Abstract
As an effective means for improving both railway vehicle's tractive performance and environmental performance, we developed a new railway hybrid traction system. The Motor-Assisted Hybrid System (MA Hybrid System) we developed is the hybrid traction system that can gain the tractive power exceeding the engine power, by combining the Active Shift Transmission transmitting engine power efficiently to the wheels and a motor. This system is a diesel traction system with a high cost performance solving a trade-off problem between the improvement in tractive performance and energy conservation and environmental load reduction.

1. Introduction
Global environment conservation is vital to the international community and this issue urgently requires continuous efforts in energy conservation and emission reduction for every railway operator. Meanwhile, the achievement of higher-speed railway operation can provide more user-oriented convenience that serves as an efficient means for improving the quality of transport services and maintaining and improving associated competitiveness to other public transportation. However, the improvement in train speed primarily requires the enhancement of vehicle's power, resulting in a trade-off between environmental conservation and higher train speed operation.

In railway diesel vehicles, the development of a hybrid traction system, combined with energy storage system, seems to be an effective means of coping with both improvement of the tractive performance and environment conservation. A series hybrid traction system for railway vehicles has been developed for commercial use, however there are some disadvantages in improving tractive performance, such as larger weight of the electric system caused by battery capacity increase as well as higher initial costs.

Consequently, we have focused on a new hybrid traction system for railway vehicles, aiming at improvement of both tractive performance and environmentally-friendliness of diesel vehicles at a low cost.

2. Power transmission system for conventional diesel vehicle
In a conventional engine-driven diesel vehicle, the vehicle gains tractive efforts through the hydraulic transmission system which consists of a torque converter and a transmission as shown in Fig.1.

At a low operation speed, the engine power is transmitted through a torque converter to prevent engine stall and to...
give the vehicle a smooth start. The torque converter has the disadvantage of low transmission efficiency due to hydraulic (oil) power transmission. At a high speed, not through the torque converter, the wet-type multiple-plate hydraulic clutch units change gear trains giving the vehicle running speed. This conventional system causes friction loss in clutch plates when changing gear trains, and hydraulic power loss in idle clutch units.

3. Motor-assisted hybrid traction system

The Motor-Assisted (MA) hybrid system, as shown in Fig. 2, is the world’s first diesel hybrid system for railway vehicles combining an Active Shift Transmission which transmits engine power to the driving wheels and a motor. The system generates a higher power than the engine power with the hybrid combination.

The system is composed of an Active Shift Transmission, a motor connected with the transmission, an inverter, a battery and a controller. The tractive power is transmitted to the driving wheels with four fundamental operation modes as follows.

(1) Drive mode propelled by only the engine power through the transmission
(2) Drive mode propelled by only the motor power through the transmission
(3) Combination mode of (1) and (2), i.e. motor-assisted drive mode propelled by the engine power and additional power generated by the motor
(4) Regenerative brake mode in which battery is charged using the motor as a generator while a vehicle brakes

The Motor-Assisted hybrid system is primarily characterised by as mentioned later that one motor takes three functions which are transmission control, power assistance for the engine and generation during coasting and braking.
The transmission provides extremely small heat loss and high tractive efficiency because it does not have any torque converter or wet-type multiple-plate hydraulic clutch unit. The conventional hydraulic transmission requires a radiator installed underneath a vehicle body to cool oil used for a torque converter and hydraulic clutch units. On the other hand, the developed transmission needs lubrication oil only for gears and bearings, therefore oil temperature rise is extremely small and an oil radiator is not necessary. Subsequently, the power loss caused by an oil pump of the transmission developed is estimated to be less than 1(kW), although a conventional transmission has approx. 4(kW). In the conventional transmission, the total tractive efficiency is 77% within the vehicle speed range where a torque converter operates and 89% for the speed range without using the converter. The Active Shift Transmission improves the efficiency to more than 90% at all speed ranges.

4. Typical operation modes of the system

The typical operation modes of the system are described below referring to Fig. 3. When a vehicle stops at a station for a long time, the system stops the engine for engine noise reduction. After the system receives a powering command, the vehicle starts acceleration with motor drive mode A.

When the vehicle speed reaches around 45(km/h), the drive mode shits to mode B. In this mode, the engine starts keeping acceleration with the motor and then the engine power is transmitted to the wheels. At this moment, the vehicle is accelerated with the motor-assisted drive mode in which the vehicle gains tractive efforts exceeding engine power.

After acceleration, the vehicle coasts with no traction. Because the electricity of the battery usually decreases after acceleration, the system mode shifts to coasting generation mode C. In this mode, the engine drives the motor to charge the battery.

After repeating powering and coasting, the vehicle decelerates to stop at a station. The system shifts to regeneration mode D in which the motor is driven by the wheels to gain power to charge the battery. The MA system recovers brake energy, which is thermally diffused in the conventional diesel vehicle, storing in the battery and reuses it effectively for the next acceleration.

![Fig.3 Typical operation modes of MA system](image-url)
When the vehicle is at a station for a short stop, the system does not stop the engine. In this case, the vehicle accelerates with the motor up to about 20(km/h), although the engine is in idle operation. After the vehicle reaches 20(km/h), the system mode shifts to mode B.

In addition to these typical operation modes, the system has over 30 modes such as:

- engine brake mode in which brake power of the vehicle is transmitted to the engine as of the conventional diesel vehicles,
- downshift control for regenerative brake to improve charging power,
- engine start mode when State of Charge(SOC) of the battery is low,
- powering generation mode in case of unexpected battery consumption by auxiliary equipment.

The MA system controls all these operation modes considering parameters such as vehicle speed and SOC giving the vehicle tractive efforts.

5. Simulated run

The effect of reducing fuel consumption in the MA system is examined by numerical simulation. By assuming tractive efficiency for each device as in Fig. 4, the engine workload is calculated under the conditions of a station distance and a maximum running speed. Fig. 5 shows an example of the simulation results. The fuel consumption rate (L/km) is obtained by converting engine workload to fuel consumption and dividing the fuel consumption by the vehicle mileage.

Compared to the consumption rate of the reference vehicle described later, it is expected that the MA system reduces the rate by about 20% for a mean station distance of 2.3(km) and about 15% for long distance vehicles such as inter-city trains.

6. Bench test

Our development process started with the trial production of only Active Shift Transmission as shown in Fig.6. Its operation was checked assembled with an inverter, a motor used for electric trains and a set of lithium-ion battery modules. Fig. 7 shows the bench test configuration.
The engine power is limited to approx. 190(kW) due to the limitation of experimental facilities. The bench test was carried out to verify a series of fundamental functions of the transmission. Fig. 8 shows the data obtained from the bench test. After finishing the bench test, we moved to the next development step, i.e. running tests on the track using a real vehicle.

7. Running tests
7.1 Vehicle system
Vehicle running test was carried out as the next stage. As well as the Active Shit Transmission, an assist motor, an inverter, a battery, etc. were produced and installed on/under a vehicle. The engine and the transmission of the vehicle were replaced by the MA hybrid system. An assist motor and an inverter were also installed underneath the vehicle body and the main circuit devices such as a battery and a main circuit breaker are placed inside the vehicle to reduce modification work. The test vehicle is named as Innovative Technology Train (ITT) shown in Fig. 9.

Summarised specifications of the original vehicle and ITT are shown in Tab. 1.

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Tab. 1 Specifications of ITT and reference vehicles
The engine used for the MA system is a common-rail diesel engine with a displacement of 13.32L and a maximum rated power of 331 (kW). The actual maximum power is reduced to 243 (kW) that is equivalent to the original vehicle.

The motor is a three phase induction motor whose rated output is 123(kW) for traction, and for generation and regeneration, its rated output is 150(kW) due to less frequent operation than traction. The installation of MA hybrid system increases the weight of the original vehicle by approx. 1.7 ton.

The targeted tractive performance of the MA system is also described as the reference vehicle in Tab.1. We aimed to design the hybrid tractive performance of ITT whose engine power is 243(kW) to be the same as that of the 331(kW) powered reference vehicle in 0 to 95(km/h) acceleration performance. In other words, our target for development can be said to reduce engine power output by 27% keeping acceleration performance.

Some tractive effort patterns of the MA hybrid system are shown in Fig.10. The transmission has four speed stages. It gives the vehicle a tractive effort with motor drive and upshifts to the 1st speed at around 20(km/h), then upshifts to further speeds according to the vehicle speed. The efforts at the 1st speed and higher depend on the assist torque that the motor generates. The maximum effort pattern the system generates is indicated as “full assist”. This pattern is designed as the target performance. The “normal assist” shown in the figure is set aiming effort continuation among motor drive and each speed stage. In the normal assist pattern, motor assist torque is designed as 20% of full torque for the 1st speed, 50% for the 2nd speed, 80% for the 3rd speed and 100% for the 4th. For the 4th speed, motor assist torque expires at 95(km/h) because a large torque assist at over 95(km/h) ineffectively consumes battery energy.

7.2 Running tests

Although, running tests will be still continuing at the moment, some results obtained from the tests carried out from August 2007 through February 2008 are described as follows.

(1) Overall transmission operation

The typical situation of the system operation running on a track is shown in Fig.11. The vehicle speed, state of gear change and SOC are indicated in the figure. It is found that the vehicle starts with the motor drive mode and accelerates through 1st to 4th speed up to 110(km/h). Although SOC decreases from 60% as the vehicle speed rises, it recovers while the vehicle coasts by the coasting generation mode and decelerates with regeneration brake. The
(2) Acceleration performance
The acceleration performance curves of ITT, the original and reference vehicle is shown in Fig.12. For ITT, curves obtained by both the full and normal assist performance are specified. With the full assist performance, it is found from the figure that the acceleration time up to 95(km/h) is exactly the same as that of the reference vehicle. Despite the engine power of ITT is 243(kW), it is verified that the acceleration performance of ITT is equivalent to the reference vehicle with 331(kW) satisfying our development target successfully.

(3) Ride comfort
Longitudinal vibration occurring in ITT and a diesel vehicle having a four-speed conventional transmission is shown in Fig.13. The MA system generates a longitudinal vibration of 0.20 to 1.13(m/s^2 p-p) during shift changes up to 4th speed, while a conventional transmission generates 1.08 to 1.67 (m/s^2 p-p). It can be thought that a 30% reduction of longitudinal vibration gives passengers better ride comfort.

(4) Battery charge and discharge control
Fig.14 shows a typical trajectory of SOC obtained while ITT gets acceleration, coasts keeping a certain top speed then brakes to a stop.
SOC is controlled within a range of 30% to 60% in consideration of a battery lifetime. Battery energy is managed as a function of the vehicle speed and SOC. Mode transition for battery control among the motor assist mode, coasting generation, regeneration brake, etc. is decided by the real-time state of the system on the SOC-speed plane. According to an energy control system, SOC is successfully managed within the designated range.
8. Advantages of MA system

System configuration of the conventional traction system, the MA hybrid system and a series hybrid system is compared in Fig.15.

In a series hybrid system (c), one traction system requires one generator and at least one driving motor. Approximately 10% of energy loss will arise because the engine power must be all converted into electricity. Therefore, to ensure tractive performance equivalent to the conventional diesel vehicle, a high-power engine will be required, along with a high-capacity generator, inverter and battery.

The MA hybrid system (b) can be made with only one motor which acts as a driving motor and a generator. A small-output motor realises the hybridisation of diesel vehicles because the system directly utilises the engine power with high transmission efficiency. It also remarkably contributes to the reduction of battery capacity and power, system weight reduction and the initial cost reduction as a consequence. It is expected that the “small, light and low cost” feature of the system significantly contributes to the early mass production and the spread of diesel hybrid railway vehicles.

In the point of tractive performance, compared with the conventional diesel vehicle with the same performance, the engine power can be lowered resulting in about 15 to 20% reduction of fuel consumption and hazardous emissions. Utilising the motor as additional power source, the MA system achieves higher tractive performance than those of any other conventional traction systems.
9. Conclusion
The cost effective MA hybrid traction system was developed, aimed at solving a trade-off problem between the improvement in tractive performance of diesel vehicle and, energy conservation and environmental load reduction. Through bench and on-track running tests, etc., it is successfully found that the system has the following functions and performance.

(1) As basic functions, motor drive, motor-assisted drive, coasting generation and regenerating brake are accomplished.
(2) Battery charge and discharge control retains enough electric energy for traction with operation mode management for coasting generation and regeneration brake.
(3) The MA system with a 243(kW) engine realises the same acceleration performance as the conventional vehicle with a 331(kW) engine installed.
(4) Fuel consumption reduction is estimated to be 15 to 20%.
(5) Motor controlled speed changes reduces gear change shocks and improves ride comfort.

A remarkable feature of the MA system is that one motor equipped with a highly efficient Active Shift Transmission has three functions;
- Transmission control
- Adding tractive power to the engine
- Charging the battery during coasting and regeneration brake.

Particularly, the tractive performance of series hybrid vehicles largely depends on the output power of the driving battery and the motor(s) having severe difficulty in improving tractive performance due to large scale electric equipment. The MA system has a potential capability to contribute to the performance improvement of diesel vehicles for the reason that the motor power is added to the tractive efforts generated by an engine.

It is also expected that the MA system realises a “small, light and low cost” diesel hybrid traction system because the main tractive power source is generated by an engine and consequently the output power of the electric equipment is considerably small, and contributes to the early mass production and the introduction of more diesel hybrid railway vehicles.

10. Future plan
We have almost finished verifying the fundamental operations, performance and availability of the MA hybrid system through on-track test runs. We are now planning long term operation of ITT from around June 2008 to examine the influence of hybrid parameters such as motor power on fuel consumption, etc. The examination results will be applied to the mass production system and we are aiming to complete the development of commercial vehicles equipped with the MA system within next three years.

References