Simulation Evaluation and Analysis of Heavy-load Train Maintenance Mode Based on Petri Net

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Abstract. In China's comprehensive transportation system, railway is an important mode of transportation, and heavy-load railway is a large-capacity transportation channel, which can quickly improve efficiency and relieve the capacity of railway transportation. The efficiency and synergistic capability of each connecting point of heavy-haul railway determines the success or failure of the whole system. In this paper, two different maintenance modes, "planned repair" and "unit centralized repair", are used to discuss the turnround procedure of rolling stock and the empty wagon's operation procedure respectively. The Petri net model of the empty wagon’s operation procedure under different maintenance modes is established, and the simulation is completed by Visual Object Net++ software. The results show that "unit centralized repair" is beneficial to compress the operation time and accelerate the turnround of rolling stock.

1. Introduction
The heavy-load railway transport has the advantages of high load capacity, large capacity and low cost. The development of heavy-load railway transport can improve transport capacity, realize scale operation and improve transport efficiency. It is a way to achieve high-quality development of transport and provides a strong support to promote the increase of railway freight transport and improve transport support capacity. The heavy-load railway transport system can be seen as a series of the gathering subsystem, the channel subsystem and the distribution subsystem. The gathering subsystem is mainly composed of the loading station, the gathering line and the technical station. The technical station sends empty cars to the loading station, and after the empty cars are loaded at the loading station, they are assembled at the technical station and sent to the unloading station.

In this procedure, the problem of empty wagon maintenance is involved. At present, China's railways mostly adopt the mode of "planned repair", that is, the planned preventive repair is mainly based on "daily inspection and regular maintenance". With the continuous upgrading of vehicle technology and equipment, the service life and reliability of vehicle parts have been greatly improved. Moreover, due to the different use efficiency of trucks, the actual technical status of vehicles during regular maintenance is also different. The phenomenon of "cure without disease" is common, resulting in the waste of maintenance costs. For heavy-load transportation of ten thousand tons, especially for some vehicles with high turnover frequency and aggravated wear, unified maintenance is conducted according to the time cycle, which leads to some vehicles "running with illness" and causes hidden danger of operation safety. It has become the common goal of domestic railway freight car maintenance industry to find a more targeted and more economical maintenance way to avoid "excessive repair" and "insufficient repair".

The mode of "unit centralized repair" is a new mode of "fixed vehicle grouping, fixed train number, fixed cycle crossing, fixed running time and fixed maintenance cycle" for unit trains of heavy-load
railway. In this mode, the vehicle technology state is basically the same, can quickly and accurately locate the fault, fast maintenance and batch replacement of parts, fault disposal is more thorough. To realize the whole train maintenance into the train, the precise repair of the whole train, the whole train departure, improve the maintenance efficiency and accuracy of railway self-provided freight cars. In addition, through the comprehensive inspection and maintenance of vehicle faults by the listed unit, the amount of train inspection and temporary repair is reduced, the work pressure of train inspection is effectively relieved, the time of train technical inspection is compressed, and the transportation efficiency is greatly improved. In this mode, rolling stock maintenance does not require marshalling operation, which greatly releases the hump capability. Therefore, the adoption of the "unit centralized repair" mode is beneficial in reducing the turnaround time of the rolling stock and improving the efficiency of the vehicle operation.

2. Analysis of average rolling stock turnaround time of heavy-load train under different maintenance modes

2.1. Turnaround procedure of heavy-load train’s rolling stock under the "planned repair" mode
Under the condition of planned maintenance, different rolling stocks of the same heavy-load train have different requirements for maintenance in the same period of time due to different service efficiency of wagons. Therefore, when the empty heavy-load trains arrive at the combination station, there are still a large number of trains that need to be unpacked through the hump. The vehicles to be repaired are taken off for maintenance and sent to the loading station again through the departure yard after being reorganized. From the point of view of the train, the operation procedure that affects the rolling stock turnaround time is mainly the disintegration and marshalling operation of the combination station, so in the turnaround procedure of heavy-load train’s rolling stock under the "planned repair" mode, the maintenance operation time of the vehicles to be overhauled in the depot can be ignored.

2.2. Turnaround procedure of heavy-load train’s rolling stock under the "unit centralized repair" mode
In the mode of "unit centralized repair", after the completion of a certain amount of transportation mileage, the whole train is overhauled without disintegration and marshalling operation. However, due to the maintenance of the whole train, the average rolling stock turnaround time is mainly affected by the maintenance time, so the overhauling operation procedure should be considered in the turnaround procedure of the heavy-load train’s rolling stock under the mode of "unit centralized repair". The turnaround procedure of heavy-load train rolling stock under the mode of "unit centralized repair".
2.3. Comparative analysis of turnround procedure of heavy-load train’s rolling stock under different maintenance modes

Comparing and analyzing the above two maintenance modes, it is found that the heavy-load vehicles are not overhauled under the heavy-load condition, so the two procedures are basically the same during the operation of the heavy-load vehicles. This paper mainly discusses the influence of different maintenance modes on the turnround time of rolling stock heavy-load train, and focuses on the empty train operation procedure for the differences between ordinary heavy-load trains and whole train heavy-load trains. In the procedure of empty wagons running, the main difference lies in the disintegration and marshalling operation and maintenance operation.

At the same time, for the whole train with heavy load, its vehicles are fixed, so its rolling stock’s turnround procedure is periodic, with a cycle from the end of one overhaul to the end of the next overhaul. For ordinary heavy-load trains, because the combined vehicles are not fixed and the maintenance time is not fixed, there is no obvious periodicity. Operation cycle pairs of heavy-load trains under different maintenance modes are shown in the following figure. In this paper, the influence of different maintenance modes on the average turnround time of heavy-load trains is analyzed based on the operation cycle of the whole train.
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Figure 2 Comparison of operation cycle of heavy-load trains under different maintenance modes.

3. Modeling of empty wagon’s operation procedure of heavy-load train under different maintenance modes

Combined with the characteristics of empty train operation procedure, the empty wagon’s operation procedure model of heavy-load train is established based on Petri net theory, and the simulation is completed by using Visual Object Net++ software.

3.1. Modeling of empty wagon’s operation procedure of heavy-load trains under "Planned Repair" mode

The empty operation procedure model of heavy-load train under the mode of "planned repair" is shown in the following figure. From left to right are unloading station, loading station and combination station.

Figure 3 Empty wagon’s operation procedure model of heavy-load train under "planned repair" mode.

In the above model, the explanation of each place and transition is shown in the following table:

| Place  | meaning                                      | Transition | meaning                                      |
|--------|-----------------------------------------------|------------|-----------------------------------------------|
| S1     | Unloading station                             | C1         | Departure operation                           |
| S2     | Combination station                           | C2         | Arrival operation                             |
| S3     | Determine whether to disintegration and marshalling | C3        | Disintegration and marshalling                |
| P1     | Prepare for disintegration and marshalling operation | C4        | No disintegration and marshalling             |
| P11    | Prepare for departure                         | C5         | Disintegration and marshalling operation      |
| S4     | Loading station                               | C6         | Departure operation                           |
| S5     | End                                           | C7         | Arrival operation                             |

Further model the sub-procedure C5 of disintegration and marshalling operation, as shown in the following figure. From left to right are empty wagon arrival yard, hump, shunting track, lead line and combination station.
In the above model, the explanation of each place and transition is shown in the following table:

**Table.2** Description of variables in the sub-procedure model of disintegration and marshalling operations.

| Place   | meaning                      | Transition | meaning                                           |
|---------|------------------------------|------------|---------------------------------------------------|
| P2      | Throat area occupied         | T1         | Start disintegration and marshalling operation    |
| P3      | Throat area unoccupied       | T2         | Throat area occupied to unoccupied                |
| P4      | Hump occupied                | T3         | Wagon coupling operation                          |
| P5      | Hump unoccupied              | T4         | Hump occupied to unoccupied                       |
| P6      | Shunting track               | T5         | disintegration operation                          |
| P7      | shunting engine occupied     | T6         | wagon detention                                   |
| P8      | shunting engine unoccupied   | T7         | shunting engine occupied to unoccupied            |
| P9      | Lead line occupied           | T8         | Wagon coupling operation                          |
| P10     | Lead line unoccupied         | T9         | Lead line occupied to unoccupied                  |
|         |                              | T10        | The train is running on the lead line             |

### 3.2. Modeling of empty wagon’s operation procedure of heavy-load trains under "unit centralized repair" mode

The empty wagon’s operation procedure model of heavy-load train under the mode of "unit centralized repair" is shown in the following figure. From left to right are unloading station, loading station and combination station.

**Figure.5** Empty wagon’s operation procedure model of heavy-load train under "unit centralized repair" mode.

In the above model, the explanation of each place and transition is shown in the following table:

**Table.3** Variable description of empty wagon’s operation procedure model of heavy-load trains under "unit centralized repair" mode.

| Place | meaning            | Transition | meaning                        |
|-------|--------------------|------------|--------------------------------|
| R1    | Unloading station  | B1         | Departure operation in unloading station |
| R2    | Combination station| B2         | Arrival operation in combination station |
Further model the sub-procedure B5 of disintegration and marshalling operation, as shown in the following figure. From left to right are empty wagon arrival yard, lead line, car depot, lead line and empty wagon departure yard.

![Figure 6: Sub-procedure model of maintenance operation.](image)

In the above model, the explanation of each place and transition is shown in the following table:

| Place meaning                  | Transition meaning                  |
|-------------------------------|-------------------------------------|
| Q2 Throat area occupied       | K1 Start maintenance operation      |
| Q3 Throat area unoccupied     | K2 Throat area occupied to unoccupied |
| Q4 Lead line occupied         | K3 Wagon coupling operation         |
| Q5 Lead line unoccupied       | K4 Lead line occupied to unoccupied |
| Q6 Car depot                  | K5 The train is running on the lead line |
| Q7 Shunting engine occupied   | K6 Maintenance operation of the whole train |
| Q8 Shunting engine unoccupied | K7 Shunting engine occupied to unoccupied |
| Q9 Lead line occupied         | K8 Wagon coupling operation         |
| Q10 Lead line unoccupied      | K9 Lead line occupied to unoccupied |
|                               | K10 The train is running on the lead line |

4. Model analysis and simulation of the empty wagon’s operation procedure of heavy-load trains under different maintenance modes

4.1. Analysis of the empty wagon’s operation procedure model of heavy-load trains under different maintenance modes

After the Petri net model is established, the rationality of the model needs to be analyzed. Based on the mathematical properties of Petri nets, the rationality of the model structure and whether there are potential problems are analyzed. In the Petri net model, the connection of elements can only exist between the place and the transition. If there is a connection between the place and the place, there is a connection between the transition and the transition, or there are isolated elements, redundant and incomplete information are regarded as model errors. Using this as a standard to check the model. After inspection, the models established in the previous section meet the specifications.

Then, use the analysis method based on the incidence matrix to analyze the mathematical characteristics of the model established in the previous section. T-invariant refers to the procedure of a set of transitions from a certain mark to the original mark through enabling, that is, a cyclic procedure.
There is no cyclic structure in the above Petri net model, and the T-invariant is 0. The S-invariant is used to study the activity and boundedness of Petri nets, etc., and represents the weighted conservation of token numbers in some positions. The following study analyzes the mathematical properties of the Petri net model of the port station operation procedure, and obtains the S-invariant of each model. According to the calculation results, the nature of the Petri net model is judged.

An association matrix is established for the empty wagon’s operation procedure model of a heavy-load train in the "planned repair" mode, and the S-invariant is solved to obtain the association matrix as:

\[
A = \begin{pmatrix}
-1 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & -1
\end{pmatrix}
\]

According to \( A^T X = 0 \), S-invariant is:

\[
X_1 = (1,1,1,1,1,1)^T \\
X_2 = (1,1,1,0,1,1)^T
\]

In the S-invariant, the component of token flowing through this place is 1, otherwise it is 0. As long as the token distribution satisfies the conditions, the model is bounded and conserved in structure. At the same time, the number of S-invariants is fixed, which is equal to the number of free variables in the linear equation. The S-invariant can also be transformed into the following form here:

\[
X_1 = (S1,C1,S2,C2,S3,C3,P1,C5,P11,C6,S4,C7,S5)^T \\
X_2 = (S1,C1,S2,C2,S3,C4,P11,C6,S4,C7,S5)^T
\]

Therefore, the route taken by Token in the empty wagon’s operation procedure model of the heavy-load train in the "planned repair" mode may be:

1. S1,C1,S2,C2,S3,C3,P1,C5,P11,C6,S4,C7,S5.
2. S1,C1,S2,C2,S3,C4,P11,C6,S4,C7,S5.

According to the definition of Petri net model activity, boundedness and accessibility, the empty wagon’s operation procedure model of heavy-load trains in the "planned repair" mode is active, bounded and reachable. Similarly, analysis of other models shows that the model is reasonable.

### 4.2. Time parameters of the empty wagon’s operation procedure model of heavy-load trains under different maintenance modes

#### 4.2.1. Petri net model time parameters of the empty wagon’s operation procedure of heavy-load train in "planned repair" mode

**① Top model**

The operation time and proportion results of each link in the empty wagon’s operation procedure of heavy-load trains under the mode of "planned repair" are shown in the following table.

| Place          | Procedure                          | Time(min) | Proportion |
|---------------|------------------------------------|-----------|------------|
| Unloading station | Departure operation               | 25        |            |
| Combination station | Arrival operation                 | 35        |            |
|                | Disintegration and marshalling     | 0         | 7%         |
② Disintegration and marshalling job sub-procedure model

The operation time and proportion results of each link in the disassembly sub-procedure are shown in the following table:

Table 6. Operation time of each link in marshalling sub-procedure

| Place                 | Procedure                          | Time(min) |
|-----------------------|------------------------------------|-----------|
| Empty wagon arrival yard | Start disintegration and marshalling operation | 30        |
|                       | Throat area occupied turn to unoccupied | 0-240     |
|                       | Wagon coupling operation            | 30        |
| Hump                  | Hump occupied turn to unoccupied    | 0-180     |
|                       | Disintegration operation            | 90        |
| Shunting track        | Wagon detention                     | 280       |
|                       | Shunting engine occupied to unoccupied | 0-90     |
| Shunting track        | Wagon coupling operation            | 30        |
| Lead line             | Lead line occupied to unoccupied    | 0-20      |
|                       | The train is running on the lead line | 20        |

③ Average initiation velocity of each time transition of the model

After the delay of time transition in the model, it is necessary to obtain the average induced velocity $\lambda$ of transition according to the delay time of transition. Since the average induced velocity $\lambda$ represents the average initiation times of transition in unit time, it can be assumed that the unit time is "1". At the same time, because in the above model, part of the transition time obeys the uniform distribution in the $\{t_{\min}, t_{\max}\}$, in order to obtain the average induced velocity of transition $\lambda$, the expected value is selected as the transition time. Then the average triggering rate table of each time transition in the model can be obtained, as shown in the following two tables:

Table 7. Numerical table of average induced velocity of each transition in top-level model.

| Transition(T) | Delay of the time(min) | Induced velocity($\lambda$) |
|---------------|------------------------|-----------------------------|
| C1            | 25                     | 0.0400                      |
| C2            | 35                     | 0.0286                      |
| C6            | 40                     | 0.0250                      |
| C7            | 35                     | 0.0286                      |

Table 8. Numerical table of average induced velocity of disintegration and marshalling operation sub-procedure model.

| Transition(T) | Delay of the time(min) | Induced velocity($\lambda$) |
|---------------|------------------------|-----------------------------|
| P1            | 10                     | 0.0100                      |
| P2            | 40                     | 0.0250                      |
| P3            | 20                     | 0.0500                      |
| P4            | 5                      | 0.2000                      |
| P5            | 30                     | 0.0333                      |
| P6            | 90                     | 0.0111                      |
| P7            | 12.5                   | 0.0800                      |
| P8            | 20                     | 0.0500                      |
| P9            | 5                      | 0.2000                      |
| P10           | 20                     | 0.0500                      |

4.2.2. Petri net model time parameters of the empty wagon’s operation procedure of heavy-load trains in "unit centralized repair" mode
① Top model
The operation time and proportion results of each link in the empty operation procedure of heavy-load trains under the mode of "unit centralized repair" are shown in the following table:

| Operation place   | Operation       | Operation time (min) | proportion |
|-------------------|-----------------|----------------------|------------|
| Unloading station | Departure       | 25                   |            |
|                   | operation       |                      |            |
| Combination station| Arrival         | 35                   |            |
|                   | operation       |                      |            |
|                   | Maintenance     | 0                    | 0.3%       |
|                   | No maintenance  | 0                    | 99.7%      |
|                   | Departure       | 40                   |            |
|                   | operation       |                      |            |
| Loading station   | Arrival         | 35                   |            |
|                   | operation       |                      |            |

② Disintegration and marshalling job sub-procedure model
The operation time and proportion results of each link in the disassembly sub-procedure are shown in the following table:

| Operation place          | Operation                        | Operation time (min) |
|--------------------------|----------------------------------|----------------------|
| Empty wagon arrival yard | Start maintenance operation      | 10                   |
|                          | Throat area occupied to unoccupied | 0-240               |
|                          | Wagon coupling operation         | 30                   |
| Lead line                | Lead line occupied to unoccupied | 0-20                 |
|                          | The train is running on the lead line | 20                  |
| Car depot                | Maintenance operation of the whole train | 720               |
|                          | Shunting engine occupied to unoccupied | 0-80              |
|                          | Wagon coupling operation         | 30                   |
| Lead line                | Lead line occupied to unoccupied | 0-20                 |
|                          | The train is running on the lead line | 20                  |

③ Average induced velocity of each time transition of the model
Similarly, the average induced velocity table of each time transition in the model can be obtained, as shown in the following two tables:
Table.11 Numerical table of average initiation rate of each transition in top-level model.

| Transition(T) | Delay of the time(min) | Induced velocity(λ) |
|--------------|------------------------|---------------------|
| B1           | 25                     | 0.0400              |
| B2           | 35                     | 0.0286              |
| B6           | 40                     | 0.0250              |
| B7           | 35                     | 0.0286              |

Table.12 Numerical table of average initiation rate of disintegration and marshalling operation sub-procedure model.

| Transition(T) | Delay of the time(min) | Induced velocity(λ) |
|--------------|------------------------|---------------------|
| Q1           | 10                     | 0.0100              |
| Q2           | 40                     | 0.0250              |
| Q3           | 20                     | 0.0500              |
| Q4           | 5                      | 0.2000              |
| Q5           | 20                     | 0.0500              |
| Q6           | 720                    | 0.0014              |
| Q7           | 12.5                   | 0.0800              |
| Q8           | 20                     | 0.0500              |
| Q9           | 5                      | 0.2000              |
| Q10          | 20                     | 0.0500              |

4.3. Average operating time of empty wagon’s operation procedure of heavy-load trains under different inspection modes

According to the simulation results, the average operation time of the empty wagon’s operation procedure under different maintenance modes of heavy-load trains can be obtained, as shown in the following table:

Table.13 Average operation time of empty wagon’s operation procedure under different maintenance methods for heavy-load trains.

| Mode                        | Name                  | Average operation time(min) |
|-----------------------------|-----------------------|-----------------------------|
| planned repair              | marshalling           | 745                         |
|                             | The operation of empty wagon | 187.15                     |
| unit centralized repair     | maintenance           | 1010                        |
|                             | The operation of empty wagon | 138.03                     |

4.4. Average turnaround time of heavy-load train under different maintenance modes

The above model calculates the average operation time of the empty train operation procedure of heavy-load trains under different maintenance modes, and the average turnaround time of the train rolling stock is composed of the heavy-load train operation time, empty operation time and train in transit time.

Taking the Datong-Qinhuangdao Railway as an example, the average turnaround time of the rolling stock of heavy-load trains under different maintenance methods is obtained, as shown in the following table.

Table.14 Description of variables in the sub-procedure model of maintenance operations.

| Mode                        | Average operation time for loaded wagon(min) | Average operation time for empty wagon(min) | Average travel time of the train(min) | Average turnaround time for rolling stock(min) |
|-----------------------------|---------------------------------------------|---------------------------------------------|--------------------------------------|-----------------------------------------------|
| Planned repair              | 130                                         | 187                                        | 4050                                 | 4333                                          |
| Unit centralized repair     | 130                                         | 138                                        | 4050                                 | 4318                                          |
| Average shorten time(min)   | --                                          | --                                         | --                                   | 49                                            |
Compared with the "planned repair" mode, the "unit centralized repair" mode can compress 49 minutes per train during a turnaround procedure. Taking Hudong Railway Station of Datong-Qinhuangdao Railway as an example, it can compress 114.3 train hours per day on average.

5. Conclusion
This paper mainly studies the influence of different maintenance modes on the train turnaround time and vehicle operating efficiency of heavy-load trains. The results show that compared with the current maintenance mode of "planned repair", the "unit centralized repair" mode can achieve an average compression of 0.82 vehicle-hours per train and 115 vehicle-hours per day in terms of the train turnaround time of heavy-load trains. In terms of vehicle operating efficiency, due to the significant compression of maintenance time, the vehicle operating efficiency can be greatly improved. Therefore, the implementation of the mode of "unit centralized repair" is of great significance to the capacity improvement of heavy-haul transportation and other heavy-haul rail track in the future.

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