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# Rail Lubrication Management Based on Real-Time Measurement of Forces Occurring Between Rails and Wheels

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## Abstract

Tokyo Metro Co., Ltd which has many curved lines, uses rail lubricators to lubricate the rail/wheel interface. Previously, engineers periodically walked the tracks and adjusted lubrication based on their experience. We investigated whether it would be possible to monitor lubrication status in real time and remotely using PQ monitoring bogies capable of continuous measurement on operational lines. In this study, lubrication condition tests of the rail lubricators were conducted to evaluate the feasibility of managing lubrication on the entire line. As a result, we were able to maintain an appropriate lubrication condition, so I present them in this paper.

**Keywords:** railway, PQ monitoring bogie, rail lubricator, rail/wheel lubrication, rail/wheel wear, coefficient of friction.

## 1 Introduction

Tokyo Metro Co., Ltd (hereafter referred to as “our company”) has a large number of curved lines. In particular, on the outer rail side of curved sections, the lateral pressure increases, which tends to accelerate wear on both the rails and wheels. Therefore, our company has used rail lubricators to apply grease from the rail side, lubricating both the rails and wheels with grease to suppress the progression of wear. The reason grease lubrication can reduce wear on rails and wheels is that it can suppress the forces generated on the rails and wheels. Furthermore, the lubrication condition provided by grease can be confirmed through the magnitude of the coefficient of friction. [1].

Conventionally, The grease lubrication management method involves technicians conducting regular track d inspections, subjectively judging the grease condition on the rails with their own eyes, and manually adjusting the rail lubricators to increase or decrease the grease discharge volume. The problems with this maintenance method are twofold: maintenance becomes dependent on the technician's experience and judgment, and it requires securing a very large number of personnel for track inspection, placing a heavy burden on company operations.

In response to the recent decline in the working-age population, our company is also required to maintain rails and wheels more efficiently. Therefore, to achieve efficient rail and wheel maintenance, we attempted to develop a method for remotely and in real time measuring the lubrication state of rails using grease, using the friction coefficient acting between rails and wheels as an indicator.

## 2 Purpose of this research

The lubrication condition of the outer rail closely affects two points: wear of the rail and wheel, and the occurrence of wheel and rail shelling [2] [3].
For example, increasing lubrication to suppress wear on a specific curve raises the risk of shelling occurring on that curve or the next curve, while also increasing grease costs. Conversely, reducing lubrication to lower the risk of rail shelling or grease costs accelerates wear on both rails and wheels. Therefore, maintaining optimal rail lubrication—neither excessive nor insufficient—is crucial.

Therefore, this study aims to develop a method for achieving optimal lubrication conditions to suppress wheel and rail wear while minimizing shelling risk. To assess rail lubrication status, we attempted to develop a method for remote, real-time measurement through the friction coefficient acting on the outer rail between the rail and wheel.

To achieve optimal lubrication conditions, we propose the following three-step method:
Step 1: Real-time data measurement on the tracks
Step 2: Calculation of the friction coefficient based on measurement results
Step 3: Management of the lubrication state based on the friction coefficient

In this study, the correlation between the "estimated friction coefficient results" and the "grease quantity dispensed using a rail lubricator on the tracks" is confirmed to determine the optimal grease quantity. The above tests were conducted on the operational lines of Tokyo Metro Co., Ltd. to verify their effectiveness. Figure 1 shows the flow presented in this study, including the three methods described earlier.

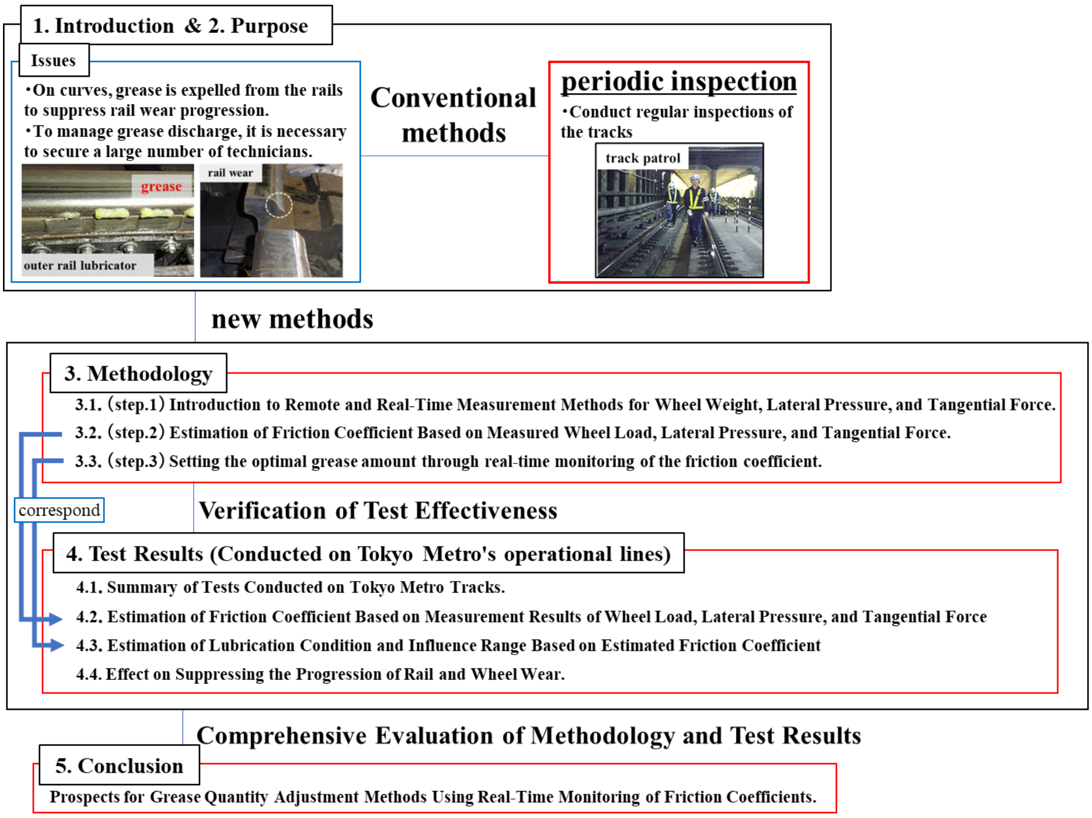


Figure 1: Flowchart of this Study

# 3 Methods

Estimating the friction coefficient requires measured values for three components: P, Q, and T. T is the tangential force, Q is the lateral load, and P is the vertical load. This chapter introduces the method for “monitoring the friction coefficient” in three steps: Step 1 through Step 3.

## 3.1 Real-time Measurement Methods for P, Q, and T on the tracks

In this research, we utilized PQ monitoring bogie to help us understand the state of rail lubrication. PQ monitoring bogies can measure the forces acting between rail/wheel, as shown in Fig 2. T is tangential force, Q is lateral pressure and P is wheel weight. Each tangential force (T), lateral pressure (Q) are forces that depend on the coefficient of friction. Therefore, we can predict lubrication conditions by observing these forces. In this research, we utilized PQ monitoring bogie to help us understand the state of rail lubrication.

PQ monitoring bogie uses non-contact sensors to measure the forces acting between rail/wheel on commercial trains. The advantage of the PQ monitoring bogie is that it can monitor the lubrication condition of the entire line. [4] [5] [6] [7] [8] [9] Figure 2 shows an actual photograph of the PQ monitoring bogie and P, Q, T Force .

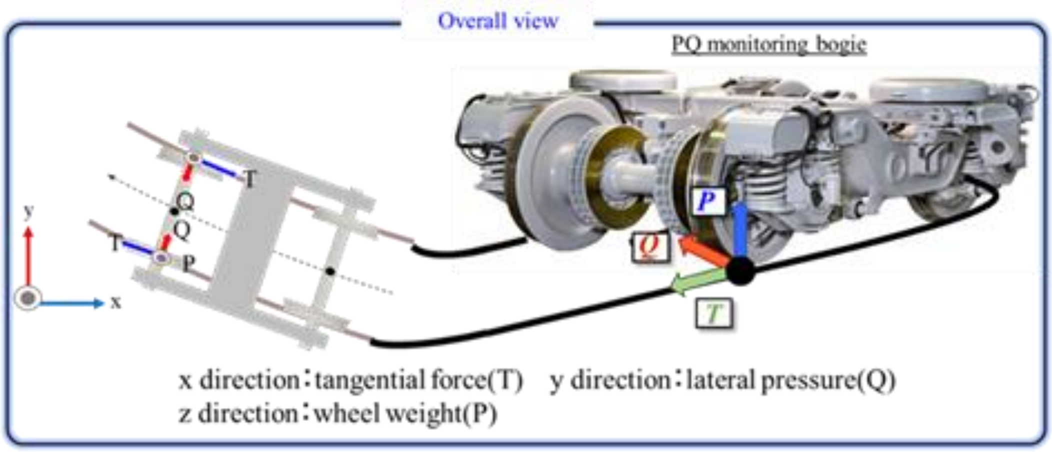


Figure 2: Forces acting on rail/wheel.

The PQ monitoring bogies can monitor the lubrication condition of the entire line, not just one section. Due to the feature that the grease in the rail lubricator reaches not only the curve immediately behind it but also the curve beyond it, it is useful to confirm that a single lubricator is able to lubricate multiple curves. The monitoring of rail/wheel lubrication conditions is used to adjust the rail lubricator for the entire line and is presented in this paper.

### 3.2 Conversion and Estimation of Friction Coefficient Based on On-Site PQT Measurements (Step 2)

To evaluate the lubrication state of the outer rail side where the wheel flange contacts on curves of the operational line, a method for calculating the wheel flange friction coefficient (hereinafter referred to as the friction coefficient) was investigated. [10]
The friction coefficient was estimated by overlaying measured PQT values from operational line measurement data onto a Lookup Table (hereinafter LUT) derived from vehicle curve-passing simulation results based on SIMPACK simulation. The method for creating the LUT is described below. Vehicle specifications and curve parameters for the line under evaluation were reproduced, and the friction coefficient between the wheel and rail was varied while performing iterative calculations. For example, on a sharp curve with a radius R=200m, the friction coefficient at the outer rail side of the front axle wheel flange and the friction coefficients at the inner rail sides of the front and rear axles were varied in 0.1 increments between 0.1 and 0.7, performing a total of 49 analyses. The friction coefficient at the outer rail side of the rear axle was fixed at 0.5. For each friction coefficient, the simulation outputs T/P (tangential force divided by wheel load) for the front axle outer rail side and κ (inner rail Q/P) (lateral pressure divided by wheel load) for the front axle inner rail side. Using these outputs, a lookup table (LUT) was created to estimate the friction coefficient, κ, and T/P relationship shown in Figure 3 in three dimensions.

For the input to this estimator, κ and T/P were obtained using actual measured values obtained from the PQ monitoring bogie running on the main line. The average values of κ and T/P during steady-state curves were used as representative values, input into the estimator, and the friction coefficient was obtained as the output. (Figure 3)

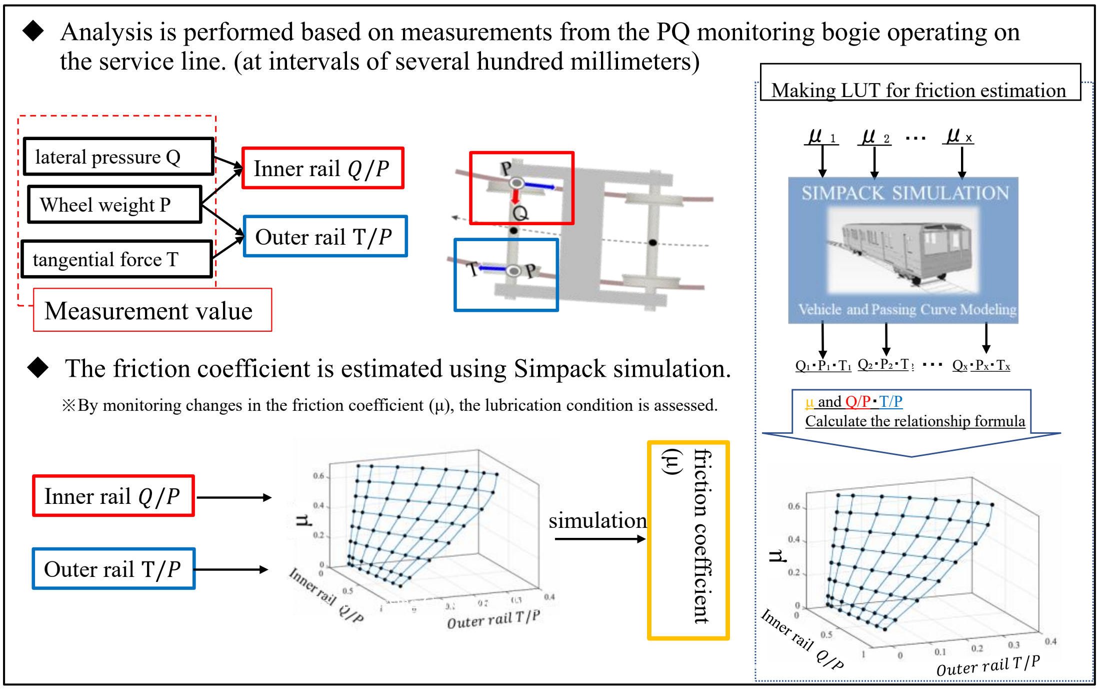

Figure 3: Estimation Method for Friction Coefficient Using SIMPACK Simulation

## 3.3 Determining the Grease Quantity for Rail Lubricators to Achieve Optimal Rail Lubrication Conditions (Step 3)

### 3.3.1 Assumptions Regarding Grease Consumption

To begin with, we will explain the reason for managing rail lubricators with multiple curves. Past studies have shown that grease in rail lubricators reaches not only the curve on which they are installed, but also the curves in the same direction beyond them. [11] Therefore, the use of multiple curve lubricators allows for subtle adjustment of lubrication conditions. Figure 4 shows the example of multiple curves lubrication management. With multiple curves management, we can adjust fine-tuning of lubrication. In single curve management, if we want to decrease lubrication, the conventional grease that was 100 can only be adjusted to 50. However, with multiple curves, if we want to decrease lubrication, the conventional grease that was 100 can be adjusted to 75.

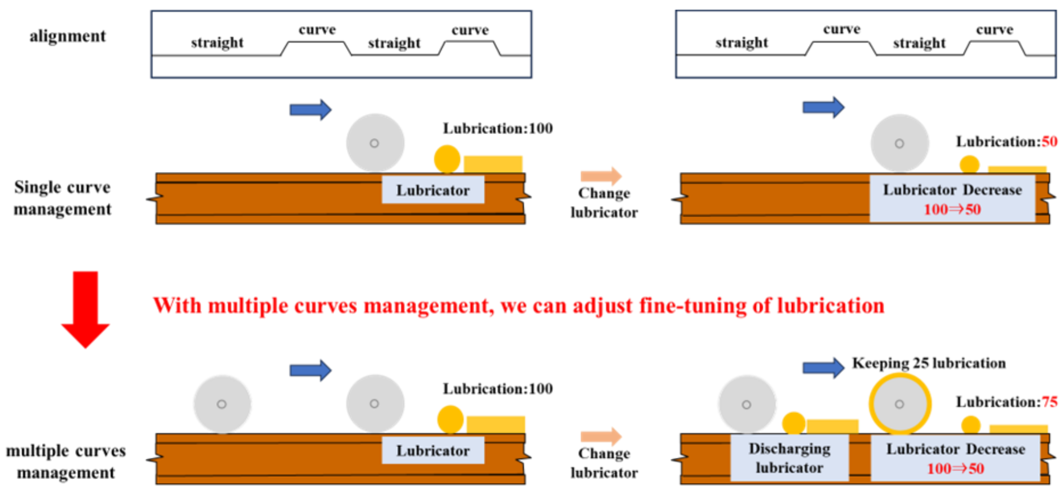


Figure 4: The difference of single curve management and multiple curves management

Furthermore, regarding the consumption of outer rail grease in this study, based on past simulation results, it was assumed that the grease applied to the wheel flange from the outer rail lubricator would be uniformly consumed along each curve between the start and end points. This is because curved running ensures stable contact between both the outer rail wheel flange and the rail gauge corner (Figure 5). Conversely, on straight sections and reverse curves, the contact positions differ from those described above. Therefore, grease consumption was judged to be negligible and excluded from estimation. The greater the amount of grease discharged to the outer rail, the longer the distance of the outer rail that can be lubricated. (Figure 6)

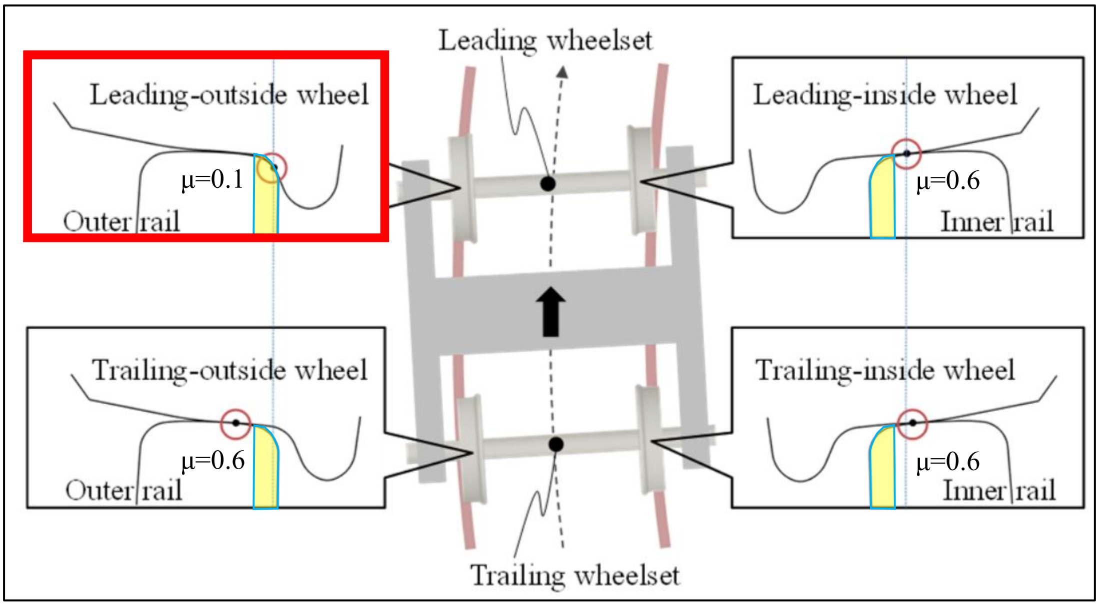


Figure 5: Contact state between wheel and rail on a curve

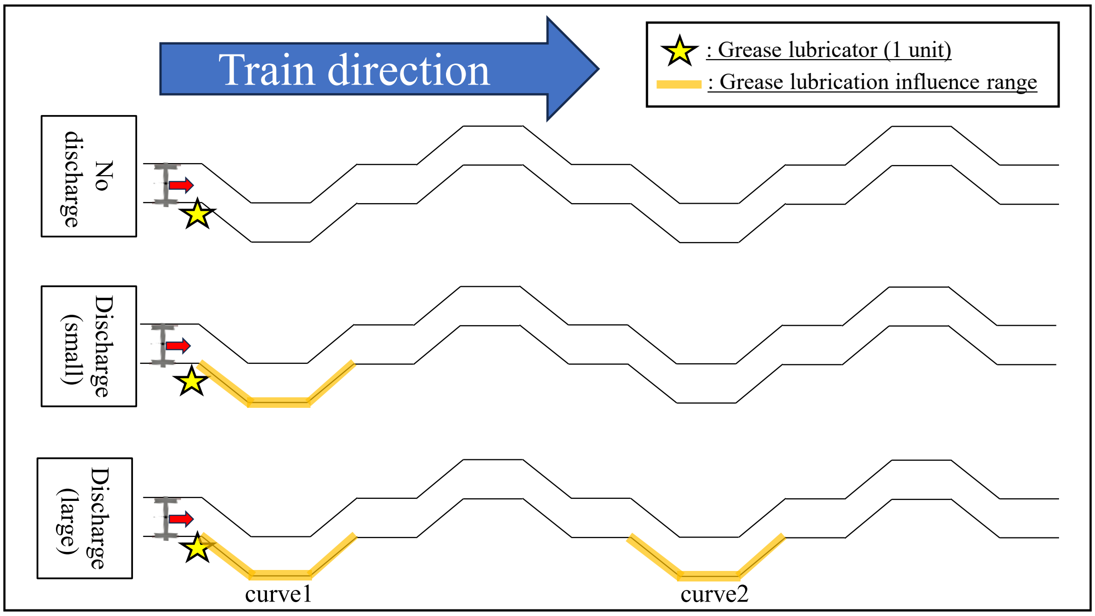


Figure 6: The difference of single curve management and multiple curves management

### 3.2.2 Estimating Rail Lubrication Status Based on Friction Coefficient Changes

The lubrication status for each curve was evaluated using the friction coefficient as the discharge volume increased.

First, while gradually increasing the discharge volume of a single lubricator, we confirmed whether the friction coefficient of the outer rail changed for each curve. Since the friction coefficient is an estimated value, we qualitatively evaluated whether changes occurred before and after the discharge volume increase.

Second, once the lubricatable distance per grease quantity is determined, grease application begins from the second lubricator at the farthest position reachable by grease. This process is repeated until the end point.

If the effective lubrication distance of the grease is miscalculated, resulting in a curve where grease lubrication is not applied, significant rail wear will occur on that curve. Conversely, if the grease effects from two lubricators overlap, there is a risk of shelling on the outer rail due to excessive grease, necessitating careful management. (Figure 7)

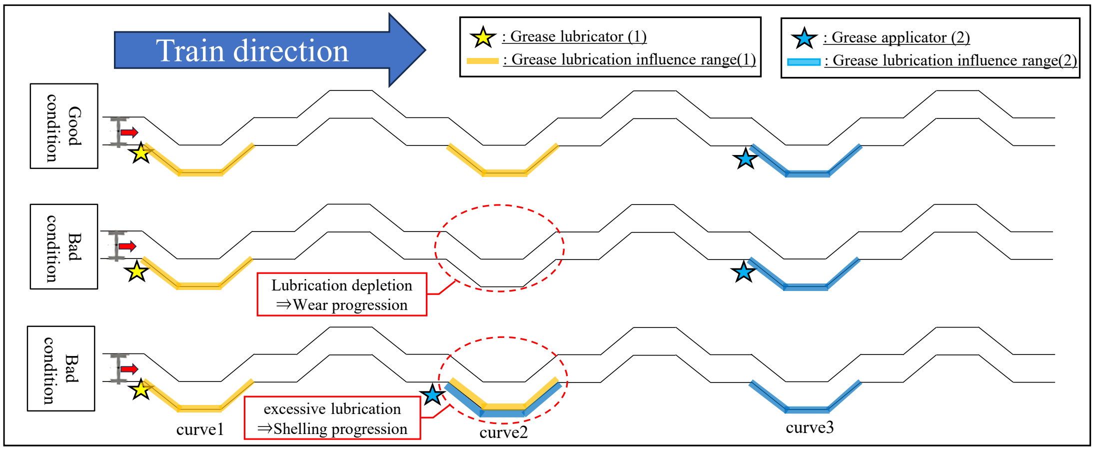


Figure 7: Lubrication Effect Distance of Grease and Optimal Lubricator Installation Position

# 4 Results of Tests Conducted on Tokyo Metro's Operating Lines

## 4.1 Summary of Tests Conducted on Tokyo Metro Tracks

### 4.1.1 Target Curve and Lubricator Installation Curve

In this study, in order to understand the extent of the influence of an arbitrary discharge rate of an outer rail lubricator on Tokyo Metro Line A, the discharge rate of only the lubricator installed on the first curve in the direction of train travel (hereinafter referred to as the lubricator in question) was changed, and the other lubricators were stopped to eliminate the influence of grease discharge, and a follow-up survey was conducted on 22 curves in the same direction (Figure 8).

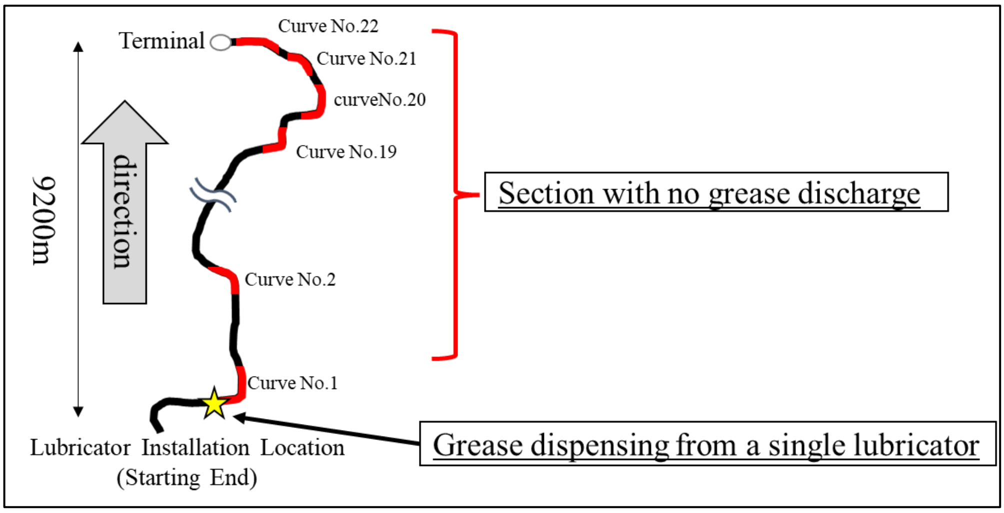


Figure 8 : Test target curve and rail lubricator installation locations

### 4.1.2 Changing the discharge volume

The history of changes in the discharge volume of the oiler in question is shown in Table 1. The discharge volume was increased a total of three times over a 34-day period, and analysis was carried out using Pattern A, Pattern B, and Pattern C. The daily discharge volume for each period was calculated from the discharge volume per time (actual measured value), the discharge frequency (how many trains pass before a discharge occurs), and the number of passing trains (Table 1).

| Discharge Amount Pattern | Elapsed Days | Discharge Amount (g/day) (a=b*c*d) | | | |
|---|---|---|---|---|---|
| | | a: grease discharge amount (g/day) | b: Discharge amount per cycle (g/time) | c: Discharge frequency (times/train) | d: Number of trains passing (trains/day) |
| No discharge | ~0 | 0 | 0 | 0 | 0 |
| Pattern (A) | 0~19 | 128 | 8 | 1/20 | 320 |
| Pattern (B) | 19~34 | 510 | 8 | 1/5 | 320 |
| Pattern (C) | 34~ | 850 | 8 | 1/3 | 320 |

Table 1: Change History of Grease Discharge Volume.

### 4.2 Estimation of Friction Coefficient Based on Measurement Results of Wheel Load, Lateral Pressure, and Tangential Force

The influence range from the point where discharge volume was changed for each curve was estimated based on the following procedure.

Step 1: The changes in friction coefficient for 22 curves were tabulated, and the presence or absence of changes before and after increasing the discharge volume was qualitatively evaluated. Specific examples are shown in Figures 9 and 10.
When a decrease in the friction coefficient was confirmed, it was evaluated as lubrication by grease.

Step 2: For results like those shown in Figures 9 and 10, the lubrication state for each curve was evaluated. When a decrease in the friction coefficient was confirmed, it was evaluated as lubrication by grease.

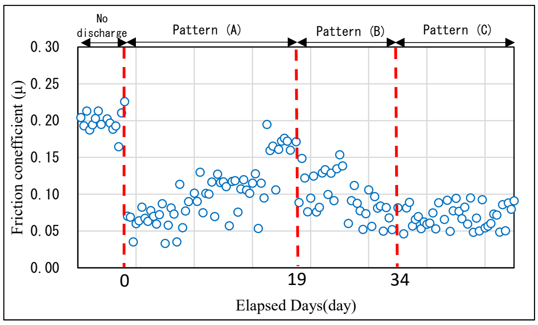


Figure 9: Friction Coefficient for No. 1 Curve

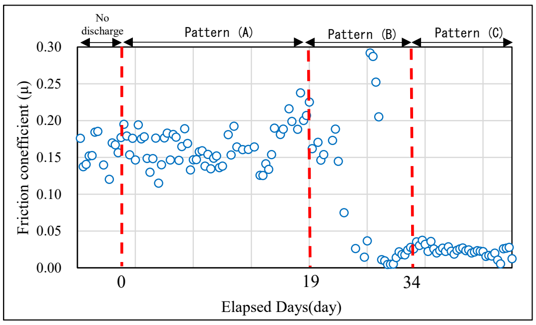


Figure 10: Friction Coefficient for No. 22 Curve

### 4.3 Estimation of Lubrication Condition and Influence Range Based on Estimated Friction Coefficient

The range of influence from the point where the discharge rate was changed for the representative curve was estimated based on the following procedure.

Step 1: Based on the trends shown in Figures 9 and 10, the evaluation criteria for lubrication status were established (Table 2).
Step 2: The lubrication condition on the curves was evaluated based on the results shown in Figures 9 and 10, using the evaluation criteria shown in Table 2 (Table 3).
Step 3: Based on Tables 2 and 3, the extent to which a given discharge rate affects the lubrication state was estimated. The extent of the effect was evaluated using the cumulative curve length of the same direction curve shown in the assumptions in 3.3.1 (Table 4).

| Lubrication evaluation | Evaluation details |
|---|---|
| ◎ | The lubrication condition remains unchanged during the period ( saturation state) |
| ○ | The lubrication condition is declining during the period (decreasing state) |
| × | Grease discharge has stopped and the rail has run dry (depleted state) |

Table 2: Lubrication Condition Evaluation Details

| CurveNo | No.1 (Settings changed) | No.4 (No discharge) | No.13 (No discharge) | No.20 (No discharge) | No.22 (No discharge) |
|---|---|---|---|---|---|
| Cumulative curve length (m) | 111 | 665 | 2155 | 2835 | 3287 |
| No discharge | × | × | × | × | × |
| Pattern (A) | ○ | ○ | × | × | × |
| Pattern (B) | ◎ | ◎ | ○ | ○ | ○ |
| Pattern (C) | ◎ | ◎ | ◎ | ◎ | ○ |

Table 3: Evaluation Results of Lubrication Condition

| pattern | Discharge volume (g/day) | Lubrication range (m) | |
|---|---|---|---|
| | | decreasing state | saturation state |
| Pattern (A) | 128 | 665 | × |
| Pattern (B) | 510 | 3,287 | 111 |
| Pattern (C) | 850 | 3,287 | 2,835 |

Table 4: Relationship between Discharge Volume and Lubrication Influence Range

The optimal rail lubrication condition is considered to be more lubrication than a depleted state (×) but less than excessive lubrication (◎). Therefore, the optimal grease management method is to install lubricators every 665 meters and dispense grease at the discharge rate for Pattern (A), taking into account that Pattern (A) affects up to 665 meters ahead. If managing under Pattern (B) and Pattern (C), the installation intervals for lubricators must be set wider.

### 4.4. Effect on Suppressing the Progression of Rail and Wheel Wear.

We also evaluated outer rail side wear and the amount of flange wear. We have been measuring rail wear in 21 cross sections every six months on rail inspection cars and based on this data, we have expressed the rail wear in terms of square measure. The image is shown in Figure 10. Figure 11 shows the amount of wear at three specific points in curve B. The average of the wear progression at the three points before the adjustment of the lubricator was compared with the wear progression after the adjustment. The wear progression in about 18 months after rail renewal was reduced from 188 mm$^2$ to 112 mm$^2$. Flange wear was estimated using PQ monitoring bogie data and Simpack simulation. Figure 12 shows the amount of flange wear. It also shows the wheel exchange cycle. The less flange wear, the longer the exchange cycle. Before test start, we must exchange wheel once 4 years. However, the amount of flange wear began to decrease after the test start, and by the beginning of 2024, the exchange cycle had extended to 12 years. In addition to these parameters, we also observed instances of overrun and shelling. Overrun and shelling occurred only rarely.

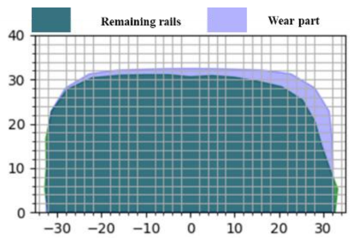


Figure 10: The image of rail wear in terms of square measure

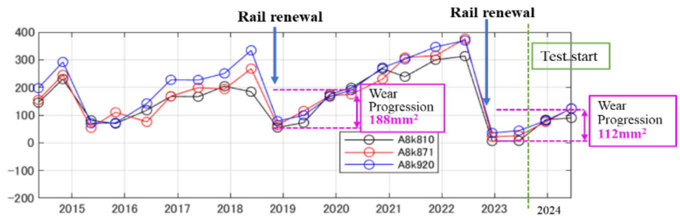


Figure 11: The amount of rail wear at three specific points of curve B

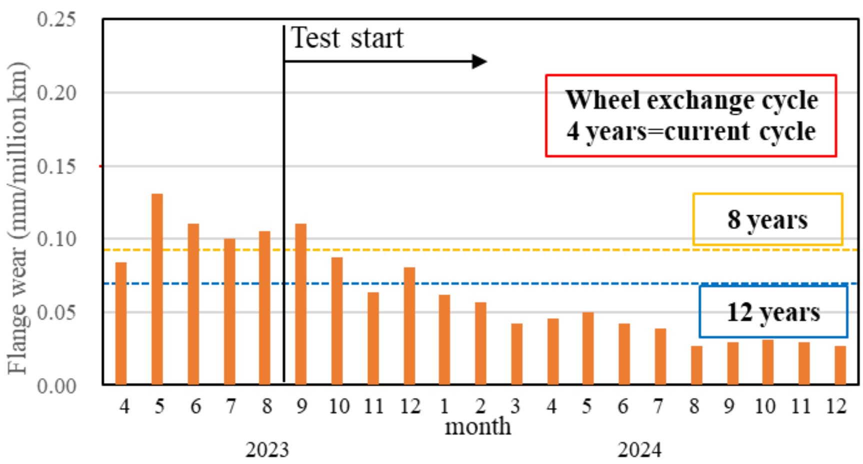


Figure 12  Flange wear of Line A

## 5 Conclusions and Contributions

This study evaluated the feasibility of real-time management of lubrication conditions for outer rails along entire lines. Alongside proposing a real-time management method, we monitored lubrication conditions and conducted adjustment tests for rail lubrication devices using a PQ monitoring bogie capable of continuous measurement on actual revenue service lines. The results demonstrated that appropriate lubrication conditions could be maintained, reducing both flange wear and rail flank wear.

These results demonstrated the effectiveness of improving conventional rail lubrication methods and implementing full-line lubrication management using the PQ monitoring bogie, providing direction for future rail maintenance.

In order to maintain proper lubrication conditions going forward, it is necessary to establish an operational system that adjusts grease discharge volume even more quickly than before, in response to changes in lubrication conditions due to temperature and wheels.

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