Change in Surface Condition of Turned Wheel and Effectiveness of Lubrication against Flange Climb Derailment

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A number of flange climb derailments have occurred in sharp curves or curves with turnouts within relatively short accumulated running distances subsequent to wheel turning. This indicates that a change in the condition of the turned wheel surface might be a factor inducing flange climbing. Through several experiments and numerical simulations, the authors investigated the relationship between the running safety of a vehicle and its wheel surface condition especially in terms of wheel/rail friction. Furthermore, lubrication just after wheel turning was proposed as a countermeasure to flange climb derailments and its effectiveness and persistence were evaluated.

Keywords: running safety, wheel turning, flange climb derailment, coefficient of friction, sharp curve, lubrication

1. Introduction

Flange climb derailments in sharp curves or in curves with turnouts are generally attributed to track irregularities and initial imbalance of wheel loads. There is, however, the possibility that changes in the surface conditions of a freshly turned wheel are also related to flange climbing incidents since a number of them occurred after relatively short accumulated running distances subsequent to wheel turning [1]. An increase in the wheel/rail coefficient of friction in particular is considered to be one of the most essential elements inducing flange climbing. However, the mechanism which leads to a rise in the friction coefficient of the flange surface after the wheel turning is not well known yet since there are many influencing factors, such as surface conditions of both the wheel and the rail, contact conditions, material specifications, temperature and humidity in the environment, etc.

In this study, several experiments and numerical simulations, therefore, were performed to evaluate the relationship between the running safety of a vehicle and wheel surface condition after turning, with special attention paid to the flange surface, in terms of friction between the wheel and the rail. Lubrication just after wheel-turning operations was then proposed as a countermeasure to flange climb derailments and evaluations were made of its effectiveness and persistence.

This study examined a lead curve into a simple turnout on a side track with JIS 50kgN rail ($T_{50N}$, 8-201, called “s-#8 turnout” in this paper) since this study was originally initiated following a derailment in a similar lead curve with a s-#8 turnout at the Oku marshalling yard belonging to the East Japan Railway Company (EJR) in February, 2008 [2]. The s-#8 turnout has a lead curve of radius of 100.701m and twisted structure. The design (in new condition) profile of wheel is the Shusei-Enko profile used on EJR lines which has a flange angle of 65 degrees.

2. Surface texture of flange and flange climbing

The investigations presented in references [3] and [4] on a flange climb derailment incident at Naka-Meguro station on the Hibiya line refer in particular to an increase in wheel/rail friction coefficient as one of the causes of this event. Past studies, such as those presented in references [5] and [6], show that the coefficient of friction
reaches a high value when the surfaces of materials are very clean. Taking the above investigations and studies into account, the authors examined changes in the wheel flange surface through wheel turning in terms of surface texture by conducting running tests. A laboratory experiment was also carried out to investigate the relationship between surface roughness of the wheel and the friction coefficient, while simultaneously considering surrounding temperature and humidity.

2.1 Running tests of the turned wheel in a sharp curve

Running tests involving the repeated passage of a vehicle ran in a sharp curve were performed on a line in a yard in an EJR vehicle maintenance depot to monitor the flange surface texture subsequent to wheel turning. The curve’s radius and length were 200m and 100m respectively. Turned wheels were mounted on the vehicle. In addition to the conditions above, the wheel lathe was set at three different feed rates 0.5, 1.0 and 1.5mm/rev, in order to evaluate how feed rate influenced the wheel’s surface. Measurements were taken on the flat section between the flange root and toe where the flange angle is 65 degrees when the wheel profile is in new (brand-new) condition. The surface texture was measured by using a contact (stylus) instrument.

Figure 1 shows the change in flange surface profile of the leading wheel on the outer rail according to the number of runs through the curve. The feed rate of the lathe in Fig. 1 is 1.5 mm/rev. The wheel profile before the runs displays a set of peaks spaced at intervals of around 1.5mm, depending on feed rate. After the fifth passage in the curve, the peaks disappear leaving a relatively flat surface. After a large number of runs, loss of wheel material leaves a rough surface. Figure 2 shows the arithmetical mean roughness (Ra) of the profiles shown in Fig. 1. Figure 2 also shows Ra of other profiles for feed rates of 0.5 and 1.0 mm/rev. The evaluated roughness shows a trend where roughness diminishes, or the surface becomes smoother, by around the fifth wheel run (in relation to the original state before running), and then increments again after around the fifth passage, after this temporary period of surface smoothness. This trend was almost the same for all the feed rates tried in these running tests.

2.2 Effect of surface roughness, environmental temperature and humidity on coefficient of friction

Laboratory rolling contact experiments were performed using a twin-disc rolling contact apparatus to evaluate the influence of surface roughness, environmental temperature and relative humidity on the coefficient of friction [7]. The diameters of both the wheel and rail discs were set to 30 mm. The two discs employed in the experiments representing the rail and wheel, were made of the same material as those used in actual wheels and rails. The wheel-disc surfaces were prepared with two
levels of roughness: a smooth surface \((Ra = 0.17\mu m)\) and a rough surface \((Ra = 18.9\mu m)\). The roughness of the rail disc was set to \(Ra = 0.60\mu m\). The other main conditions of the experiment were as follows: the rotational speed of the wheel disc was set to 200 rpm; the normal force between the two discs, 195 N; and the slippage between the two discs, 0.3 \%.

Figure 3 shows the relationship between the tangential force ratio \(T/N\) and the normal force \(N\), i.e. \(T/N\), and the surface roughness or the environmental temperature and relative humidity. \(T/N\) is considered to be equivalent to the coefficient of friction during slippage. \(T/N\), therefore, is called the equivalent coefficient of friction in this paper.

As shown in Fig. 3 (a), the equivalent coefficient of friction increases when the relative humidity decreases in the case of the smooth-surface wheel disc, however there is no recognized influence of the relative humidity on the equivalent coefficient of friction in the case of the rough surface. In Fig. 3 (b), no correlation seems to appear between the equivalent coefficient of friction and the temperature set in the experiment. Furthermore, the equivalent coefficient of friction is larger under smooth than under rough surface conditions. These results indicate that the smoother surface roughness corresponds to a larger real contact area between the twin discs, which causes an increase in the coefficient of friction.

### 2.3 Surface condition of wheel and coefficient of friction

Section 2.1 shows that wheel surface texture changes through wheel turning and that peaks resulting from wheel tuning disappear in the course of a few repeated runs; Section 2.2 shows the possibility of the coefficient of friction rising depending on environmental humidity and surface roughness. Moreover, according to past studies such as in references [5] and [6], it is considered that the coefficient of friction increases when contact surfaces are clean (without contaminants or metal-oxide layers) or contact is between metallic substrates. It can therefore be inferred that the coefficient of friction increases when the turning peaks have been worn down by repeated runs, especially over short intervals, since during the process of smoothing metallic substrates are exposed, expanding the real contact area and removing contaminants or metal-oxide layers.

### 3. Verification of the countermeasure against flange climbing derailment

#### 3.1 Effect of the coefficient of friction on flange climbing

In order to evaluate how the wheel/rail coefficient of friction affects flange climbing, a vehicle dynamics simulation was made of a vehicle passing through a s-#8 turnout in the facing direction [8]. In this simulation, the coefficient of friction on the outer/inner rails was set individually. The wheel/rail profiles were set to the design (brand-new) profile, and the vehicle velocity was set to 20 km/h.

The calculation results in the lead curve are shown in Fig. 4. \(Y/Q_{\text{max}}\) and \(z_{\text{max}}\) are the maximum values of the derailment quotient and the vertical displacement of the leading wheel on outer rail respectively. \(\kappa\) is the mean value of the ratio of the lateral and vertical forces of the leading wheel on the inner rail in the lead curve. Figure 4 (a) shows the result where the coefficients of friction on the inner and the outer rails are the same. Figure 4 (b) shows the result where the coefficient of friction on the inner rail \(\mu_{\text{in}}\) is a constant of 0.5 and the coefficient of friction on the outer rail \(\mu_{\text{out}}\) is set to various values from 0.2 to 0.7. The vertical displacement \(z_{\text{max}}\) increases rapidly if \(\mu_{\text{out}}\) exceeds 0.5. On the other hand, \(z_{\text{max}}\) is less than 2 mm if \(\mu_{\text{out}}\) is less than 0.5 and \(\mu_{\text{in}}\) reaches a large value such as 0.5 as shown in Fig. 4 (b). Therefore, it is considered that flange climb derailment is not likely to occur if \(\mu_{\text{out}}\) is controlled in order not to exceed a critical value even if the value of \(\mu_{\text{in}}\) is fairly large.

#### 3.2 Effectiveness and persistence of lubrication on flange

Lubrication on the flat section between the flange root and toe immediately after wheel turning is one of the practical countermeasures against wheel climbing as it maintains low coefficient of friction. Running tests were performed on wheels on which a lubricant (oil) had been applied just after turning. The repeated running tests on a s-#8 turnout validated the assertion that lubrication of the flange suppressed vertical displacement of the lead-

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![Fig. 4 Evaluation of running safety in relation to wheel/rail coefficient of friction](image-url)
ing wheel on the outer rail [9].

However, it is also expected that the lubricant might be removed and lose its effectiveness due to frequent contact between the flange and rail gauge corner. Accordingly, an investigation was made with wheels from vehicles in commercial use and running tests were performed with a test vehicle to determine the condition of the lubricant (oil) on the flange surface.

(1) Persistence of oil attaching to the flange surface

Investigations were then made into the relationship between the accumulated running distance subsequent to wheel turning and the amount of oil attached to flange surfaces of wheels in commercial use in order to grasp how long and how much oil, after application on the flat section between the flange root and toe immediately after turning, remains attached. The vehicles to be examined were those running on a commercial line, Line A. In some sections of Line A, the lubricant (oil) is applied to the rail gauge corner of the outer rail in curves from lubricators mounted on vehicles. The investigation was executed in the period not long after lubrication of the flat section between the flange root and toe where was introduced for all vehicles in commercial use.

The investigation results are shown in Fig. 5 where the amounts of oil on the flat section between the flange root and toe and the flange root are exhibited separately. It is possible to see that the amount of oil decreases rapidly when the accumulated running distance reaches about 60 km. Then the amount of oil converges to around 0.1 mg/cm² when the accumulated running distance is over 1,000 km.

(2) Running tests on the turnout

Running tests using lubricated wheels in which a test vehicle ran repeatedly over s-#8 turnouts were performed on a test track in the Railway Technical Research Institute in order to evaluate the persistence of effectiveness of lubricating the flat section between the flange root and toe. The running velocity of the test vehicle was set to 15 m in length. The test vehicle then passed all five turnouts in a single running. The rail was cleaned after every ten runs to remove the oil attached to the rail as shown in Fig. 6 (return runs to the test starting point were not counted).

Figure 6 shows the experimental results of $Y/Q_{\text{max}}$, $z_{\text{max}}$ and $\kappa$ in the two turnouts, Turnout A and Turnout B, of the five turnouts along the test-track section. The test vehicle passed through Turnout A in the facing direction and Turnout B in the trailing direction. In Fig. 6, $\kappa$ is the mean value over each lead curve, and $Y/Q_{\text{max}}$, $z_{\text{max}}$ are the maximum values from the whole set of turnouts.

$\kappa$ decreased somewhat just after rail cleaning and $z_{\text{max}}$ decreased as the interval between repeated runs was extended for instance, when measurements were performed on different days. A trend appeared showing that $z_{\text{max}}$ increased gradually with the number of runs performed on each measurement. However, all the indexes of $Y/Q_{\text{max}}$, $z_{\text{max}}$ and $\kappa$ changed little overall and there was no indication of flange climbing. In these running tests, the flanges on the right and left hand side as the vehicle faced the test direction, contacted the rail gauge corner 150 times and 100 times respectively. After this amount of contact, the oil still attached to the flanges stood at around 0.2 to 0.5 mg/cm².

Other running tests with no flange lubrication were...
also executed in dry conditions to evaluate the effectiveness of the lubrication. The results are shown in Fig. 7, and show that with no lubrication, \( z_{\text{max}} \) rises as the number of passages over the turnout increases whereas with lubrication, in the same instance \( z_{\text{max}} \) changed only a little.

The above validates the effectiveness of oil on the flange, which keeps vertical displacement of the wheels at a low level, and displays suitable persistence demonstrated in the repeated running tests over a short distance.

### 4. Flange surface in steady condition

The previous section showed that flange lubrication is effective against flange climb derailment in sharp curves and turnouts at a low running speed. It was also verified that this effectiveness persists even after repeated flange/rail gauge corner contact for relatively short accumulated running distances. Furthermore, the investigation of vehicles in commercial use showed that the amount of oil attached to the flange surface decreased rapidly over a running distance of 60 km. Based on these results, more investigations were made on wheel flange surfaces for accumulated running distances exceeding 10,000 km subsequent to wheel turning, since it is considered that the amount of oil attached to the flange and surface roughness converge to a stable level after such long accumulated running distances.

#### 4.1 Stability in amount of oil attached to the wheels flanges of vehicles in commercial use

Figure 8 shows oil quantities attached to flange surfaces for the three commercial lines: Line A, Line B and Line C. Oil amounts appearing in Fig. 8 include not only the oil applied with vehicle-mounted lubricators, but also that applied just after wheel turning. As stated in section 3.2(1), lubricators applied oil to the rail gauge corner of outer rail in curves whose radii are under a certain value and that these amounts vary according to how the lubricant is applied and the number of curves along the line etc. Furthermore, comparing Fig. 8 and Fig. 5 at a same given distance, the mean value of the amount of oil in Fig. 8 is larger than in Fig. 5 where the value converges to around 0.1 mg/cm\(^2\) at running distances of over 1,000 km, although Fig. 8(a) indicates the results from Line A in the

![Fig. 7 Y/\(Q_{\text{max}}\), \(\kappa\) and \(z_{\text{max}}\) versus numbers of passage over the turnout (in case of no lubrication and dry conditions) ](image)

![Fig. 8 Amount of oil attached to flange surface versus accumulated running distance after wheel turning longer than \(10^4\) km (vehicles in commercial use)](image)
same way as Fig. 5. Figure 5 shows the result of measurements taken in the period soon after application of lubricant subsequent to wheel turning had been introduced. The measurements shown in Fig. 8 were carried out four months after the measurements shown in Fig. 5. The reason for the increase in the amount of oil attached on flange in Fig. 8 compared with that in Fig. 5 is considered to be that during additional four months oil attached on the rail surface by a considerable number of lubricated wheels was reattached to the flange, so the amount of oil steadily attached to the flange increased.

4.2 Evaluation of equivalent coefficient of friction of substances attached to the wheel

Oil attached to the flange is mixed with substances such as wear debris from the wheel and the rail, etc. As such, it is unclear whether the oil mixed with other substances is still effective for keeping the coefficient of friction low. Accordingly, substances attached to the wheel, including oil were examined for their composition and coefficient of friction. Samples of the substances in question were taken from the flange surfaces of vehicles in commercial use.

Results of the analysis of the above substances revealed that the oil content in the sample was 25% in terms of mass. Fluorescent X-ray spectrochemical analysis showed that more than 90% of the solid matter in the samples was ferrum (Fe). It is considered that most of the Fe was wear debris from the wheel and rails. The maximum particle size of the solid matter was around 6µm, and the most common solid matter particle size was around 1µm.

An apparatus for measuring creep force [10] evaluated the coefficient of friction of the various substances attached to the wheels. Each substance was applied between a test rail and the wheel of the apparatus to which between 0.2 or 0.5 mg/cm² of oil was added.

Figure 9 shows the result of the equivalent coefficient of friction of the wheel-attached substance including oil compared to that of oil itself. The outcome shows that the equivalent coefficient of friction of the wheel-attached substance is considered to be almost the same as oil itself if the amount of oil included in the substance is at least 0.2 mg/cm². In this case therefore, it is considered that oil mixed with substances such as wear debris still keeps its effectiveness in preventing flange climbing.

According to Fig. 8 (a), the mean value of the amount of oil on the flat section between the flange root and toe is about 0.2 mg/cm² at the accumulated running distance of 130,000 km, which is the point at which the amount of oil reaches a minimum compared to other accumulated running distances. In other words, in the lines shown in Fig. 8, the amount of oil attached to the flange is more than 0.2 mg/cm². The effectiveness therefore of oil against flange climb is considered to persist even after an accumulated running distance of 200,000 to 300,000 km according to the results shown in Fig. 9.

4.3 Equivalent coefficient of friction of the flange surface in steady condition

After a long accumulated running distance of more than 10,000 km, where the flange surface is considered to have reached a steady condition, pits and hollows are formed on the flange surface as shown in Fig. 10. A wheel taken from commercial service with pits and hollows (a pitted-wheel), was used as a specimen in an experiment utilizing apparatus [5] capable of simulating flange climbing conditions. This was done to estimate the equivalent coefficient of friction of a wheel in such a condition where it begins to climb on the rail gauge corner. In order to evaluate the effect of a pitted surface on the equivalent coefficient of friction precisely, the oil attached to the test wheels surface was removed before performing the experiment. In the tests, a sample wheel with a turned shape as shown in Fig. 1 was also employed for comparison with the wheels with a pitted surface. The experiment was carried out in dry conditions and the attack (yaw) angle was set to 1.5 degrees.

When a flange begins to climb the rail gauge corner and the flat section between the flange root and toe comes into contact with the rail, the equivalent coefficient of friction is obtained by a calculation based on the contact (flange) angle and vertical and lateral forces. The equivalent coefficients of friction of the pitted and turned wheels were calculated as 0.13 and 0.37, respectively. The pitted wheel results were low, and equivalent to the coefficient of friction of oil, even though the experiment was implemented under dry and oil-removed surface conditions. The reason for the pitted wheel to have such a low equivalent coefficient of friction is considered to be because there was no yielding of the material during the experiment and the real contact area was small because of the pits. On the other hand, the peaks on the turned wheel surface disappeared during the flange climbing. It is considered that the larger equivalent coefficient of friction found with the turned-wheel was due to an extended real contact area and exposure of metallic substrata as the material (the peaks) yielded.

From the above, even if there is no oil on the surface, the possibility of occurrence of flange climbing should be lower in the case of a pitted wheel surface resulting from long accumulated running distances, than in the case of a freshly turned surface with no oil.
or the number of curves or turnouts. Oil is an important introduction of vehicle mounted lubrication, for instance to wheels differed according to commercial line, since the numerical simulations, can be summarized as follows: the results obtained in running tests, experiments and numerical simulations, can be summarized as follows:

- **(1)** Regarding the relationship between wheel surface condition after wheel turning and flange climb derailment, it is estimated that the coefficient of friction between the flange and the rail gauge corner increases as peaks from turning are worn down, due to exposure of metallic substrata on the surface and extension of the real contact area.

- **(2)** Lubrication as a countermeasure to flange climb derailment applied to the flat section between the flange root and toe just after wheel turning is effective since it is able to prevent coefficient of friction from increasing during the period of dynamic change in the wheel surface.

- **(3)** On the commercial lines investigated in this study, it was found that the amount of oil on the flange stabilized after a long accumulated running distance. The coefficient of friction of oil mixed with wear debris is as low as that of oil itself. Therefore, it is considered that oil’s effectiveness in keeping the coefficient of friction low remains even after long accumulated running distances on the commercial lines.

This study also showed that the amount of oil attached to wheels differed according to commercial line, since the introduction of vehicle mounted lubrication, for instance or the number of curves or turnouts. Oil is an important factor that influences surface condition and forces acting between the wheel and the rail. Further research is planned to continue investigation of amounts of oil attached to wheel surfaces.

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