Technology

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Braking Systems

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Early Brakes

All rolling stock has some form of braking device, so that it can decelerate and stop when necessary. The first cars with a braking system were apparently small trucks running on rails in mines. The miners used a lever to push a wood block against a wheel. However, such manual devices became insufficient as the mass and speed of rolling stock increased, so braking systems using motive power were introduced.

By the 1860s, express trains were achieving speeds of about 80 km/h in England. But at that time, brakes were not used on all cars in a train. The engine driver and a brakeman in the last passenger car would each apply a hand brake, with the driver using the whistle to signal to the brakeman when it was time to brake. This rudimentary system caused many accidents that might have been avoided. Realizing this, railway companies began installing braking equipment, generally using either vacuum brakes or air brakes. Of these two systems, only air brakes still remain in use.

George Westinghouse, an American, invented the air brake. In April 1869, he invited the public to a trial run of a Pennsylvania Railroad train fitted with his air brake system. The train had to make an emergency stop to avoid hitting a horse carriage that had stopped on a level crossing. This famous incident ensured that all major railways in the USA would adopt Westinghouse's new air brake system. In 1878, Westinghouse participated in a famous experiment conducted by Galton in England. During this experiment, a train travelling at 96 km/h came to a complete stop in the amazingly short distance of just 183 m, a record that still stands today. The triple valve that Westinghouse developed in 1879 for his air brake system was of such a high design standard that it remained in use with only slight modifications until very recently.

In an air-brake system, compressed air forces a piston-driven brake shoe against the wheel. The brake shoes can be made from a number of different substances, including cast iron and synthetic materials. In some modern systems, the braking force is not applied directly to the wheel. For example, in a disc brake system, the force is applied by clamping brake calipers to both sides of axle-mounted or wheel-mounted discs, thereby stopping the wheel.

Braking Systems of Japanese Railways

A steam locomotive with a steam brake pulled the train on Japan's first railway from Shimbashi (Tokyo) to Yokohama opened in 1872. Only the locomotive, which generated the steam, had a steam brake (Fig. 1), so the last car had a hand-braking device. A vacuum brake powered by a steam ejector was later developed, making it possible to apply braking force

Figure 1 Early Braking System

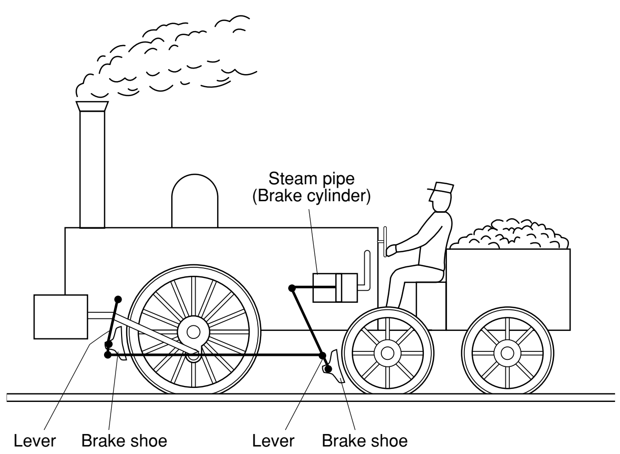
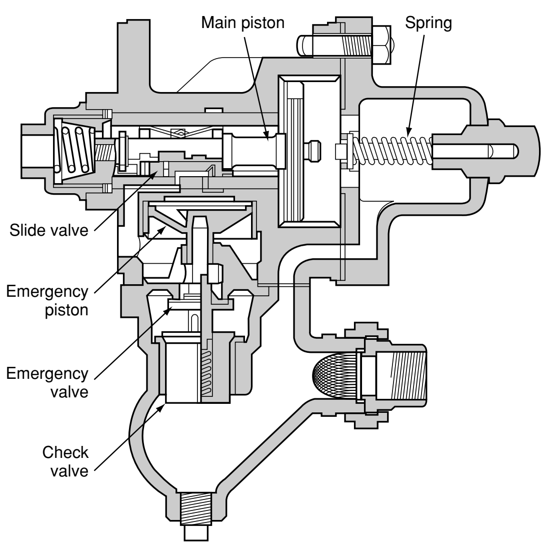


Figure 2 K Triple Valve Air Brake Device in Japan



to each car using the difference between atmospheric pressure and the vacuum. Train travel became safer after this system was introduced on passenger cars in about 1895.

When Japan's railways were nationalized in 1906, the total track length was 7153 km. In 1918, the Ministry of Railways stipulated that air brakes were to be installed on all rolling stock, because they were easier to maintain than vacuum brakes. To meet this regulation, rolling stock braking systems were modified over a period of about 10 years, starting in 1920. By 1931, all Japanese trains had air brakes based on the K triple valve (Fig. 2), which was itself based on Westinghouse's triple valve.

Today, most of Japan's passenger trains are electric; of the approximately 2000 carriages manufactured each year in Japan, 97% are for electric trains. Air brakes with solenoid valves were introduced in every car of electric rolling stock in 1955, providing a more efficient braking system.

Dynamic brakes, which generate electricity, were introduced at the same time. When the Tokaido Shinkansen opened in 1964, it had a combination of two systems: an air brake system and a dynamic brake system. The more efficient electric command air brake system was introduced around 1970, and is used in recent shinkansen and narrow-gauge EMU trains.

Figure 3 Automatic Air Brake System

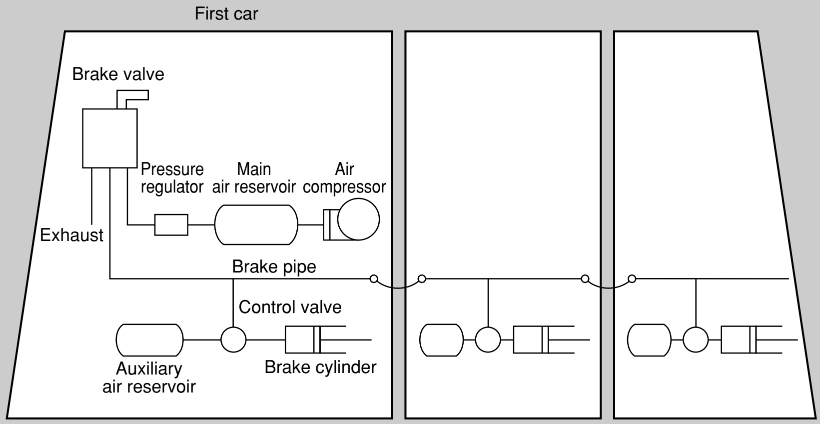
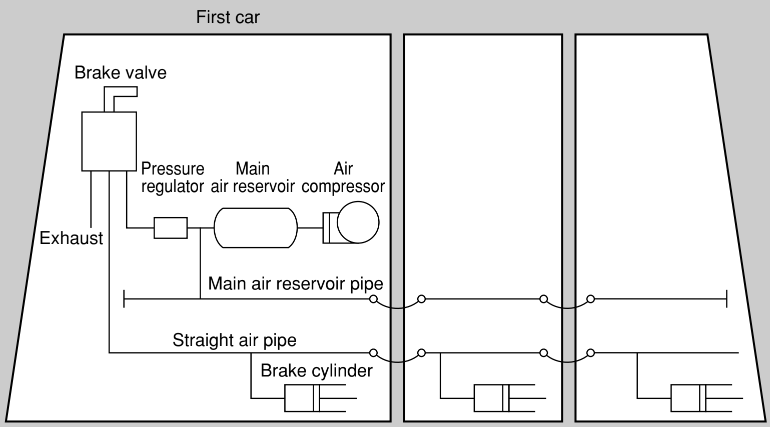


Figure 4 Straight Air Brake System



Basic Principles of Air Brake Systems

Figure 3 shows the arrangement of an automatic air brake system. Air compressors mounted every two to four cars supply compressed air to the air brakes. The air, which is compressed to 700 to 900 kPa, is piped under the car floors to main air reservoirs. The air pressure is lowered to 490 kPa by a pressure regulator and the air is fed via the brake valve, brake pipes, and control valves to the auxiliary air reservoirs. When the compressed air in the brake pipes and auxiliary air reservoirs of each car is at 490 kPa, the brakes are not activated. However, the activated brake valve cuts the flow of air from the pressure regulator, so the air pressure in the brake pipes falls. The fall in air pressure is detected by the control valves on each car. The control valves then regulate the flow of compressed air from the auxiliary air reservoirs to the brake cylinders. The brake cylinders activate the basic braking mechanisms (explained later) to slow down and stop the car. The control valves regulate the flow of air from the auxiliary air reservoirs to the brake cylinders at a pressure that is proportional to the pressure drop in the brake pipes.

Figure 4 shows a straight air brake system. Unlike the automatic air brake system

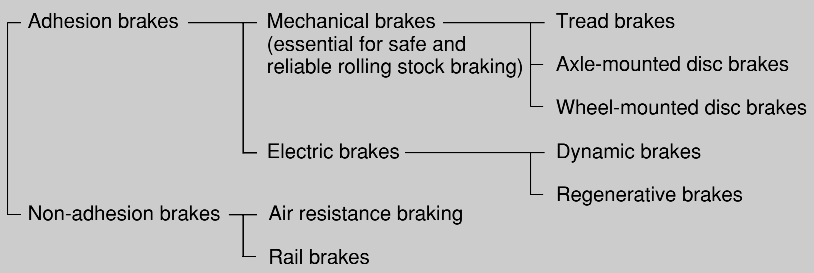


Figure 5 Braking Mechanisms

described above, the straight air brake system does not have a control valve or auxiliary air reservoir in each car. Activation of the brake valve forces compressed air through the straight air pipe to the brake cylinders, activating the basic braking mechanism.

However, since the straight air pipes do not contain compressed air during normal running conditions, the brakes would fail if cars became uncoupled. To avoid this problem, the straight air brake system can be used in conjunction with the automatic air brake system. It can also be avoided by running another pipe, called a main air reservoir pipe, from the first to the last car. The air pressure in this pipe acts like the compressed air in the brake pipes of the automatic air brake system. If the compressed air in this main air reservoir pipe falls, or if it leaks from air pipes or from air hoses between cars, etc., the pressure drop is detected and the brakes are applied automatically. For example, in shinkansen, the brakes are applied automatically if the air pressure in the piping falls to 600 kPa.

Braking Mechanisms

Government regulations specify braking distance and deceleration rates to ensure safe operation of rolling stock. Japanese regulations require that narrow-gauge trains travelling at maximum speed must be able to stop within 600 m. To ensure this short braking distance, narrow-gauge trains presently have a maximum speed of 130 km/h, but research is now being conducted into development of more efficient braking technologies that will achieve shorter braking distance, meaning faster speeds for the same braking distance. Shinkansen regulations specify deceleration rates for each speed slot, so here too new braking technologies must be developed to permit deceleration at rates greater than those currently specified. If trains were not equipped with fail-safe mechanisms to ensure quick stops, they could not run at high speeds, and transit systems could not operate trains at short headway. The 300 km/h speeds of shinkansen and the two-minute headway of Tokyo commuter trains are only possible due to the precision and superior response of their braking systems. It is worth remembering that earlier brake failures and improper use of braking systems resulted in many trains overrunning the bumpers at the end of track sections, causing serious damage.

The amount of energy produced by braking is tremendous. This can be illustrated by one example. A 16-car Series 500 shinkansen with all seats occupied weighs about 509 tonnes. The amount of energy that must be absorbed when this train is stopped from its maximum speed of 300 km/h is 1.77×10^9 joules. This is enough to raise the temperature of 4200 liters of water from freezing point to boiling point and is equivalent to 1,000 to 2,000 times the amount of energy used by an automobile. When a braking force is applied to stop the cars, the force must be transmitted to something other than the cars, for example, to the rails. The braking force can be transmitted either through adhesion, which makes use of friction at the point where the wheels touch the rails, or through ways that do not involve adhesion (Fig. 5). Most rolling stock in Japan currently uses adhesion braking methods. Non-adhesion methods do not use friction at the point where the wheels touch the rails and include mounting panels on cars to increase air resistance, or the direct application of pressure from the car to the rail, using shoes. This latter technique involves a device called a rail brake.

Most rolling stock braking systems use either electrical brakes, or mechanical brakes.

Electric Brake Systems

Another braking system used by electric trains is electrical dynamic braking that converts the motor into a braking generator dissipating the kinetic energy as heat. Regenerative braking uses the generated electricity instead of dissipating it as heat, and is becoming more common due to its ability to save energy.

Figure 6a shows the principles of the electrical traction, dynamic braking and regenerative braking systems. Although the traction motor drives and accelerates the train, during braking, it acts as an electric generator instead,forming part of a circuit that consists of a main resistor (rheostat), armatures and a field system. Electricity flows through the circuit and is consumed by the main resistor, which converts the kinetic energy of the train into heat and thereby acts as a brake.

Regenerative braking uses the same type of circuit, but the electricity generated by braking is not consumed by the main resistor. Instead, it is transmitted to the overhead wire. The flow of this electricity is controlled by a controller under the pantograph that opens and closes with split-second timing.

Electrical brake systems are economical because they do not use friction elements, unlike mechanical brake systems. The regenerative braking system is even more economical because the electricity regenerated from the train's kinetic energy is transmitted to the overhead wire, and becomes available to power other rolling stock (Fig. 6b). The problem with electrical brake systems is that they occasionally malfunction because they have complex circuits. For this reason they cannot be used as emergency brakes. In an electrical braking system, the braking force of the traction motor (generator) is transmitted to the wheels via gears (Fig. 7). The generated electricity is adjusted to control braking force.

Figure 6a Principles of Electrical Braking

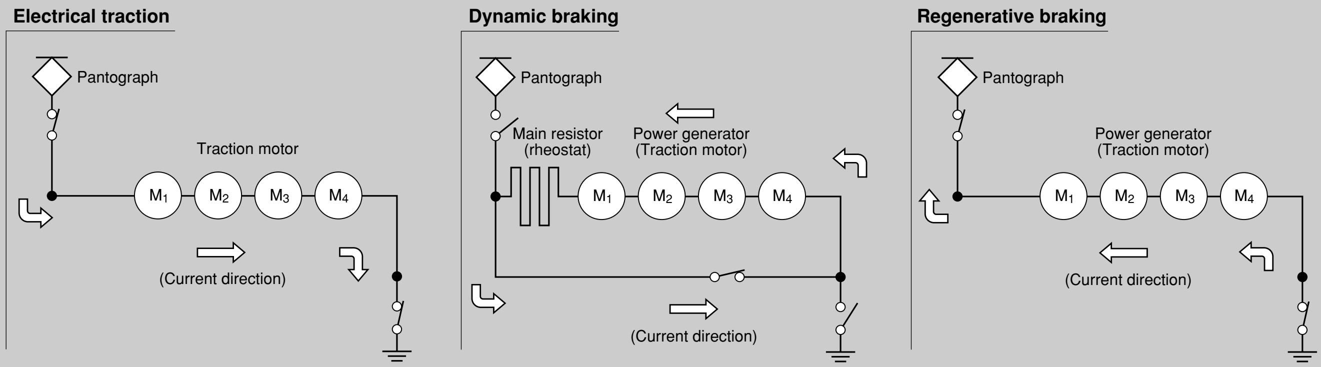


Figure 6b Recycling Regenerated Electric Power

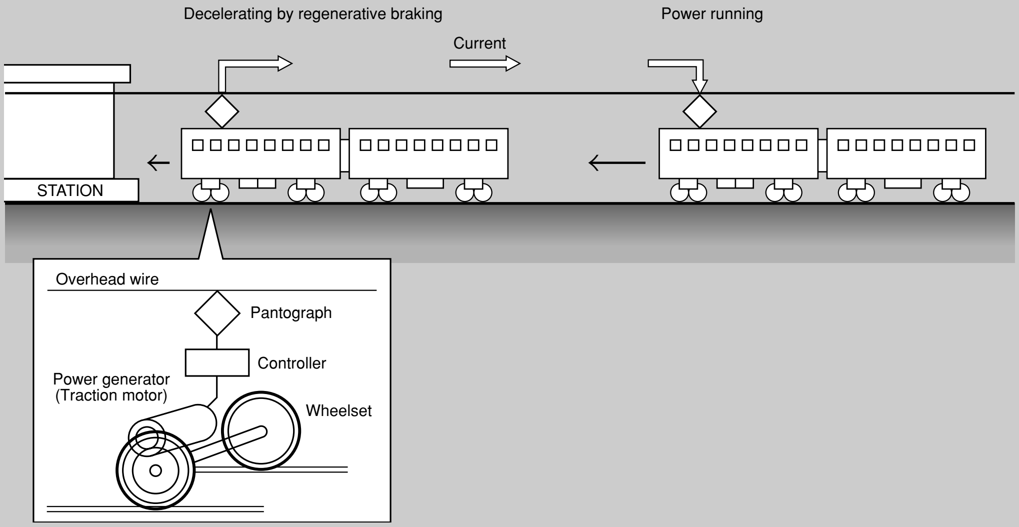
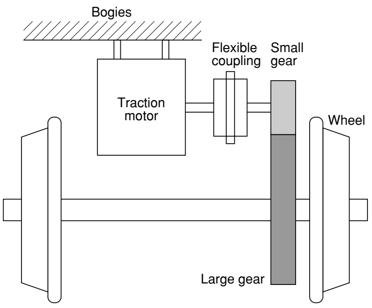


Figure 7 Transmission of Braking Force from Traction Motor to Wheels



Mechanical Braking Systems

The basic braking devices used by mechanical braking systems are: wheel-tread brakes (Fig. 8), axle-mounted disc brakes (Fig. 9), and wheel-mounted disc brakes (Fig. 10). All these mechanisms use an object (a brake shoe or lining) that applies friction to the disc. The applied pressure is adjusted to control the braking force. In the wheel-tread brake, the brake shoe applies friction to the wheel tread, creating a sliding effect. High-speed trains cannot use this type of brake, since doing so would damage the wheel tread. Instead, they use axle- or wheel-mounted disc brakes. Axle-mounted disc brakes are used on trailer bogies, because they have sufficient space to accommodate such a system. Wheel-mounted disc brakes are used on motor bogies that must accommodate the traction motor and have insufficient space for an axle-mounted brake. In both systems, compressed air or oil is applied to a brake cylinder that forces the brake lining against the disc. Brake discs are dead weight that are useful only during braking, so operators are keen to install lighter discs. Carbon/carbon-

Figure 8 Wheel-Tread Brake System

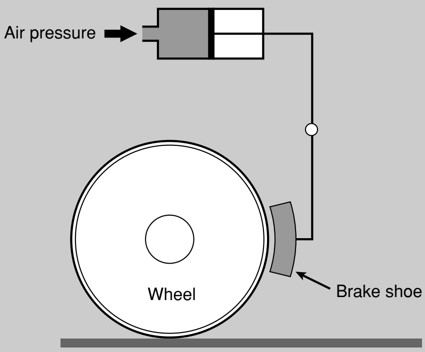


Figure 9 Axle-Mounted Disc Brake System

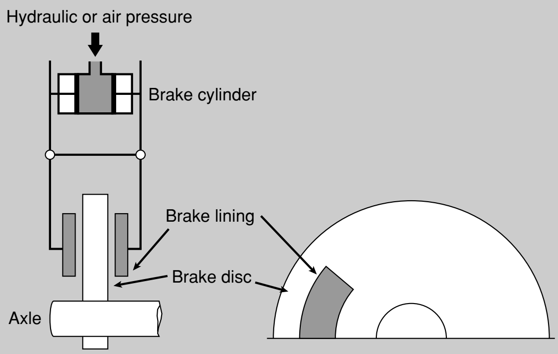


Figure 10 Wheel-Mounted Disc Brake System

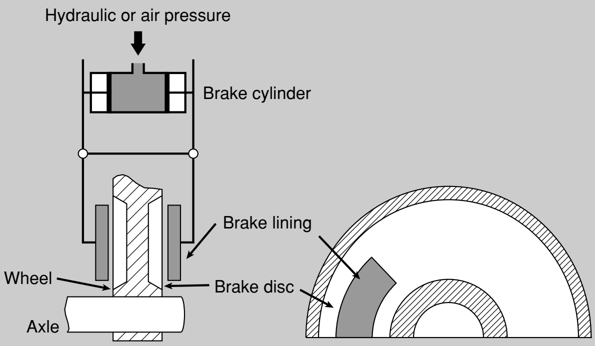
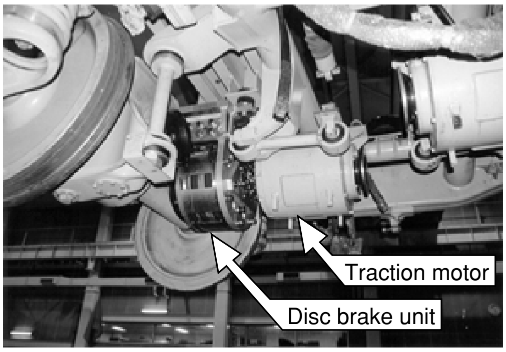


Figure 11 Carbon/Carbon-Composite Multi-Disc System



(RTRI)

Figure 12 Digital Electric Command System

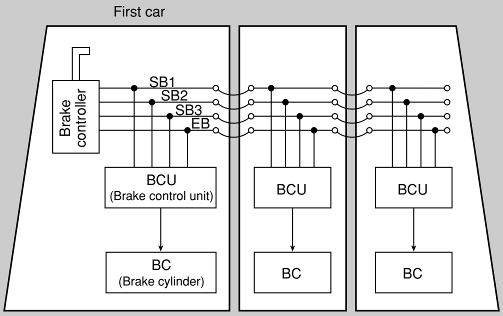


Figure 13 Examples of Air Command lines

	Brake notches							
Command lines	1	2	3	4	5	6	7	EB
SB1	○		○		○		○	
SB2		○	○			○	○	
SB3				○	○	○	○	
EB	○	○	○	○	○	○	○	

SB: Service brake
EB: Emergency brake

composite multi-discs and aluminium composite discs offer lighter weights and are viewed with considerable interest.

The carbon/carbon-composite multi-disc has alternate sections of carbon-fiber rotors and stators. During braking, they rub against each other to create a frictional force that slows down the wheel or axle. The disc is lighter than conventional materials and has excellent heat-resistant properties. (Fig. 11)

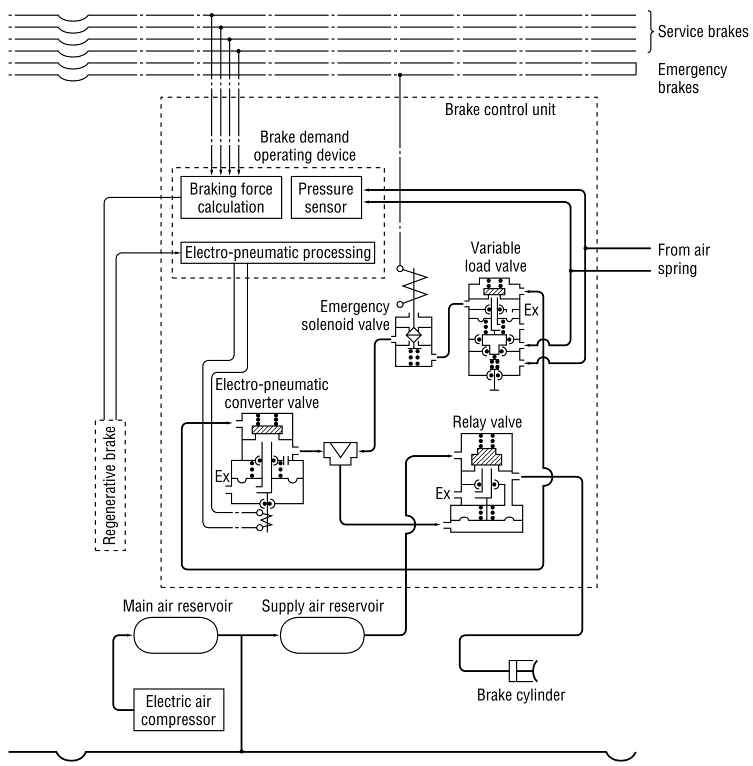
Aluminium-composite brake discs can be made much lighter than today's forged steel and cast-iron brake discs. In addition, their structure is the same for both axle- or wheel-mounted discs, achieving a much lighter disc without design changes.

Braking Command

Brakes must function on every car at the same moment and at the exact required force. The timing and the braking force are controlled by an electrical command system or an air command system.

Figures 12, 13 and 14 show a digital electric command system, an air pressure command line, and the systems in a brake control unit (BCU) system, respectively. The digital electric command system controls braking force by applying digital voltage through wires running the full length of the train. The air command system, otherwise known as an analog dispatcher system, controls the air pressure in pipes that also run the full length of the train. The air command system is used in freight wagons and some passenger cars, and can transmit braking commands in rolling stock with no power supply. The electric command system is used in shinkansen and other new trains, and offers lighter weight and better response times, even in long trains. The BCU system keeps the braking force at the optimum level by adjusting it in accordance with braking commands, electrical

Figure 14 Brake Control Unit (BCU) System



braking force (regenerative braking), number of passengers, and speed, etc.

Improving Brake Performance

Compensating for adhesion loss and sliding

During rain and snow, wet rails make it impossible to apply a strong braking force at the front of a train. If such a force were applied, the result would be similar to the skidding of an automobile when it brakes suddenly on an icy road. To prevent this sliding, adhesion base values determined using data from rolling stock and bench tests, provide norms that must not be exceeded (Fig. 15). Incidentally, braking force is not applied uniformly to all cars, but to a greater extent to rear cars.

If brakes are applied too strongly in wet conditions, the wheels stop turning but the train continues to slide forward, wearing down the wheel and creating small flat sections that become the source of noise and vibration. To prevent this wear, a wheel slide protection device that detects wheel sliding and automatically reduces the braking force has been developed (Fig. 16). It has been installed on shinkansen from the first models and is now used on conventional and special express trains, and even on new commuter trains.

Ceramic particle jetting system

The wheel tread and top surface of the rail have minute surface unevenness that promotes adhesion and facilitates transmission of the driving power from the wheels to the rails. However, if there is a water film at the point of contact between the wheel tread and rail, the adhesion is lost. Higher train speeds and lower temperatures increase the water film; at speeds of 300 km/h, the film thickness is estimated to be approximately 1 μm.

To improve wheel-rail adhesion under such conditions, a ceramic particle jetting

Figure 15 Shinkansen Deceleration Rates

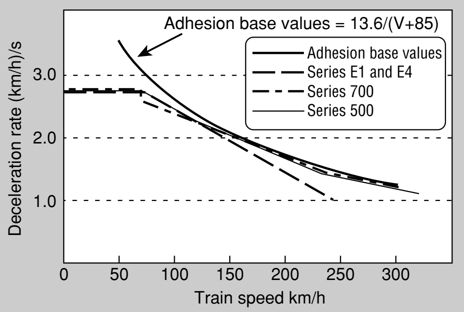


Figure 16 Wheel Slide Protection Device

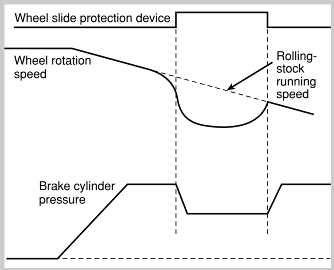


Figure 17 Ceramic Particle Jetting System

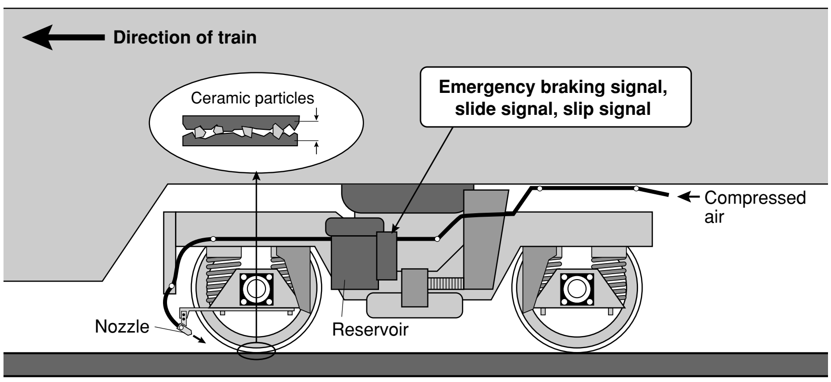
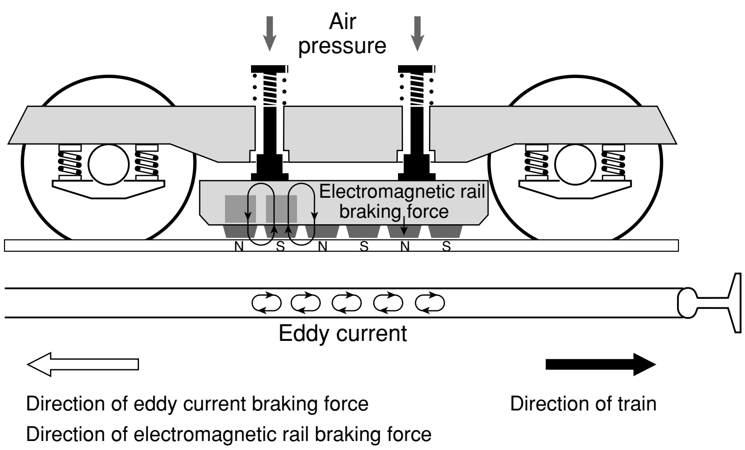


Figure 18 Rail Brake System

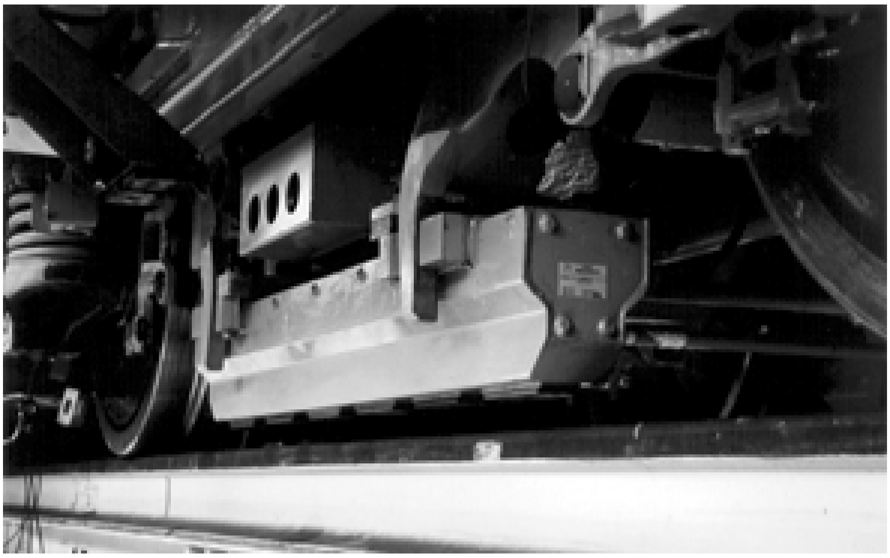


system uses compressed air to spray fine ceramic particles (about 10-μm diameter) between the wheel tread and rail. The ceramic particles act as tiny wedges, increasing adhesion. This system is used on the Series 500 *Nozomi* shinkansen and on conventional rolling stock operating on steep gradients (Fig. 17.)

Rail brakes

Current train braking systems depend heavily on adhesion between the wheel tread and the rail. But in the case of shinkansen and other high-speed rolling stock, adhesion decreases as speeds increase, making it necessary for the train to reduce braking force to avoid wheel sliding. The end result is longer braking distances. To solve this problem, a rail brake system that does not depend on adhesion was developed.

The rail brakes developed for the first shinkansen were never put into use. It would have produced a braking force by using magnetic repulsion obtained from eddy currents generated on the top surface of the rails. It was not installed because of the fear that the eddy currents would heat small sections of the rail to such a degree that the rail would bend sideways. The problem has been solved by development of a rail brake that uses eddy currents and frictional force. Figure 18 shows the structure of this system. The rail brake on the bogie is connected to batteries that create alternating north and south poles forming magnetic fields between the poles. The magnetic fields generate eddy currents in the top surface of the rails, creating a force acting in an opposite direction to the movement of the train, in other words, a braking force. This type of rail brake system shows considerable potential as a non-adhesion braking mechanism able to complement adhesion braking. ■



Rail brake system (RTRI)

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