CHEMICAL ENGINEERING TRANSACTIONS
VOL. 76, 2019

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

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976152

Effects of Working Temperature on Route Planning for Electric Bus Fleets Based on Dynamic Programming

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A route planning method for the electric bus fleets (EBFs) system was proposed based on dynamic programming. It highlights the effect of working temperatures on capacity fading of batteries and route planning for EBFs. A case study was conducted to investigate the effect of varied temperature in a year on the route planning for EBFs. The results show that the optimal scheme of route planning for EBFs varies significantly with the change of working temperature. There are different choices for the specific route planning, including the number of optimal paths and the matches between the EBFs and the routes. Thus, the effect of temperature on the dynamic capacity fading of batteries should be considered when the route planning strategy is applied in a large-scale public transportation system. The operational costs of EBFs can then be reduced due to reducing replacement of the battery packs in EBFs. The proposed method provides useful guidance for the route planning for EBFs in practical applications.

1. Introduction

Lithium-ion batteries are widely used for electric vehicles (EVs) due to high energy density (Capasso et al., 2014). However, the present battery-based energy storage system commonly suffers from short cycle life and high replacement cost. The battery life can be prolonged effectively by optimizing the battery management system for the internal operations of EVs (Chia et al., 2015), and the operational costs of EVs can be reduced by route planning for the external operations of EVs (Rogge et al., 2018). However, few studies can be found to enhance energy management for batteries in EVs with both internal operations and external operations.

The performances, cycle lifetime and safety of the Lithium-ion batteries are very sensitive to temperature (Jing et al., 2018). At low temperatures, the degradation of batteries becomes particularly severe due to lithium plating on the negative electrode (Petzl et al., 2015). On the other hand, at high temperatures, the capacity fading rate of batteries may increase due to the increase in the rate of side reactions (Ping et al., 2014). With regard to the battery performances, both the loss of active materials and the loss of cyclability lead to capacity fade (Wang, 2018). The temperature fluctuation of batteries is usually inevitable because of environmental conditions and exothermic chemical reactions during charging and discharging (Waldmann et al., 2014). It is necessary to consider the influence of temperature on the operations of electric vehicles (Wang et al., 2016). Zhu et al. (2017) considered the effect of temperature on battery performances, coupling the thermal model and capacity degradation model with the battery electrical model to optimize the energy management strategy of EVs. Song et al. (2018) analysed the influence of different temperatures and battery prices on the integrated optimization of a hybrid energy storage system, including the size of supercapacitors and energy management strategy for the EV applications. The abovementioned investigations show that it is imperative to consider the influences of temperature on the operations of EVs.

Traction batteries have the most suitable working temperature. When the working temperature is too high or too low, it will aggravate the battery capacity fade and increase the number of battery replacement for EVs. Subsequently, the influence of temperature on capacity fading of batteries should be considered when the operational routes of EVs are scheduled by dynamic programming on the basis of the optimal matches between the battery capacity losses and the battery working loads.

The major objectives of this work are to combine internal operations and external operations of EVs, study the difference of battery capacity fading at different temperatures and figure out whether the optimal strategy of

Paper Received: 22/02/2019; Revised: 30/04/2019; Accepted: 02/05/2019
Please cite this article as: Wang J., Kang L., Liu Y., 2019, Effects of Working Temperature on Route Planning for Electric Bus Fleets Based on Dynamic Programming, Chemical Engineering Transactions, 76, 907-912 DOI:10.3303/CET1976152

route planning for EBFs obtained at a constant temperature is still the optimal result when the working temperature changes. The rest of this paper is organized as follows. The problem statement and relevant assumptions are described in Section 2, and the route planning strategy and the effect of temperature on capacity fading are introduced in Section 3. In order to examine the effects of temperature on the route planning for EBFs, an illustrative case study is presented in Section 4 followed by the conclusions in Section 5.

2. Problem statement

In a bus company, there are electric buses with the same specifications running on multiple bus routes. Due to the electric buses running on different routes, the daily working loads of the electric buses lead to different behaviours of battery capacity fading. Since the change of temperature has a great influence on the behaviour of battery capacity fading, it is necessary to take the change of ambient temperature into account. Then, the working loads of EVs and the behaviour of capacity fading of batteries are integrated to plan the routes for EBFs by dynamic programming. In the course of the entire lifespan of the EVs, the number of replacements of the battery can be reduced via the optimization of scheduling schemes for EBFs. The operating cost of the EBFs can therefore be reduced.

3. Route planning of electric bus fleets considering temperature changes

3.1 Route planning method for electric bus fleets

The procedure of the route planning for EBFs based on the dynamic programming method is shown in the Figure 1. At first, the scheduling for the EBFs is divided into several stages, and then the scheduling states the EBFs are enumerated, including the unscheduled state that matches the fleets with the routes by the original matching method and the scheduled state that matches the fleets with the routes by the reverse order matching strategy, in which the battery capacity fading sequence and the working load sequence of EBFs are matched in the reverse order. The reverse order matching process for the EBFs and the routes is described as follows. Firstly, the fleet sequence is arranged in a descending order in terms of battery capacity loss. Secondly, the sequence of all the routes is arranged in an ascending order in terms of the working load. Thirdly, the EBFs are matched with the routes in one-to-one pairs.
It is necessary to consider the effects of temperature on the battery capacity loss to determine the optimal scheduling scheme for the EBFs. The main variables are the percentage of battery capacity loss and the number of battery replacements. The objective function is to minimise the number of battery replacements of the entire bus system in the lifetime of electric buses. Since the number of battery replacements, the change in the battery capacity fading, and the matches between the fleets and routes can be determined for each state in each stage during the implementation of scheduling. Based on the proposed dynamic programming method, the optimal scheduling strategy for all the EBFs can be obtained by following the path backwards from the last stage to minimise the number of battery replacements over the lifespan of the EVs.

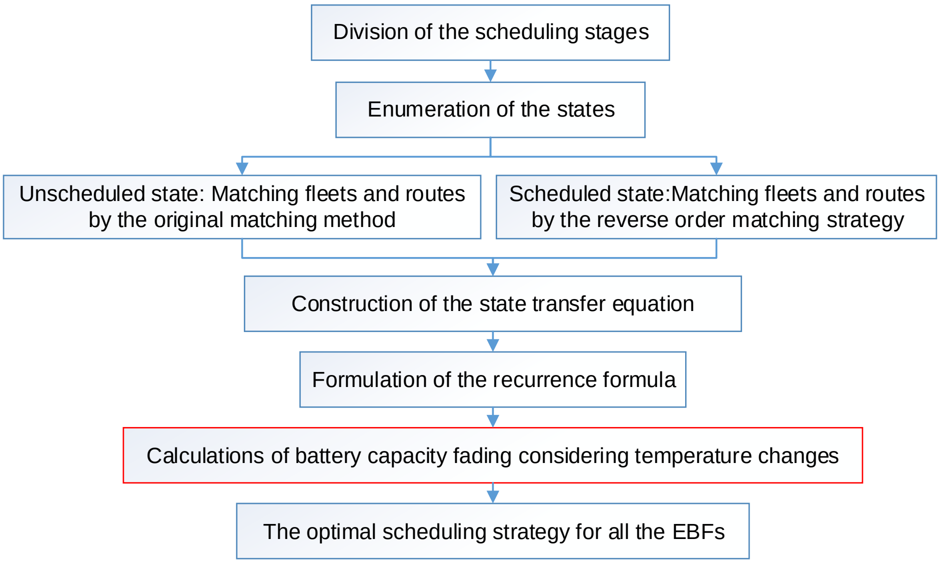


Figure 1: A dynamic programming method of route planning for the electric bus fleets

3.2 Effects of working temperature on capacity fading of batteries

A dynamic degradation model for batteries (Song et al., 2015) is effective under various temperature conditions. In this model, four parameters, including time, temperature, depth of discharge, and discharge rate, are involved, as presented in Eq(1)

$$\varphi = A\exp[-\frac{E_a + B\cdot C}{zR(|T_b - T_{bat}| + T_C)}](A_h)^z \tag{1}$$

where φ is the percentage of battery capacity loss, R is the gas constant (J/(mol×K)), A_h is the Ah-throughput, it represents the amount of charge delivered by the battery during cycling, which is expressed as A_h = (cycle number)×(DOD)×(full cell capacity). C is the discharge rate, B is the compensation factor, and z is the time factor. In addition, T_b is the baseline temperature where the battery is assumed to work most effectively, and T_C is the compensation temperature. After the experimental calibration, the final battery degradation model adopted is given as

$$\varphi = 0.0032\cdot\exp[-\frac{15,162 - 1,516\cdot C}{R(|285.75 - T_{bat}| + 265)}](A_h)^{0.849} \tag{2}$$

The influence of different discharge rates and temperatures on the battery degradation rate is analysed. It shows that the battery degradation rate increases with the increase of discharge rate and the absolute value of (T_{bat}-T_b). Regardless of the discharge rate, the battery reaches the minimum degradation rate at about 13 °C. Moreover, as the discharge rate increases, the working temperature influences the degradation rate more significantly.

4. Case study

In this section, an urban public transit system with EBFs is used as an example case to illustrate the effects of temperature on capacity loss of batteries and route planning for EBFs. The fundamental data and base case are given in Section 4.1. The route planning at different temperatures is discussed to illustrate the effects of temperature on capacity loss of batteries in Section 4.2, and route planning at constant temperature and varied temperature are compared and analysed in Section 4.2. The modelling and solution of the dynamic programming model are implemented in the MATLAB (Matlab, 2019).

4.1 Fundamental data and base case

There are five bus fleets running on five routes respectively in the bus company, and there are ten electric buses in each fleet. The working load of the electric buses, the change of the average temperature per month, and the number of battery replacement are given in this Section. The average velocity in Table 1 is derived from the typical bus driving cycle of several cities in China. According to the basic dynamic model of electric buses (Song et al., 2015), the output power of the battery can be calculated from the average velocity of the working load, and the battery discharge rate and the Depth of Discharge (DOD) can be obtained from the output power and the discharge current. The DOD represents the percentage of battery discharge capacity to battery rated capacity. In this case, the working load and the basic parameters obtained from the working load are summarized in Table 1.

Table 1: The working loads of electric buses running on five routes

Route	Average velocity (km/h)	Battery power (kW)	Current (A)	Discharge rate (1)	DOD (1)
1	14.14	7.40	19.30	0.06	0.45
2	24.5	13.76	35.96	0.12	0.60
3	28	16.22	42.41	0.14	0.71
4	34.2	21.08	55.18	0.18	0.74
5	36	22.63	59.25	0.20	0.79

The average temperatures in Beijing in a year are considered in the case study, as shown in Table 2. The highest temperature is 26 °C in July, whereas the lowest temperature is -4 °C in January.

Table 2: The average temperatures of Beijing

Month	1	2	3	4	5	6	7	8	9	10	11	12
Temperature (°C)	-4	-1	5.9	14.2	20.2	24.3	26	25.3	20.1	13.4	5.1	-2

Table 3 lists the cycle life and the number of battery replacements for the five fleets. It can be seen that cycle numbers obtained at the constant temperature are less than that at the actual temperature. Therefore, it is inaccurate to plan routes with the battery capacity fading at a constant temperature.
When the capacity of a battery decays to 80 % of the rated capacity, the battery needs to be replaced by a new one. The cycle number of the battery at the constant temperature and the actual temperature and the number of battery replacement during the life of the EVs within eight years can be obtained, as shown in Table 3. When considering the varied temperature, the total number of battery replacement is 80. The optimization result after scheduling in Section 4.3 will be measured by taking this as the baseline.

Table 3: The cycle life and the number of battery replacement for the five fleets

Fleet	Cycle number (Constant temperature)	Number of replacements (Constant temperature)	Cycle number (Varied temperatures)	Number of replacements (Varied temperatures)
1	2,126	10	2,366	10
2	1,523	10	1,689	10
3	1,267	20	1,411	10
4	1,178	20	1,305	20
5	1,087	20	1,204	20

4.2 Route planning of electric bus fleets under different temperatures

In this section, battery capacity fading and route planning for the EBFs at different temperatures are discussed. Then the route planning schemes under varied temperatures are analysed in the next section.
According to the battery degradation model, the battery capacity fading rate is the smallest at 12.6 °C, which is the optimum temperature for battery operations. Three temperatures, -4 °C, 12.6 °C and 20 °C, are selected to obtain the route planning schemes for the EBFs by the route planning strategy proposed in this paper. As shown in Table 4, there are differences in the number of replacements in the cases obtained at different temperatures, and the number of replacements that can be reduced is also different after scheduling. It implies that the working temperature has a great influence on the route planning schemes for EBFs. Therefore, it is necessary to consider the effect of temperature changes on the battery capacity fading process to accurately predict the capacity fading of the batteries, and more rationally perform route planning, thereby reduce the battery replacement cost of the EBFs.
The optimal path obtained from the route planning at 12.6 °C is that the EBFs continue driving in the original matching routes, whereas the route planning scheme of the EBFs at -4 °C is that the EBFs is simply scheduled in the eighth stage. Figure 2a shows the route planning of the EBFs at 20 °C. The comparison of the route planning schemes indicates that the difference in capacity fading at each stage makes the optimal scheduling schemes different. When combining the capacity fading of batteries and the working loads of electric buses to plan routes, the influence of temperature change on battery capacity fading should be considered. Otherwise, the optimal scheduling scheme cannot achieve the goal of extending battery life and fully utilizing the remaining capacity of the batteries.

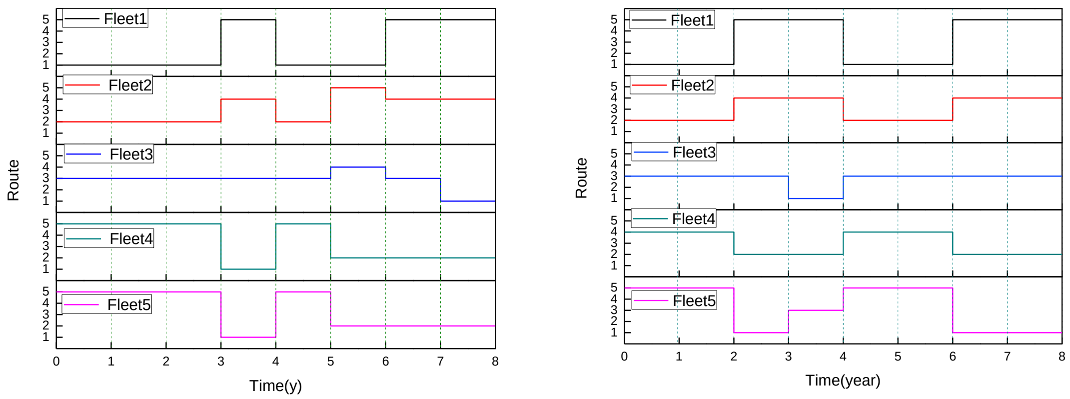
Table 4: The influence of different temperatures on the number of replacement of batteries

Temperature (°C)	Number of replacements in the base case	Number of replacements after route planning	Reduction in the number of replacements
-4	100	90	10
12.6	40	40	0
20	80	50	30

4.3 Route planning of electric bus fleets under varied temperature

The route planning schemes under varied temperatures are analysed in this Section. When the temperature change is considered, the capacity fading rates are calculated in segments, where different temperatures correspond to different capacity fading rates. The EBFs run for eight years without scheduling as a base case in Section 4.1 for the subsequent evaluations for the route planning schemes with scheduling.
For the route planning of EBFs, the scheduling period is divided into eight stages for eight years. Thus, there are eight stages and a total of 128 paths. The minimum number of battery replacement is fifty and the minimum scheduling times is four.
Figure 2 shows the route planning of the EBFs in eight years. The route planning schemes under the constant temperature and the varied temperatures are compared. After the route planning is carried out according to the optimal path, it can be seen that the EBFs are scheduled in the fourth stage, the sixth stage, the seventh stage

and the eighth stage at a constant temperature 20 °C. In contrast, the EBFs are scheduled in the third stage, the fourth stage, the seventh stage and the eighth stage at the varied temperatures. For example, in the third stage at the varied temperatures, the matches between the fleets and the routes are: Fleet1-Route5, Fleet2-Route4, Fleet3-Route3, Fleet4-Route2, Fleet5-Route1. In the remaining stages, the EBFs run on the original matching routes. The results show that there are differences in the number of optimal scheduling paths and the matches between the EBFs and the routes when the optimization results under the constant temperature and the varied temperatures are compared. The dynamic capacity fading of batteries can be more accurately described by considering the temperature changes, which is more realistic under the working conditions of EBFs. Therefore, the lifespan of the batteries can be effectively prolonged, and the redundant capacity of the batteries can be fully utilized by scheduling EBFs with the optimal schemes at the varied temperatures.



(a) (b)

Figure 2: Route planning schemes for the electric bus fleets (a) at constant temperatures (b) at varied temperatures

Figure 3 shows the dynamic process of battery capacity fading of the five fleets under the varied temperature in Beijing. The orange lines represent the capacity fading of the fleets without scheduling, whereas the green lines represent the capacity fading of the fleets with scheduling. When the capacity loss of the battery is 20 %, the battery is replaced by a new one. Therefore, the capacity loss of the new battery starts at 0. Fleet 3, Fleet 4 and Fleet 5 used the redundant capacity of batteries in the Fleet 1 and Fleet 2 to reduce the number of battery replacement by ten times. Therefore, the battery replacements of the EBFs are reduced by thirty times for all fleets.

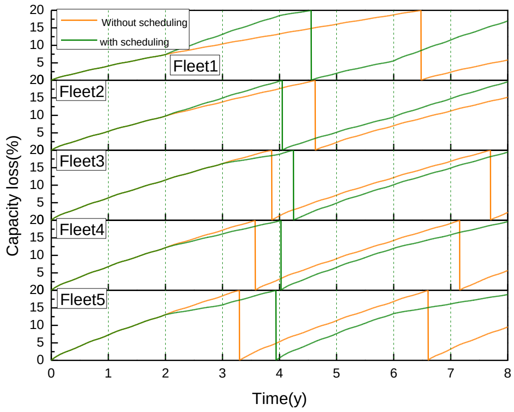


Figure 3: The battery capacity fading processes of the five fleets

5. Conclusions

In this work, a dynamic programming method of route planning for the EBFs was proposed. In the proposed method, the reverse order matching strategy for the matches of fleets and routes was highlighted. The battery capacity fading sequence and the working load sequence of EBFs were matched in the reverse order, where

the fleet sequence arranged in a descending order in terms of battery capacity loss and the sequence of all the routes arranged in an ascending order in terms of the working load were matched by the pairs of the EBF and the route. A case study was conducted to investigate the effect of working temperature on the capacity fading of batteries and route planning for EBFs. Results showed that the optimal scheme of route planning varies significantly with the change of working temperatures. In comparison to the route planning for EBFs at the constant temperature, the dynamic capacity fading of batteries can be more accurately described by considering the temperature change, which is more realistic under the working conditions of EBFs. Compared with the optimization results under the constant temperatures, there are differences in the number of optimal scheduling paths and the matches between the EBFs and the routes. In the case study, three temperatures, -4 °C, 12.6 °C and 20 °C, were selected to obtain the route planning schemes for the EBFs by the proposed route planning strategy. The results showed that the number of replacements can be reduced by 30 times after scheduling.
The significance of the route planning strategy is that the number of battery replacements can be reduced by the EBFs scheduling. Therefore, when the proposed route planning strategy is applied in the practical transit systems, the effect of temperature on capacity fading of batteries should be considered to effectively extend the lifespan of batteries and minimise the battery replacement cost during the entire service life of EBFs. The optimal scheduling strategy and the findings obtained from the solutions to this conceptual model can provide useful guidance for electric bus drivers and administrators in the economic operation and EBFs scheduling.

Acknowledgments

The authors gratefully acknowledge funding by the projects (No.21676211, No. 21878240, and No. 21808179) sponsored by the National Natural Science Foundation of China (NSFC), China's Post-doctoral Science Fund (No.2018M633518), Key Research and Development Program of Shaanxi Province (2018GY-072) and the Fundamental Research Funds for the Central Universities (No. 1191329819).

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