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Curving Performance Enhancement in Link-Type Steering Bogies: Concepts and Applications in Japan

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Abstract

This paper presents an overview of link-type forced steering bogies, focusing on their development and practical implementation in Japan. These bogies enhance curving performance by achieving radial alignment of wheelsets while maintaining a relatively simple and reliable mechanical structure, in contrast to actively controlled systems. Despite their effectiveness, conventional steering bogies have seen limited practical application due to structural complexity and difficulties in integrating traction and braking components. To address these challenges, an asymmetric bogie with single-axle steering has been developed and successfully implemented in Japanese metro systems. This paper reviews the historical development of steering bogies and examines their dynamic characteristics based on field measurements and numerical simulations. The results demonstrate significant reductions in lateral force and derailment coefficient, thereby confirming the practical effectiveness of the proposed concept. Quantitative analysis indicates a substantial reduction in the angle of attack and derailment coefficient under sharp curve conditions. The widespread implementation of this concept in commercial metro operations demonstrates its maturity and practical significance in Japanese railway engineering practice.

Keywords: railway dynamics, steering bogie, asymmetric bogie, curving performance, single-axle steering, lateral force

1 Introduction

The conventional railway wheelset possesses inherent self-steering and self-centering characteristics, which have enabled its widespread use since the early development of railway systems. Owing to its structural simplicity and favorable dynamic behavior, the wheelset-based bogie remains the dominant configuration in modern railway vehicles. A fundamental challenge in bogie design is achieving a balance between curving performance and hunting stability. Although extensive research over several decades has established well-accepted design methodologies, further improvement in curving performance remains desirable, particularly in sharp curves where wheel–rail interaction increases lateral forces and wear [1-5].

In this context, steering bogies have attracted renewed attention. Among various approaches, link-type forced steering bogies provide an effective solution by improving curving performance through mechanical linkages. Compared with active steering systems [6][7], they offer higher reliability and lower system complexity. Their primary function is to achieve radial alignment of wheelsets along curved tracks. Previous implementations include hydraulic steering systems based on the relative yaw angle between the car body and bogie frame, as well as mechanical linkage mechanisms connecting wheelsets and bogie frames. However, despite their effectiveness, conventional steering bogies have not been widely adopted due to structural complexity and practical challenges, particularly in integrating traction and braking components under dynamically varying wheelset orientations. To address these issues, an asymmetric bogie with single-axle steering has been developed and implemented in Japanese metro systems, achieving a practical balance between steering performance and mechanical simplicity.

This paper reviews the development of steering bogie technologies in Japan, with emphasis on asymmetric concepts, and discusses their dynamic characteristics based on numerical simulations and experimental observations.

2 Brief history of steering bogies in practical use in Japan

2.1 Asymmetric steering bogie with different primary stiffness

In Japan, various types of steering bogies, including active steering systems and independently rotating wheelsets, have been extensively studied. However, this paper focuses only on those that have been put into practical use. Despite these extensive studies, only a limited number have been realized in practice. Under such circumstances, one of the earliest practical implementations in Japan is found in the JR Central Series 383 EMU express trains, as shown in Figure 1, which marked the beginning of practical application of steering bogie technology in Japan. The initial train sets were introduced in 1994, followed by mass-production vehicles in 1995.

The basic concept is to employ a lower longitudinal primary stiffness at the leading wheelset and a higher stiffness at the trailing wheelset, thereby achieving near-perfect steering during curving [8]. The asymmetry is realized through a difference in longitudinal primary stiffness between the leading and trailing wheelsets, while the lateral stiffness remains symmetric.

The first train sets developed in 1994 of the Series 383 EMU were equipped with a switching mechanism. However, in subsequent train sets, the design was improved to reduce initial and operating costs. In these improved configurations, asymmetric bogies are arranged symmetrically within the car body to enable bi-directional operation, thereby eliminating the need for switching and sensing mechanisms. Instead, a “soft–hard–hard–soft” spring configuration is adopted, as shown in Figure 1. The stiffness of the soft spring is approximately 25% of that of the hard spring, a value determined based on the condition for optimal steering performance.

This vehicle is noteworthy for introducing an asymmetric bogie design, which later provided significant inspiration for the development of single-axle steering bogies in Japan.

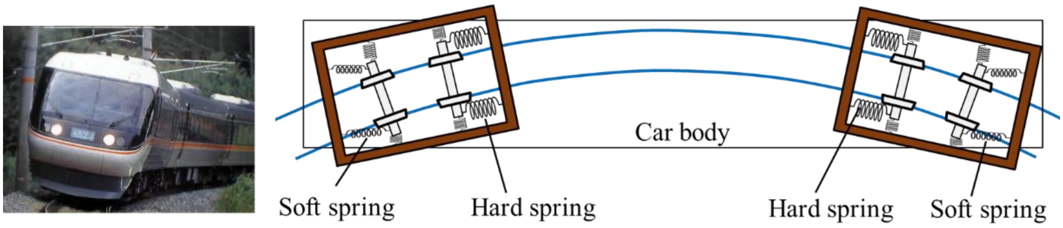


Figure 1. Series 383 EMU tilting train with steering bogie of JR Central
(Second generation train with asymmetric primary suspension design)

2.2 Link-type forced steering bogie with double-axle steering

Link-type forced steering bogies have been widely studied because curving performance can be effectively improved using a mechanical linkage mechanism, which is simpler and more reliable than active steering systems. The aim of the steering mechanism is to achieve radial steering of each wheelset along curved tracks. In earlier developments, radial steering of single-axle running gear was realized using hydraulic steering systems, in which the relative yaw angle between the car body and the bogie frame was used as an input signal, or through mechanical linkages connecting car bodies and wheelsets. In addition, interconnected configurations of two single-axle running gears have also been developed to achieve radial steering.

As a representative example of a Japanese steering bogie with a linkage mechanism, Figure 2 shows a Z-link steering bogie applied to the JR Hokkaido Series 283 diesel multiple unit (DMU) in 1997 [9]. In this vehicle, the diesel engine is mounted on the car body, and therefore traction components such as gear units are not installed on the bogie. This configuration is advantageous for steering bogies, as it avoids mechanical interference with the steering mechanism and allows forced steering of the wheelsets. By combining the steering mechanism with a tilting system, higher curving speeds can be achieved in operation.

The steering bogie applied to the Sendai Subway Tozai Line, shown in Figure 3 and introduced in 2015, is characterized by a mechanism that steers both the leading and trailing wheelsets according to the bogie yaw angle. A key feature of this bogie is the adoption of a linear motor propulsion system. Since it does not require conventional traction components such as induction motors, gear units, or couplings, mechanical interference with the steering mechanism is eliminated. This configuration enables effective wheelset steering without constraints from the traction system, thereby improving curving performance in urban railway operations. However, linear motor metro systems are not widely adopted in Japan; therefore, the application of this type of steering bogie remains limited to a small number of lines, including the Sendai Subway Tozai Line.

In general, it is structurally challenging to integrate traction components such as drive motors, gear units, and braking systems with mechanisms for active wheelset steering within a single bogie, due to mechanical interference and increased system complexity. This challenge becomes even greater in the case of double-axle steering. This limitation has motivated the development of alternative concepts, as discussed in the next section.

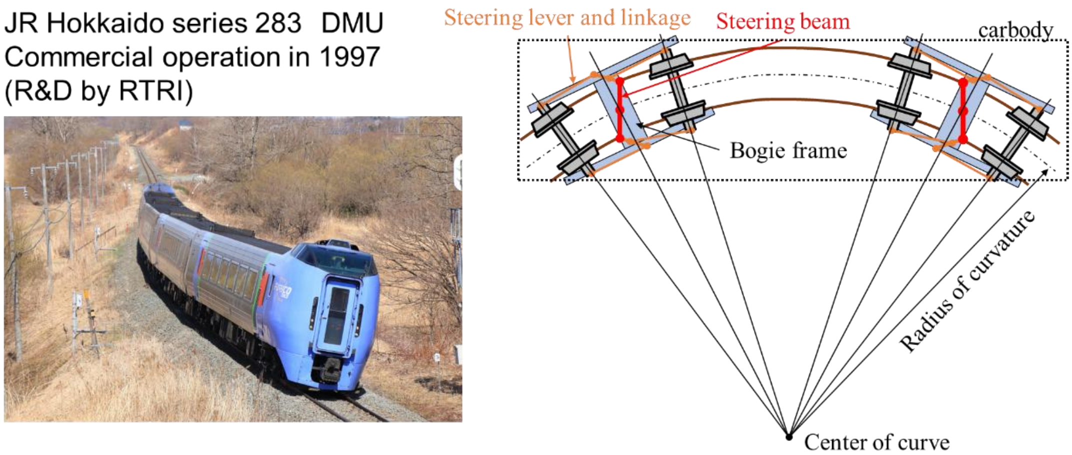


Figure 2. Alignment of Z-link type forced steering bogie on curved section and JR Hokkaido Series 283 DMU train.

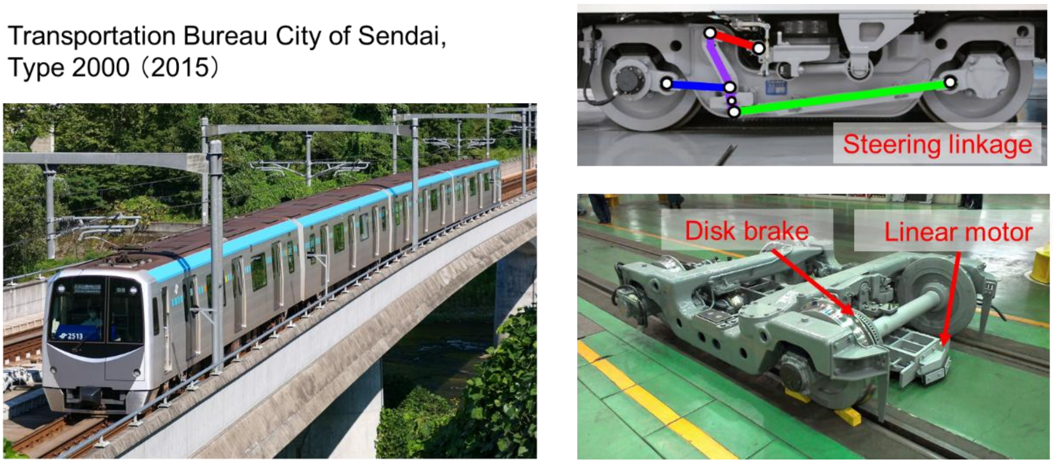


Figure 3. Steering bogie with linear motor system used in the Sendai Subway Tozai Line: overview of vehicle, steering mechanism, and bogie configuration.

2.3 Link-type forced steering bogie with single-axle steering

Although link-type forced steering bogies are effective, their application has been limited because the bogie structure becomes more complex compared with conventional bogies without steering mechanisms. A more practical problem concerns the integration of traction and braking devices, since the wheelset dynamically steers, especially in sharp curves.

In order to achieve a balance between steering performance and implementation simplicity, Tokyo Metro Co., Ltd. and Nippon Steel Corporation developed a novel concept of an asymmetric link-type forced steering bogie [10,11]. The conceptual view is shown in Figure 4. The bogie steers one wheelset per bogie, i.e., the rear wheelset in a front bogie and the front wheelset in a rear bogie, as shown in the figure. By adopting a single-axle steering system, the steering device becomes comparatively small, low-cost, and easy to maintain.

The front wheelset in a front bogie, whose angle of attack becomes the largest among all wheelsets, is equipped with traction motors and is therefore heavier than the rear wheelset of the front bogie. Therefore, wheel load reduction of the leading wheelset during curving is effectively suppressed.

In light of the great success of the bogie initially introduced in 2012 as the Tokyo Metro Series 1000 for the Ginza Line, bogies with a similar mechanism have been widely adopted in actual operation, such as on the Hibiya Line and Marunouchi Line. Not only in Tokyo Metro, but also in Tobu Railway and other subway companies in Japan, similar bogies have been introduced. The single-axle steering bogie is considered a successful example of a practical solution using an unconventional bogie concept in Japan.

Figure 5 presents an overview of the historical development of steering bogies that have been put into practical use in Japan. Initially, asymmetric self-steering bogies were implemented and further developed in conventional limited-express trains. Since around 2012, development and practical application have progressed in metro systems, aiming to improve curving performance. At present, single-axle steering bogies have been introduced by multiple railway operators, and the number of such vehicles continues to increase.

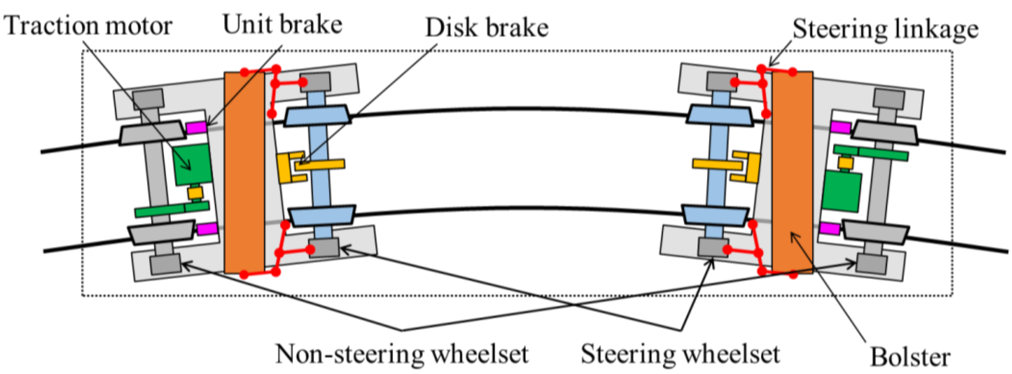


Figure 4. Arrangement of steering wheelsets, traction motors, and braking units in the asymmetric single-axle steering bogie, illustrating the separation of steering and traction functions.

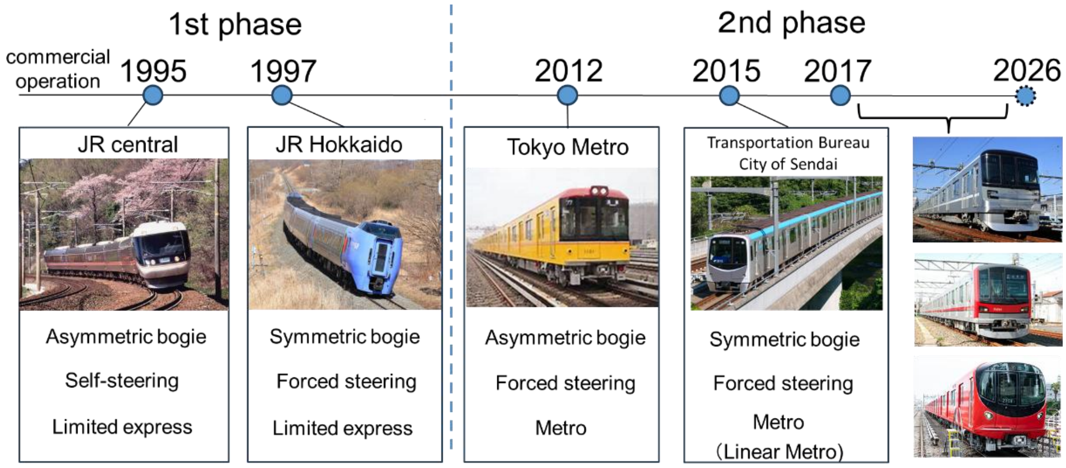


Figure 5. Overview of the historical development and practical implementation of steering bogies in Japan.

3 Dynamics of Single-Axle Steering Bogies

3.1 Mechanism of lateral force reduction

The mechanism of lateral force reduction in the single-axle steering bogie is discussed in this section. In a front bogie, the rear wheelset is steered toward the high rail, as shown in Figure 6. As a result, the angle of attack of the rear wheelset increases, causing the wheelset to shift toward the high rail. This increases the rolling radius difference between the wheels, thereby reducing the longitudinal creep force at the rear wheelset.

Furthermore, the lateral displacement of the rear wheelset toward the high rail increases the bogie yaw angle, leading to a transition of the bogie state from an under-steered condition to a radial steering condition. This transition reduces the angle of attack of the leading wheelset, which is not directly steered. Consequently, both the lateral creep force at the leading wheelset and the longitudinal creep force at the rear wheelset are reduced. As a result, the lateral force acting on the outer wheel of the leading wheelset is effectively decreased.

Figure 7 presents the results of numerical simulations, demonstrating reductions in both the angle of attack and the derailment coefficient. The circular curve radius is set to 160 m, V=25km/h and the wheel–rail friction coefficient is assumed to be 0.3. The comparison focuses on the first wheelset of the vehicle. As shown in the figure, the single-axle steering bogie reduces the angle of attack by approximately 45% compared with a conventional bogie. In addition, the lateral force is also reduced by about 30% under steady curving conditions, clearly demonstrating the effectiveness of the single-axle steering bogie.

Figure 8 compares the performance over a range of curve radii, where (a) shows the angle of attack and (b) shows the derailment coefficient. As the curve radius decreases, the reduction effect of the single-axle steering bogie becomes more pronounced. In other words, the advantage over the conventional bogie is greater in sharper curves. These results indicate that the single-axle steering bogie is particularly well suited to metro systems, where sharp curves are frequently encountered.

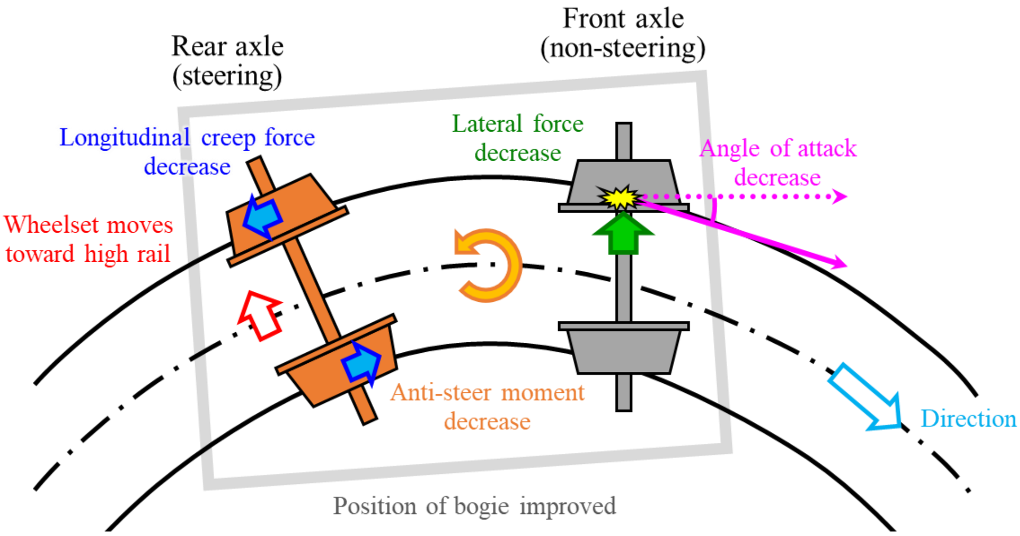
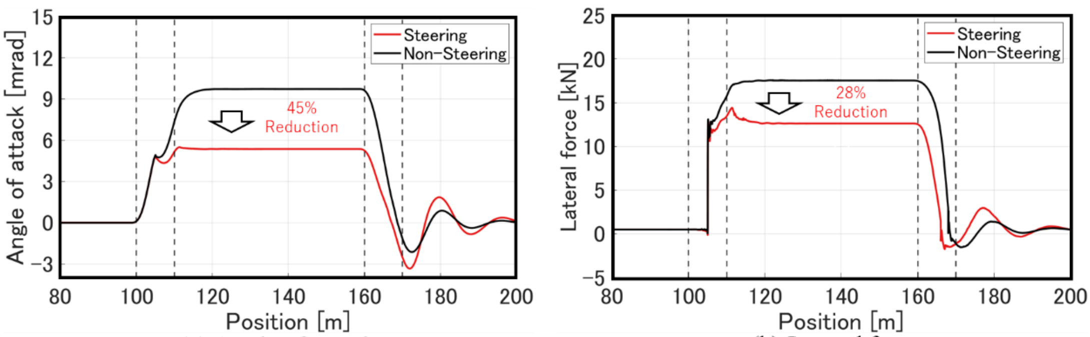
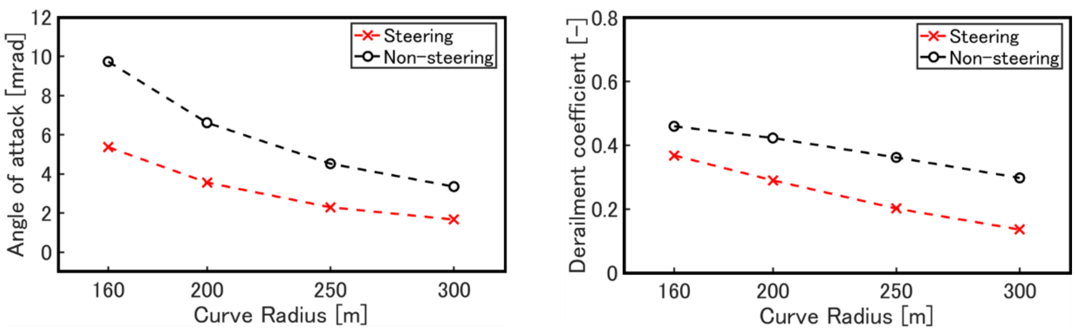


Figure 6. Behaviour of a single-axle steering bogie at the front of a vehicle negotiating a sharp curve [10].



(a) Angle of attack (b) Lateral force

Figure 7. Comparison of angle of attack (a) and lateral force (b) obtained from numerical simulations for the first wheelset.



(a) Angle of attack (b) Derailment coefficient

Figure 8. Comparison of angle of attack (a) and derailment coefficient (b) between a conventional bogie and a single-axle steering bogie over a range of curve radii.

3.2 Effectiveness of the bogie based on the field data

The effectiveness of the single-axle steering bogie is evaluated based on field measurement data. Figure 9 shows results of PQ measurements using an instrumented wheel on a commercial line with a curve radius of 167 m. The comparison is made between a condition in which the steering linkage is fixed to simulate a conventional bogie and the actual steering bogie. As shown in the figure, the steering bogie achieves a reduction in lateral force of approximately 30%, demonstrating its effectiveness under actual operating conditions.

Figure 10 shows the PQ monitoring steering bogie used for continuous measurement during commercial operation [12,13]. This bogie is equipped with sensors capable of measuring wheel–rail contact forces in service, enabling the acquisition of detailed dynamic data under actual operating conditions.

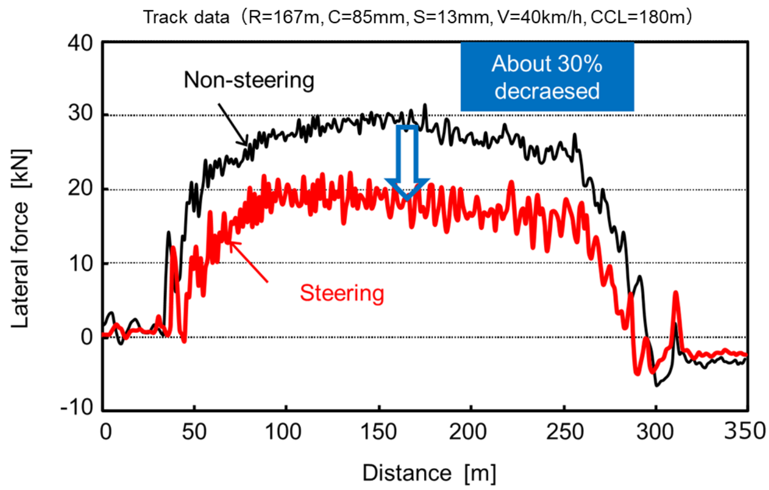


Figure 9. Comparison of lateral force on the outer rail of the leading wheelset during curving for a steering bogie and a conventional bogie [11].

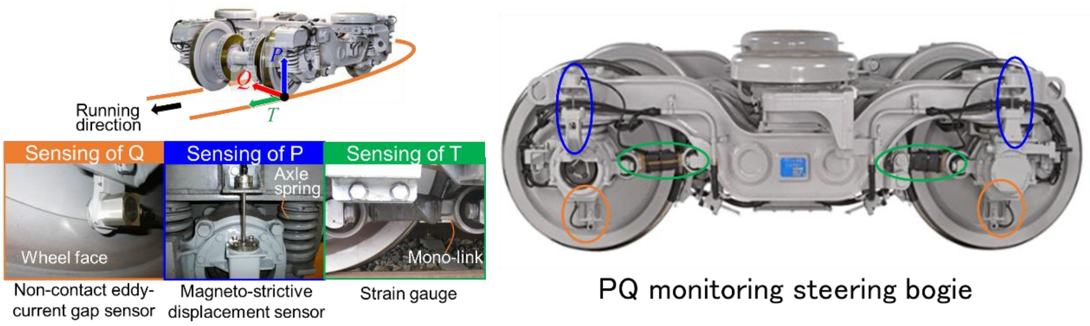


Figure 10. PQ monitoring steering bogie [13].

Figure 11 shows derailment coefficients obtained from PQ measurements during commercial operation using a PQ monitoring bogie. The horizontal axis represents the curve radius, and the vertical axis shows the maximum derailment coefficient in each curve. Each data point corresponds to a single passage through a curve. The figure compares the single-axle steering bogie with a conventional bogie. As shown, the data for the single-axle steering bogie are consistently lower than those for the conventional bogie. These results indicate that the single-axle steering bogie effectively reduces the derailment coefficient over a wide range of curve radii, thereby improving curving performance.

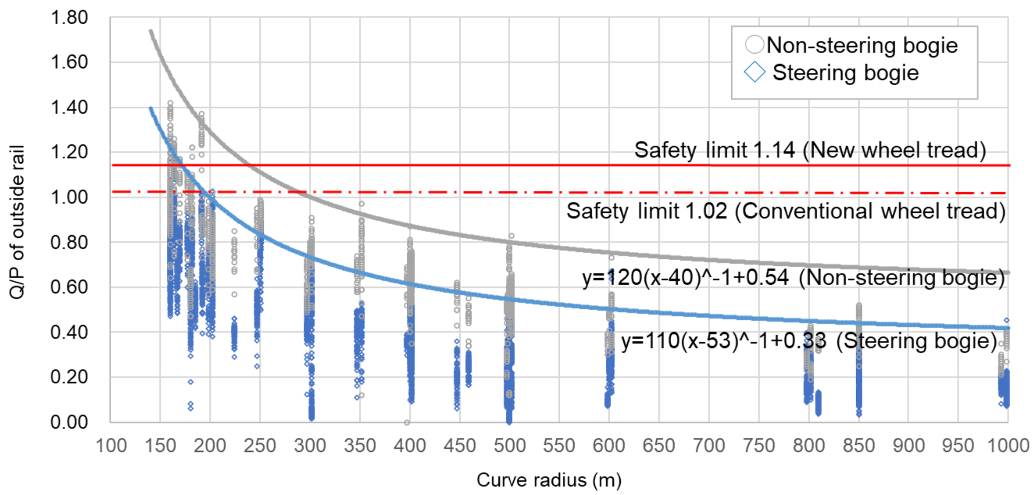


Figure 11. Maximum derailment coefficients from PQ measurements during commercial operation plotted against curve radius for a conventional bogie and a single-axle steering bogie [13].

4 Conclusions

This paper reviews the development and dynamic characteristics of steering bogies, with particular emphasis on asymmetric concepts applied in Japan. Although various steering technologies have been proposed over many years, only a limited number have been successfully implemented in practical railway systems. While conventional bogies offer excellent stability and simplicity, their curving performance remains limited under severe conditions.

Link-type forced steering improves curving performance by promoting radial alignment of wheelsets; however, its application has been restricted by structural complexity and difficulties in integrating traction and braking components. These challenges become more significant in the case of double-axle steering.

To address these issues, the asymmetric single-axle steering concept provides a practical balance between performance and simplicity. By steering only one wheelset per bogie, this concept enables effective steering while maintaining compatibility with traction and braking systems. Both dynamic analysis and field measurements confirm significant reductions in lateral force and derailment coefficient, particularly under sharp curve conditions.

The successful implementation of this concept in Japanese metro systems demonstrates that unconventional yet practical bogie designs can be realized in large-scale operation. These results suggest that future bogie design should focus on well-balanced solutions combining mechanical simplicity and effective steering performance.

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