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Real-World Exploration of Wheel-Rail Contact: Challenges for Condition-Based Maintenance

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Abstract

In general, the safety against derailment is evaluated by the derailment coefficient, which is defined as lateral force (L)/vertical force (V). In Japan, L and V are referred to as Q and P, respectively. Traditionally, these forces are only measured by the instrumented wheelset at the time of safety inspection of newly manufactured vehicles or newly constructed railway tracks. Tokyo Metro has developed a special bogie called PQ(L/V) monitoring bogie, which can monitor the forces between the wheels and the rails and the derailment coefficients on service lines during operation. At the same time, Tokyo Metro has also introduced a steering bogie that steers the wheelset in the radial direction using linkage mechanism. In recent years, the monitoring bogie with a steering mechanism has also been developed. In order to monitor all the vehicles on a line, the trackside remote monitoring system is also being developed. This paper summarises the history of the development of condition monitoring technology to ensure safer operation against flange climb derailment, and the future prospects are mentioned.

Keywords: wheel-rail contact, condition monitoring, steering bogie, running safety, derailment, wear, friction.

1 Introduction

In the railway system, safety of operation is the highest priority and wheelset derailment should be prevented. Derailment safety is evaluated by the derailment coefficient, which is defined by the lateral force (L)/vertical force (V). In Japan, L and

V are referred to as Q and P, respectively. Tokyo Metro experienced a derailment accident on the Hibiya line in March 2000. An investigation was carried out into the cause of the derailment, and various measures were subsequently taken in relation to the track, the vehicle and their boundary areas. In particular, under the high-frequency operation of subway lines, the change in the coefficient of friction between wheel and rail was significant and flange climb derailments tend to occur when the coefficient of friction was at its maximum. Since then, the mechanism of flange climb derailment has been well studied [1]-[5]. On the other hand, the importance of constantly monitoring the wheel-rail friction coefficient and the derailment coefficient on commercial lines has been recognised, and the PQ(L/V) monitoring bogie has been developed and put into practical use [6]-[10]. At the same time, Tokyo Metro had also developed and put into practical use the single-axle steering bogie [11], which reduces lateral forces by reducing the angle of attack between the wheel and the rail on sharp curves, even if the coefficient of friction between the wheel and the rail is increased. In order to fully understand the effect of the bogie, single-axle steering bogies equipped with PQ(L/V) monitoring devices are also being developed in service [12][13].

This paper explains the actual derailment accident as a starting point and details how the technology for the condition monitoring of the derailment coefficient has progressed. Future prospects for condition monitoring for running safety and wheel/rail wear are also mentioned.

2 Development and practical application of PQ monitoring bogies

2.1 Background of the development: Hibiya line derailment accident

Tokyo Metro experienced a derailment accident on the Hibiya line in March 2000. After the derailment accident of the Hibiya line in 2000, several experiments were conducted to investigate the cause of the derailment. With great difficulty, it was determined that the cause of the derailment was a multi-factor derailment caused by the track, the vehicle and the interaction between the track and the vehicle.

One of the causes of the derailment was thought to be the increased coefficient of friction between the wheel and the rail in sharp curves with a large angle of attack, resulting in a large lateral force. Figure 1 shows the results of measuring the ratio of the lateral force (Q) to the vertical force (P) of the inner side wheel, which corresponds to the coefficient of friction from at 5:00 to 11:00 for trains running. It is estimated that the coefficient of friction was around 0.2 at the start of the train, but then increased, reaching to a maximum of around 0.7 at 9:00, when the derailment occurred. This increase in the friction coefficient was thought to have led to an increase in the lateral force and an increase in the derailment coefficient. Surprisingly, the coefficient of friction between the wheel and the rail and the associated derailment coefficient were found to vary from time to time. These causes of derailments led to two countermeasures. One was to develop technology to monitor the friction coefficient and the derailment coefficient on the track at all times. The other was to reduce the angle of attack to reduce lateral forces through the development of the single-axle steering bogie.

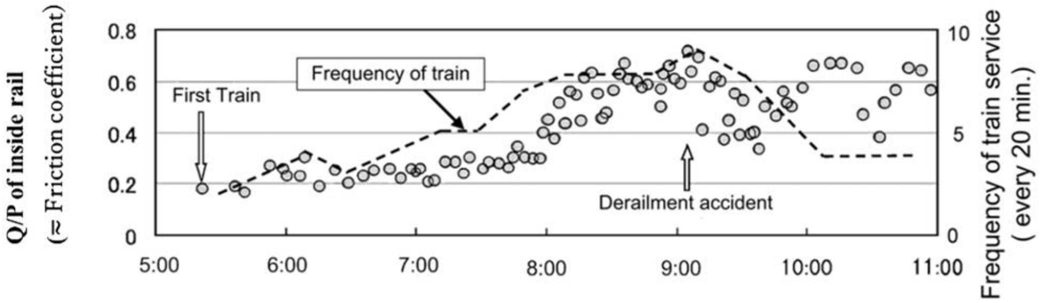


Figure 1: Change of inside Q/P (≒friction coefficient) on the sharp curve of the accident site

2.2 Development of PQ(L/V) monitoring bogie

The forces between wheel and rail are generally measured by using an instrumented wheelset (called PQ wheelset in Japan) which is not suitable for long-term measurement on commercial lines. Therefore, a non-contact measurement method for the forces and derailment coefficients from the bogie has been developed. The measurement methods are shown in Figure 2 in comparison with the conventional PQ wheelset. On the PQ wheelset, gauges are attached to the holes in the wheel to measure the wheel load. In addition, strain gauges are attached to the wheel plate and the lateral force can be measured by the deformation of the wheel plate due to the lateral force. In contrast, with PQ monitoring bogies, the wheel load is measured by the vertical deformation of the primary suspension and the lateral force is measured by the deformation of the wheel plate from the axle box with a non-contact displacement sensor using eddy current.

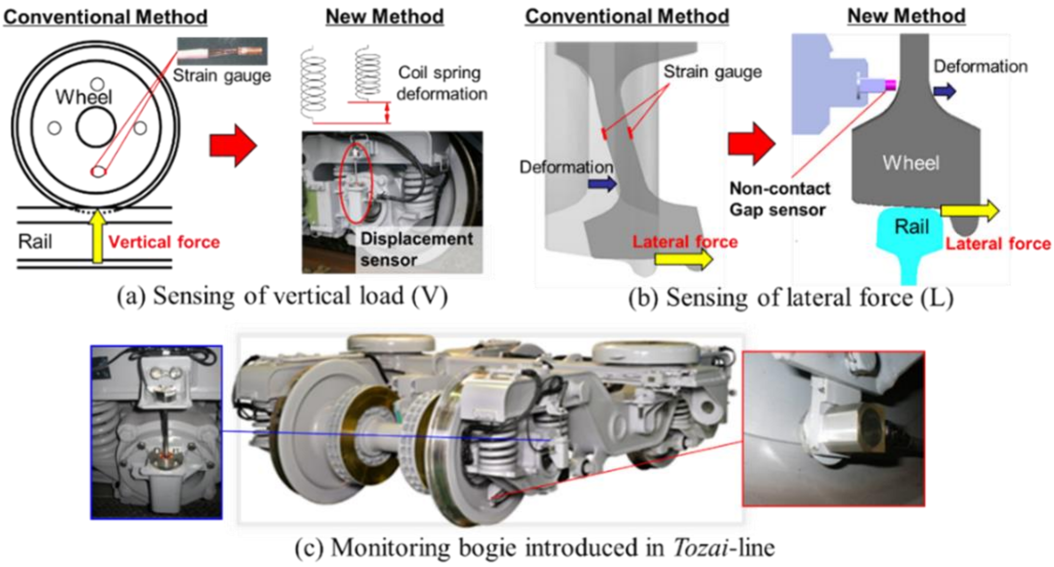


Figure 2: Wheel/rail contact force measurement method of newly developed PQ monitoring bogie compared with conventional method

Examples of measured derailment coefficients of sharp curves on the service line by the PQ monitoring bogie are shown in Figure 3. The data consists of 26 runs over 10 days on the service line and shows that the derailment coefficient changes from time to time. The point where the maximum derailment coefficient occurs was almost the same for each run. The main reason for these changes in the derailment coefficient corresponds well with the change of the friction coefficient of the inner rail. The PQ monitoring bogie has been developed in service and careful monitoring of the derailment coefficient has been carried out. As for the countermeasure for derailment, the derailment prevention guard is installed to minimise the risk of derailment. For more detailed studies on the trend of the monitored data, please refer to [14]-[16].

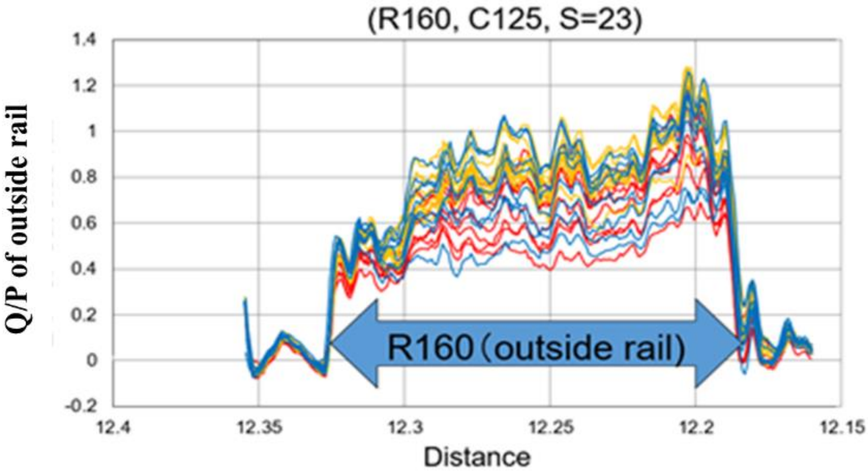


Figure 3: Change of Q/P in 26 runs over 10 days on the sharp curve in the service line

3 Development and practical application of single-axle steering bogie

On Tokyo Metro lines, especially those with many sharp curves, various problems occur, such as large lateral forces caused by the large angle of attack, squealing noise and flange wear. Therefore single-axle steering bogies have been developed and put into practical use to reduce lateral force and increase running safety against derailment. To reduce the angle of attack, a link is connected between the car body, bogie frame and axle box, and the wheelset is steered mechanically according to the bogie angle generated between the car body and the bogie frame. This mechanism allows the wheelset steering angle to be generated in accordance with the curve radius, thereby reducing the angle of attack in the curve. The steering mechanism is not feasible for motor bogies because the coupling displacement between the motor and the gearbox when the wheelset is steered is not permissible. For this reason, a system has been adopted in which the motor and trailer axles are arranged in one bogie and only one trailer wheelset is steered. The configuration of the steering wheelset of a single-axle steering bogie in a curve is shown in Figure 4. In a car, the second and third axles are steered. The first and fourth axles are non-steering axles with gearbox and coupling connected to a motor. On the leading bogie, the trailer axle is steered so that it can travel outside the curve. This allows the reduction of anti-steering moment due to the longitudinal creep forces of the trailing wheelset. In addition, the lateral displacement of the trailing wheelset can reduce the angle of attack and reduce the lateral force of leading wheelset. Figure 5 shows the Tokyo Metro's first steering bogie, which was introduced on the Ginza line in 2012.

Figure 6 shows a comparison of the lateral force between a non-steering bogie and a steering bogie on a curve radius of 197 m. The measurement was done with instrumented wheelsets. It can be seen that the lateral force of the steering bogie is 30% lower than that of the non-steering bogie. For the development history, including the characteristic development of such an unsymmetric bogie in Japan, see [17].

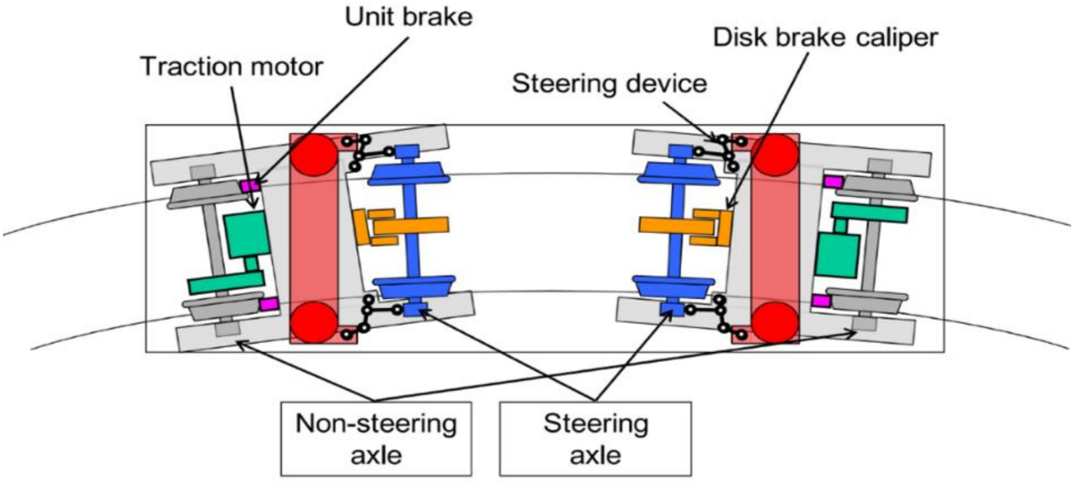


Figure 4: Schematic diagram of steering vehicle and arrangement of steering wheelset

Figure 5: Steering vehicle "Type 1000" for Ginza line and the steering bogie

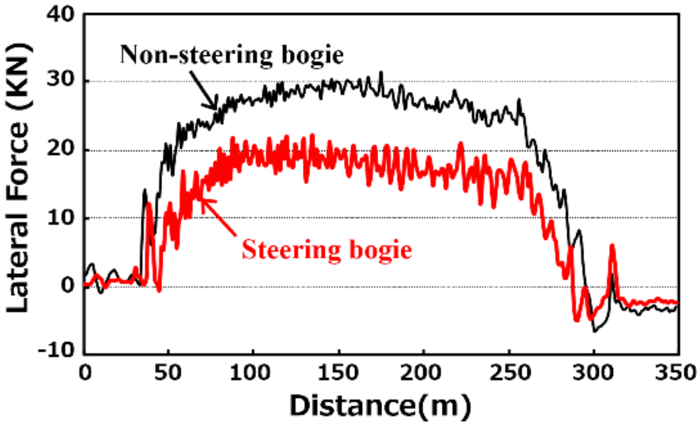


Figure 6: Lateral force of non-steering bogie and steering bogie measured by instrumented wheelset

4 Development and practical use of PQ monitoring steering bogies

4.1 Objectives of PQ monitoring steering bogies

The use of PQ monitoring bogies has made it possible to frequently assess the running safety of service lines. In addition, with single-axle steering bogies, reduction of the derailment coefficient has been observed due to the effect of reduced lateral force. However, the effect of changes in wheel/rail lubrication on the curving performance of single-axle steering bogies and the point at which the maximum derailment coefficient occurs in each curve has not been understood. In light of this, the PQ monitoring steering bogie was developed and is shown in Figure 7. The bogie is equipped with a steering link mechanism, and eddy current sensors for measuring the lateral force and magneto-strictive sensors for measuring the wheel load can monitor the forces occurring between the wheel and the rail of the steering bogie. In addition, strain gauges attached to the mono-link connecting the axle-box to the bogie frame can measure the tangential forces between the wheels and the rails. In the service line, the PQ monitoring bogie with steering device equipped with PQ wheelsets was examined to compare the lateral force, the vertical force and the derailment coefficient. It was confirmed that the measurement results of PQ monitoring bogie agreed well with the measurement results of instrumented wheelset [13]. And these results showed that this new type of PQ monitoring bogie was successful. As a result, it became possible to monitor the lateral force, vertical force, and derailment coefficient of the service line.

Figure 8. shows the results of the non-steering PQ monitoring bogie measuring the derailment coefficient repeatedly on a sharp curve during commercial operation. The curve is the same as in Figure 3. The PQ monitoring steering bogie will give a more straightforward curving behaviour on several lubricated condition rails. It can be seen that the derailment coefficients are generally lower with the steering bogie compared to Figure 3. In addition, the maximum derailment coefficient for the non-steering bogie occurred at the exit of the curve, whereas this tendency was not observed for the steering bogie.

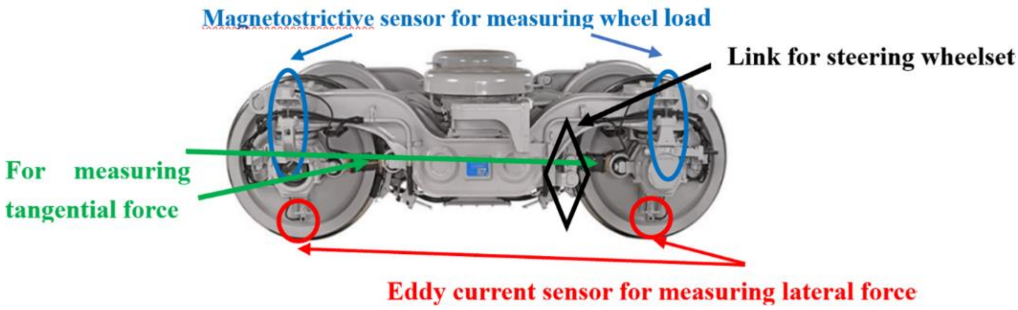


Figure 7: Layout of PQ(L/V) monitoring steering bogie

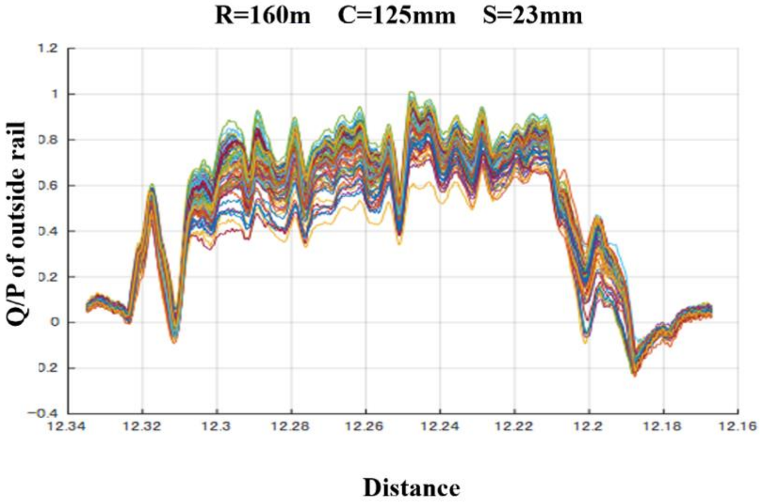


Figure 8: Change of Q/P in 70 runs over 14 days on the sharp curve

4.2 Derailment coefficient measurements for all curves in a service line

Figure 9 shows the comparison of the overall derailment coefficients for each curve on a particular line of Tokyo Metro, obtained by non-steering PQ monitoring bogies and PQ monitoring steering bogie. The derailment coefficients of the steering bogies are lower than those of the non-steering bogies for all curves. An approximation formula can be drawn by smoothly linking only the top of the different values of each curve radius. All the derailment coefficients in the service line are below the approximate formula, so we can see the safety of the curves. Comparing these formulas, the steering bogie shows a better running performance than the non-steering bogie. The flange angles of the wheels are different between non-steering bogies and steering bogies. The flange angle of a non-steering bogie is 67.11° and that of a steering bogie is 70.0°. Therefore, the target derailment coefficients with a margin of 15% to the critical derailment coefficient calculated from the Nadal formula are 1.02 for non-steering bogies and 1.14 for steering bogies.

Figure 10 shows the safety margin curve, obtained by dividing the target value of the derailment coefficient by the approximated curves obtained in Figure 9. It is clear that the use of steering bogies with new treads has increased the safety margin on each curve. In order to ensure safety on the operating lines, derailment prevention guards are installed on curves with a radius of 250 or less. As a result, safer railway operation with steering bogie and can be achieved and proven by the analysis of monitored data.

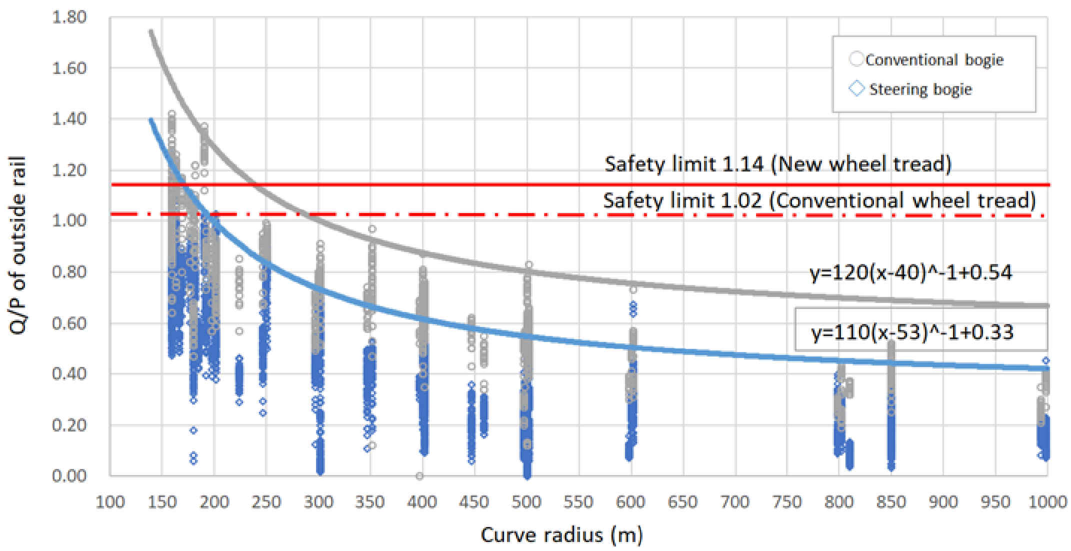


Figure 9: Comparison of derailment coefficient for all curves in the service line

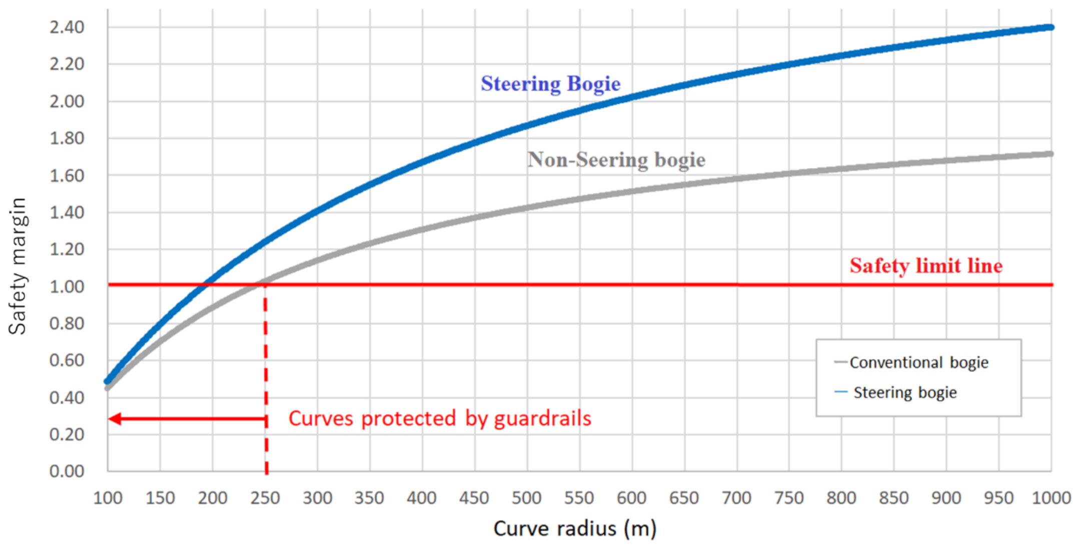


Figure 10: Safety margin of curving obtained by PQ monitoring bogie (Comparison between non-steering and steering bogie)

5 Remote monitoring system of derailment coefficient from trackside

By using the PQ monitoring bogie, it is possible to find out the tendency of the derailment coefficient. However, it is difficult to develop many PQ monitoring bogies in service operation in terms of measurement, development and maintenance costs. In order to solve the deficiency of measurement cost with many bogies running in one line, trackside monitoring system is developed [18].

Figure 11 shows the overall system of the monitoring system. The sensors, which measure lateral and vertical forces using strain-gauges, are attached to the rail. The real-time monitoring equipment consists mainly of data acquisition equipment located at specific curves on a commercial line and monitoring equipment located at train depot offices and elsewhere. Data collection equipment begins to measure the lateral force and the vertical force automatically detecting the passing of vehicle at the measurement point. Specifically, it gathers several types of data while the train passes through that point. Train information obtained beacon such as number of operations, number of trains, and operating company, taking into account interconnections between different railway companies, is attached to the measured data. The data collection equipment automatically transmits this data to monitoring equipment at the depot, office, and command center via a fiber optic network. The monitoring equipment receives data each time the wheels pass the measurement point and analyses this wave form data for specific values that indicate the performance of the vehicle dynamics.

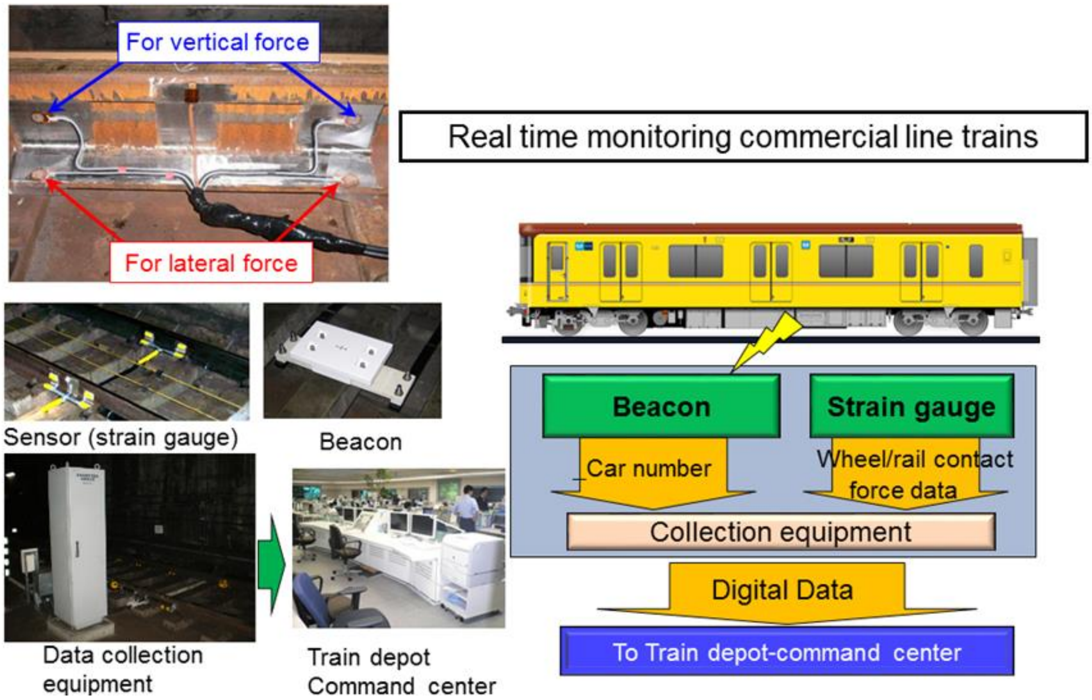


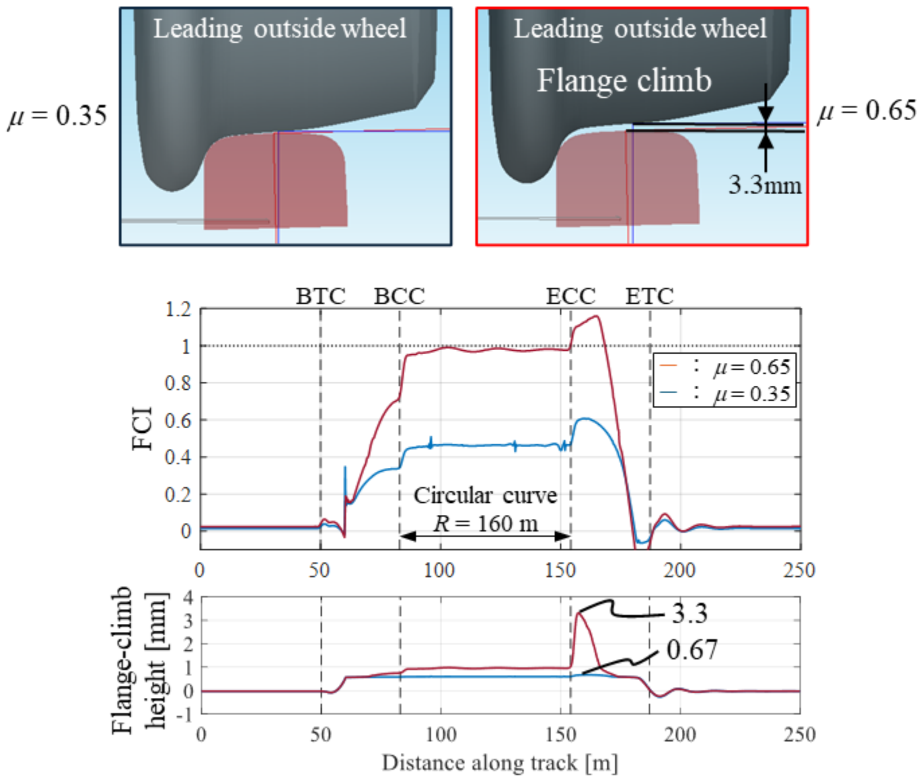
Figure 11: Realtime LV(PQ) Monitoring system from trackside

6 The future of condition monitoring on curves

6.1 Safety assessment of flange climb derailment

When discussing flange climb derailment, it is not sufficient to measure the derailment coefficient alone; it must be considered in conjunction with the critical derailment coefficient. Therefore, the authors propose the Flange Climb Index (FCI), which is the value of the Q/P divided by the critical value of Q/P for the safety limit. As shown in Figure 12, the result of the multibody dynamics simulation, when the FCI exceeds 1.0, a flange climb is likely to occur. In order to estimate the FCI in practice, the problem is how to estimate the friction coefficient between the flange and the rail.

Figure 13 shows brief illustrations of the tangential force variation when the value of the friction coefficient of the outer wheel changes. As shown in the figure, when the friction coefficient of the outer wheel becomes high, the value of the tangential force increases. In view of the mechanism, the method of estimating the friction coefficient using the tangential force obtained by the PQ monitoring bogie's mono-link is considered[19]-[23]. For more accurate estimation considering various factor of vehicle parameter, multibody dynamics simulation is used to build look-up table for the estimation as shown in Figure 14. In principle, if the simulation model is accurate, the friction coefficient of the outer wheel can be obtained in this way. As the shape of the look-up table changes with wheel/rail wear, the challenge is how to achieve robust estimation against such changes.



(a) FCI and flange-climb height calculated in MBD simulations

Figure 12: Flange climb height and flange climb index

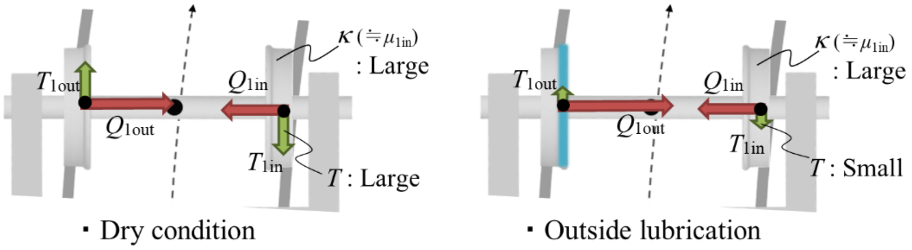


Figure 13: Relationship between friction coefficient of outside wheel and steering moment.

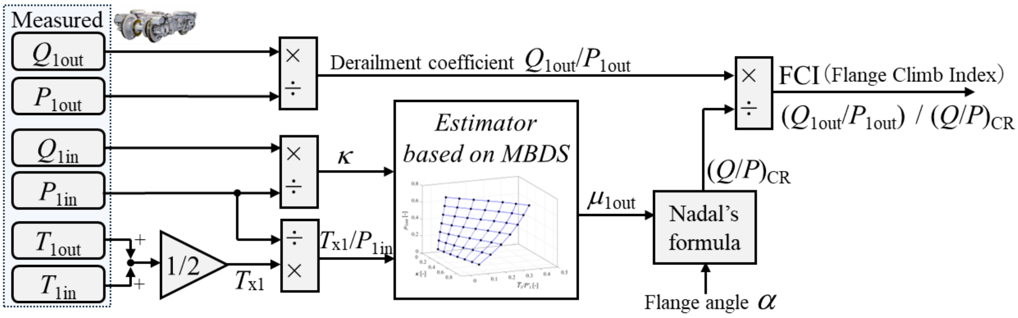
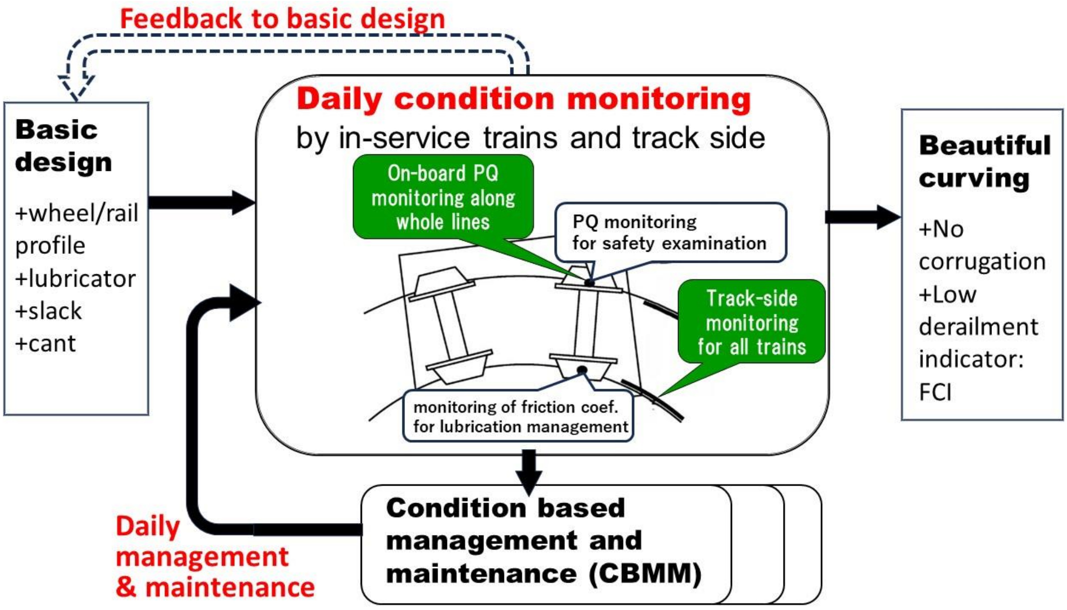


Figure 14: Flow of the estimation of the friction coefficient estimation and FCI

6.2 Concept of condition-based management and maintenance (CBMM) of wheel/rail contact system

As an example of a safety management system for wheel-rail friction and derailment, Figure 15 shows a conceptual diagram of a vehicle/track maintenance management system with a bogie and track monitoring system developed [18]. Simply improving the vehicle and track is not enough to improve the safety of daily operations on commercial routes. It is more important to maintain and manage the improved conditions.

An ideal vehicle and track management system can be achieved by installing condition monitoring equipment at specific curves on the line to evaluate and manage all vehicles passing through the measurement points, and by using PQ monitoring bogies to evaluate and manage the whole track on the operating line from the vehicle side. The maintenance and management status of vehicles and track can be checked at any time by these vertical force and lateral force monitoring systems. These systems also establish a very short-cycle feedback system that can catch the effects of maintenance and changes in PQ measurements at any time. This synergistic feedback effect on friction control [24] maintains ideal conditions for the vehicle and the track. By monitoring the forces acting between the wheels and the rails, it is possible to detect defects in the track and the vehicle and to achieve "beautiful curving".



7 Conclusions

To ensure that flange climb derailment accidents will never happen again, several measures have been taken on the vehicle, especially on the bogies of the Tokyo Metro. One of these measures, the steering bogies have been developed and put into practical use. At present, the steering bogie has been converted to PQ monitoring steering bogie, which monitors the safety of the curve running on the service line. Repeated measurements of derailment coefficients for all curves on the service lines using the PQ monitoring steering bogie have shown that the steering bogie has improved running safety compared to the non-steering bogie.

Trackside condition monitoring is also used on Tokyo Metro lines. All running bogies are monitored at specific points. The data is transmitted to the depot in real time and monitored. In order to monitor safety in real time, track and vehicle condition monitoring systems need to be organically linked. Further integration between on-board and trackside monitoring should be carried out when realizing an accurate, fast and economically feasible monitoring system. With regard to the maintenance in relation to wheel and rail wear, the estimation accuracy should be improved and the problem remains to be solved.

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