Simulation of Train Energy Consumption Based on UAS

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Abstract. High-speed trains are all electric locomotives. During the operation of EMU, the power supply network will be cut off due to bad weather, high voltage cable dropping off, catenary failure and power supply system failure, which will cause the whole train line to stop running and a large number of passengers to stay, causing serious harm. Therefore, on the vehicle energy management simulation platform UAS, a large number of simulations have been carried out for different vehicle energy storage, traction constant speed and operation modes, and the effects of initial battery power, constant speed and operation mode on traction energy consumption, auxiliary energy consumption and train operation time have been explored. The simulation has good application prospects in the future intelligent high-speed railway construction.

1. Foreword
In recent years, the construction of Intelligent Beijing-Zhangjiakou Intercity Railway has begun, aiming at creating a safer, more intelligent, more reliable and more comfortable high-speed train system. One of the important tasks in the construction of this project is to use on-board energy storage device to realize emergency self-running of trains after the loss of power from traction network, so that trains can arrive a nearby station, keeping passengers safe.

When EMU is in an emergency state, all the energy of the train is provided by the on-board energy storage device. During the whole process of emergency disposal, not only the electric energy needed for air conditioning (ventilation) and lighting, but also for traction transmission system. However, due to the limitation of installation space and energy density, the capacity of on-board energy storage devices is limited. So the energy consumption of auxiliary system and emergency traction operation put forward the demand for energy management from two dimensions of time and space respectively. In this study, a reasonable train emergency running strategy is planned by considering the geographical conditions, two-way arrival distance, train parameters and characteristics, energy management strategy of auxiliary system and capacity of on-board energy storage system, so as to achieve the optimal parking guidance. Optimized emergency travel plan can not only avoid subjective decision-making errors caused by driver's artificial estimation, but also improve the life of energy storage devices directly benefiting from energy-saving operation. With the construction of Sichuan Tibet Railway, trains will pass through countless tunnels, mountainous areas, no man's land and many harsh terrain. Once the train loses power from traction network unexpectedly, the emergency self-running of trains becomes extremely important.
2. UAS introduction

UAS [1,2,3,4,5,6,7,8,9,10] refers to the driver's guidance device for emergency operation of EMU, which is called Urgent Operation Assistant System. It is an intelligent control guidance device that prompts the driver's best emergency response plan in an appropriate way when the traction network fails. UAS has four characteristics: 1. Hot standby operation. When the traction network fails, once the driver confirms traction network fault, the train can immediately enter the emergency disposal guidance mode in time. 2. Real-time optimization calculation. According to the capacity level of energy storage device, based on the general global fast optimization algorithm, the dynamic optimization solution of emergency operation is realized. All recommended schemes are given, including the corresponding running direction, running distance and time consumption of each scheme, the estimated residual electricity situation, the proposed speed level and the control scheme. When one of the following situations occurs, the optimization calculation update is triggered immediately: (1) during emergency operation preparation period, the change of power consumption exceeds a certain extent. (2) During emergency operation period, the deviation between actual operation and planning is too large, resulting in excessive time deviation. (3) During emergency operation period, the deviation between actual operation and planning is too large, resulting in excessive power consumption. 3. Interactive customization to improve flexibility. Drivers can configure relevant requirements according to their needs: (1) Time requirement. After coordination between vehicle and ground, input instructions to meet the requirements of line operation. (2) Direction requirement. After coordination between vehicle and ground, input appropriate instructions. In addition, reverse traveling requires no trains in the current section. (3) Speed limit settings. When there is no effective signal output in the ground train control system, the speed limit should be set when the train is running in block between stations. 4. Voice cues. On the one hand, the key information is highlighted graphically through HMI, and at the same time, the voice prompt gives timely guidance to avoid distraction of drivers and improve the safety of train operation.

When traction network fails, if the distance between stations is large and the steep ramps in the forward section are long, the abnormal travelling in the section is often unavoidable. At this time, the train enters the emergency preparedness stage. In the preparation stage of emergency disposal, communication is needed between the train and the ground, and a certain signal preparation time is needed for the train to run in an emergency. In this stage, UAS will optimize the emergency operation speed curve, determine the emergency operation direction, moderate operation time, operation conditions and so on to give guiding suggestions to drivers to refer to according to the real-time power consumption of the vehicle energy storage system, the line conditions in both directions (including ramp, speed limit, operation distance, etc.). These guiding suggestions will serve as the basis for communication between drivers and station dispatching. These guiding suggestions will serve as the basis for communication between drivers and station dispatching.

The length of emergency operation time directly affects the energy consumption of auxiliary system. Under the same line conditions, the speed of train directly determines the energy consumption of train traction. The higher the overall speed of train, the higher the energy consumption, but the shorter the operation time. As one of the key constraints, the capacity of on-board energy storage system restricts the sum of the two major power consumption. Therefore, the best scheme is the comprehensive optimization of emergency operation time, emergency operation speed and operation sequence.

With the passage of time in the preparation stage of emergency operation, the cumulative energy consumption of auxiliary system increases and the power consumption of vehicle-mounted energy storage system decreases. Therefore, in the preparation stage of emergency disposal after parking, it is necessary to update the optimized proposal timely according to the power consumption of vehicle-mounted energy storage system. For example:
Especially, when the emergency operation preparation phase is time-consuming due to ground dispatching and other reasons, it may be difficult to ensure the incoming parking of the remaining electricity. At this time, the proposed scheme may be downgraded to the nearest parking operation optimization scheme considering the auxiliary energy consumption demand.

3. Model of train emergency energy consumption

The preparation time of emergency traction should be considered in 20 minutes, and the total power consumption is 16 kWh (mainly for lighting, emergency ventilation, etc.) under the normal mode after bow lowering.

Table 1. Electricity consumption of the whole train (AV380V).

|                       | Power consumption(kW) | Vehicle Battery Power Supply(kW) |
|-----------------------|-----------------------|----------------------------------|
| Air conditioning outage| 34.0                  | 37.8                             |
| Air conditioning refrigeration | 88.5             | 98.3                             |
| Air conditioning heating          | 135.5                | 150.6                            |

Traction energy consumption $Q_{tra}$, auxiliary energy consumption $Q_{aux}$, total energy consumption $Q_{tot}$, satisfy the following equations respectively:

$$Q_{tra} = F_i \times S_d \times \eta_i + 3600 \div \eta_2$$  \hspace{1cm} (1)

$$Q_{aux} = P_{aux} \times S_i + 3600$$  \hspace{1cm} (2)

$$Q_{tot} = Q_{tra} + Q_{aux}$$  \hspace{1cm} (3)

Considering that the traction characteristic is unstable when the battery power is less than 30%, 30% of the energy is reserved for air conditioning:

$$Q_{aux} = 245 \times soc - Q_{tot} - 245 \times 0.3 - 16$$  \hspace{1cm} (4)
Energy Consumption of Air Conditioning Refrigeration $Q_{\text{cold}}$, heat Consumption of Air Conditioning $Q_{\text{warm}}$ satisfy the following equations respectively:

$$
\begin{align*}
Q^i_{\text{cold}} &= T_{\text{tol}} (98.33 - 37.8) \div 3600 \\
Q_{\text{cold}} &= \min(Q^i_{\text{cold}}, Q_{\text{Air}}) \\
Q^i_{\text{warm}} &= T_{\text{tol}} (150.6 - 37.8) \div 3600 \\
Q_{\text{warm}} &= \min(Q^i_{\text{warm}}, Q_{\text{Air}})
\end{align*}
$$

Maximum refrigeration time of air conditioning $T_{\text{cold}}$ and maximum heating time of air conditioning $T_{\text{warm}}$ satisfy the following equations respectively:

$$
\begin{align*}
T_{\text{cold}} &= (Q_{\text{Air}} - Q_{\text{cold}}) + 98.33 \times 3600 + T_{\text{tol}} (Q_{\text{Air}} \geq Q_{\text{cold}}) \\
T_{\text{cold}} &= Q_{\text{Air}} + (98.33 - 37.8) \times 3600 (Q_{\text{Air}} < Q_{\text{cold}}) \\
T_{\text{warm}} &= (Q_{\text{Air}} - Q_{\text{warm}}) + 150.6 \times 3600 + T_{\text{tol}} (Q_{\text{Air}} \geq Q_{\text{warm}}) \\
T_{\text{warm}} &= Q_{\text{Air}} + (150.6 - 37.8) \times 3600 (Q_{\text{Air}} < Q_{\text{cold}})
\end{align*}
$$

Actual refrigeration time of air conditioning $T_{\text{cold, r}}$ and the actual heating time of air conditioning is $T_{\text{warm, r}}$:

$$
\begin{align*}
T_{\text{cold, r}} &= T_{\text{cold}} < 1200 + T_{\text{all}} \\
T_{\text{cold, r}} &= 1200 + T_{\text{all}} (T_{\text{cold}} \geq 1200 + T_{\text{all}}) \\
T_{\text{warm, r}} &= T_{\text{warm}} < 1200 + T_{\text{all}} \\
T_{\text{warm, r}} &= 1200 + T_{\text{all}} (T_{\text{warm}} \geq 1200 + T_{\text{all}})
\end{align*}
$$

The residual energy consumption of trains under three conditions, i.e. unopened air conditioning, open air conditioning refrigeration and open air conditioning heating, is respectively lower than that of trains without open air conditioning:

$$
\begin{align*}
Q_{\text{soc, noair}} &= soc - (Q_{\text{Tol}} + 16) \div 245 \\
Q_{\text{soc, cold}} &= soc - (Q_{\text{Tol}} + Q_{\text{cold}}) \div 245 \\
Q_{\text{soc, warm}} &= soc - (Q_{\text{Tol}} + Q_{\text{warm}}) \div 245
\end{align*}
$$

In the above formulas:

- $F_d$: Traction force;
- $S_d$: Step size calculation;
- $\eta$: Locomotive traction efficiency;
- $\eta_2$: Battery efficiency;
- $T_d$: One-step calculation time;
$P_{aux}$: Auxiliary power of train;  
Soc: Initial battery power during traction failure;  
$T_{Tol}$: Sum of Emergency Preparedness and Emergency Travel Time;  
$T_{all}$: Emergency travel time.

4. Emergency simulation of train

4.1. Setting of simulation conditions

Considering that it is impossible to guarantee the full power reserve of on-board energy storage batteries at any time in actual operation, and in extreme cases the battery power is less, four different groups of batteries are selected for simulation; because the power of on-board batteries is limited due to the loss of traction network in emergency train, the stable traction speed of on-board batteries is low; in order to meet different needs, the simulation mode is also divided into several parts, and its equipment is used. The body conditions are shown in Table 2.

| Railway                          | Initial battery capacity(percentage) | Stable traction speed | Simulation mode                                    |
|---------------------------------|------------------------------------|-----------------------|---------------------------------------------------|
| Intelligent Beijing Zhangjiakou | 60%, 70%, 80%, 90%                 | 30km/h, 35km/hm, 40km/h | Mode1-Forward driving priority  
Model2-Energy conservation priority  
Model3-Time priority |

4.2. Simulation of train arrival

![Figure 5. Bidirectional arrival judgment under priority of energy consumption.](image)
Several simulation results are obtained by choosing different traction speeds and simulation modes under different initial electric quantities. Figure 5 is taken as an example to simulate the influence of different on-board energy storage on the two-way arrival of trains under emergency conditions when the stable traction speed is 40 km/h and the influence of different traction speed on the two-way arrival of trains under the same energy consumption. It can be seen that increasing on-board energy storage can effectively improve the two-way arrival rate of EMUs, while increasing traction speed has little effect on the two-way arrival rate.

4.3. Residual electricity prediction and simulation
When the train loses power, the self-rescue power used by the train towing to the nearest station varies with the location of the forced parking. Therefore, the choice of parking location will be particularly important. Train drivers should try their best to make the train stop at an easy-to-reach location, that is, the train from here to the station consumes less energy.

The information of each station of Beijing-Zhangjiakou intercity Railway is shown in Table 3.

| Station                                | Kilometer scale(km) |
|----------------------------------------|---------------------|
| Beijing north railway station          | 12.414              |
| Qinghe railway station                 | 23.6                |
| Shahe railway station                  | 34.142              |
| Changping railway station              | 43.32               |
| Badaling Great Wall railway station    | 68.05               |
| Donghyuan railway station              | 89.565              |
| Huailai railway station                | 110.65              |
| Xiahuayuan north railway station       | 137.95              |
| Xuanhua north railway station          | 164.51              |
| Zhangjiakou South Railway Station      | 192.37              |

In the case of forward priority and 60% energy storage, simulation is carried out on three situations: air conditioning not opened, air conditioning refrigeration and air conditioning heating. The energy consumption of EMU from different parking points is predicted.
Figure 6. Prediction charts of energy consumption and residual electricity under different primary energy storage at constant speed of 30km/h.

It is not difficult to see that the nearer the station is, the lower the energy consumption is. There are many low-energy sections in the whole line, which can be used to consider choosing this point as emergency parking section, in order to facilitate train emergency running, such as section 1, section 2, etc.

In addition, because the fluctuation of auxiliary energy consumption is relatively smooth and the relative traction energy consumption is very small, according to the figure 6, the traction energy consumption and total energy consumption can be fitted once, and the fitting results are as follows:

$$Q_{Tot} = 1.52Q_{Tri} + 4.705$$  \hspace{1cm} (10)

Its mean square error is 0.9626, which has a good fit. When one energy consumption is default, another energy consumption can be estimated approximately.

4.4. Self-walking time simulation

The traction time, air conditioning refrigeration and heating time (including train parking waiting time) of different modes, different energy storage and different speeds are simulated. Suggestions on arrival time of different parking points and air conditioning time are obtained. Taking Figure 7 as an example, the emergency operation time of 60% energy storage in different ways is simulated. Comparing the positive optimum with the energy consumption optimum, the total running time is basically the same. Between 20km and 50km of mileage standard, the actual time of air conditioning refrigeration and air conditioning heating changes little under the optimal mode of energy consumption, and the curve is relatively smooth; under the positive optimal mode, the actual time of air conditioning refrigeration and air conditioning heating changes greatly, and the curve fluctuates greatly. For example, the trough of 20 km to 30 km in kilometer scale is due to the fact that the point is very close to the next station (23.6 km mark). The actual time of air conditioning refrigeration and heating in forward priority will drop sharply, and after the station there will be a sharp rise. In addition, 60% of the energy storage in many parking places in order to arrive smoothly, had to instruct drivers to turn off the air conditioning.
5. Conclusion
The above simulation results fully illustrate the influence of initial power, constant traction speed and working mode of storage battery on traction energy consumption and auxiliary energy consumption, and provide an analysis basis for determining the energy-saving research of on-board storage battery for trains.

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