heavy trailer tasks.

3.2 Solution for hazardous chemicals truck-and-trailer transportation scheduling tasks

Add the empty trailer tasks to the list of heavy trailer transport tasks; the total transport tasks are obtained.

This paper uses C language for programming in the Microsoft Visual Studio 2013 development platform.

Run the truck-and-trailer transportation scheduling program, the results are in Table 3.

A total of 5 trucks are needed. All tasks are completed and the total time spent is 2106.06 minutes. The programmer ends.

Table 3: Hazardous chemicals vehicle trajectory in Truck-and-trailer transportation

Truck	Tasks	Route	current vehicle operating cost (Unit: CNY)
1	1→2→43→16→11→42→19→35→46	O→M→O→M→A→K→F→B→M→F→A→K→J→F→G→E→H→K→O	1,040.25
2	44→25→30→5→21→29→14→40→39	O→D→K→B→D→J→K→A→H→J→A→B→K→F→J→L→K→L→K→O	2172.05
3	7→23→24→33→41→13→28→45→18→38	O→C→J→A→C→L→G→A→L→K→M→J→B→A→H→K→J→L→G→O	3021.9
4	47→32→26→34→36→31→27→20	O→H→K→G→F→B→H→G→A→G→K→B→I→B→A→J→H→O	3857.79
5	15→22→37→10→17→12→20	O→F→G→J→A→G→K→M→F→B→M→F→O	4607.17

3.3 Comparative analysis

Set the average speed V of a truck is 45 km/h, the daily operating cycle T is 8 hours, the daily usage cost of a truck is RMB 300/truck, the unit time cost is RMB60 / hour and the penalty coefficients α,β are 2.When the area do not adopt truck-and-trailer transportation, the average handling efficiency is low. If calculated according to the average loading and unloading time of 30 minutes for each vehicle, using the above algorithm, a total of 10 ordinary trucks will be needed for the tasks on the specific day. And the total time spent is 3396.06 minutes. It has been calculate that truck-and-trailer transportation program can reduce the number of the vehicles performing tasks by 50%, reduce total time consumption by 38% and total cost by 40.6%, which validates the effectiveness of the model and algorithm.

4. Conclusions

(1) Implementation of truck-and-trailer transportation can reduce the number of vehicles, the transport time and the vehicle operating cost.
(2) The truck-and-trailer transportation scheduling model with empty trailer task is established in an actual transport network of an area, and the empty trailer task and heavy trailer task are discussed together, which can provide a decision-making reference for scheduling personnel to establish truck-and-trailer transportation plans.
(3) Future studies will need to consider the truck-and-trailer transportation scheduling in multiple yards and vehicle models. Future studies will need to consider more types of hazardous chemicals.

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