

Featured Articles

Hybrid Wheel Loaders Incorporating Power Electronics

Kazuo Ishida

Masaki Higurashi

OVERVIEW: Hybrid vehicles that combine an engine and electric drive technology are becoming more common in the automotive industry, with widespread recognition of the excellence of their energy efficiency technologies. In the construction machinery sector, meanwhile, although use of hybrid drive in hydraulic excavators and other vehicles is growing, hybrid wheel loaders have yet to enter full-scale production despite the similarities between their drive trains and those of ordinary cars. Hitachi Construction Machinery Co., Ltd. has previously developed hybrid wheel loaders in the form of a concept vehicle and a vehicle available on limited release. By utilizing the technologies built up through this past experience as a base and making use of the power electronics technology of Hitachi, the company has now developed the ZW220HYB-5B, a hybrid wheel loader intended for full commercial production.

INTRODUCTION

CONSIDERATIONS such as global warming and other environmental impacts due to engine exhaust gases and the problem of oil scarcity have directed attention toward energy efficiency technologies for cars and other vehicles powered by fossil fuels. Hybrid electric vehicles (HEVs) that combine engine and electric drive technology are becoming more common in the automotive industry in recognition of the excellence of their energy efficiency technologies, with electric vehicles (EVs) and fuel cell vehicles (FCVs) also set to enter full-scale production. In the construction machinery sector, meanwhile, although use of hybrid drive in vehicles such as hydraulic excavators and bulldozers is growing, hybrid wheel loaders have yet to enter full-scale production.

Wheel loaders are equipped with a bucket and lifting arms and are used to dig up soil, gravel, rock, or other material, drive it to a dump truck or other form of transportation (carrying the material in the bucket), and then load the material into this other vehicle. Hitachi Construction Machinery models currently in production have standard bucket capacities between 0.3 and 6.1 m³ (operating weight between 1.9 and 46 t), and are classified according to bucket capacity, including small-sized models with bucket capacities up to 1.3 m³, medium-sized models with bucket capacities between 1.3 m³ and 5.0 m³, and large-sized models with bucket capacities of 5.0 m³ or larger.

The drive trains of medium-sized and large-sized wheel loaders with a capacity of 3.0 m³ or more have a four-wheel-drive configuration similar to that used in ordinary cars in which the power from the engine is transmitted via a torque converter and transmission to the axles and then to the tires.

Hitachi Construction Machinery developed a hybrid system with a drive train that combines engine and electric drive technology, similar to an ordinary car. It announced the LX70 medium-sized hybrid wheel loader (1.3-m³ bucket capacity) as a concept vehicle in 2003, and the L130 large hybrid wheel loader (13-m³

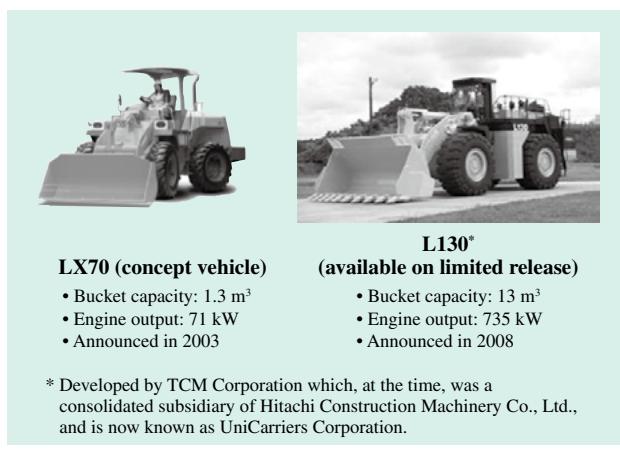


Fig. 1—Previous Hybrid Wheel Loaders Developed by Hitachi Construction Machinery.

The LX70 was announced as a concept vehicle in 2003 and the limited release of the L130 was announced in 2008.

bucket capacity) as a limited release model in 2008 (see Fig. 1). Based on technology built up from this experience and making use of the power electronics technology of Hitachi, it has now developed the ZW220HYB-5B medium-sized hybrid wheel loader (3.4-m³ bucket capacity) as a full commercial model with the aims of significantly reducing fuel consumption and carbon dioxide (CO₂) emissions.

This article provides an overview of the hybrid system in the ZW220HYB-5B and describes the results of fuel economy testing and product features.

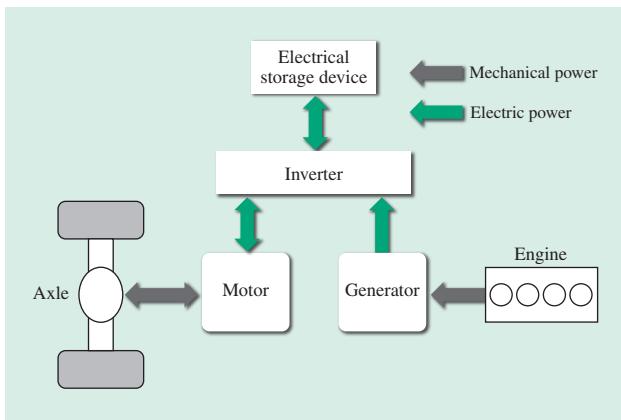


Fig. 2—Conceptual Block Diagram of Series Hybrid Configuration.

Because the engine drives the generator and the electric power from the generator drives the traction motors, a feature of this configuration is that there is no mechanical power transmission coupling between the engine and axles.

OVERVIEW OF HYBRID SYSTEM

As described above, the design of the drive trains used in conventional wheel loaders is similar to ordinary cars. Furthermore, because the dig-carry-load operation of a wheel loader involves frequent acceleration and deceleration, significant reductions in fuel consumption can be achieved by adopting a hybrid drive train, just as is the case for ordinary cars. Hybrid technologies that combine engine and electric drive technologies in a vehicle are generally thought of as being divided into series, parallel, and series-parallel (torque splitter) configurations⁽¹⁾. For the ZW220HYB-5B, the series configuration was adopted based on a study into which configuration best suited a wheel loader, taking account of such considerations as the efficiency of power transmission and the ease of incorporating the system into the vehicle and maintaining it. Fig. 2 shows a conceptual block diagram of the series configuration.

Hybrid System Configuration

Fig. 3 shows a block diagram of the hybrid system configuration on the ZW220HYB-5B. To achieve energy efficiency, the torque converter and transmission used in the past are replaced by a generator and traction drive motors that are operated in tandem with inverters, capacitors (electrical storage devices), and other components. Because it has a series configuration, in which the engine drives the

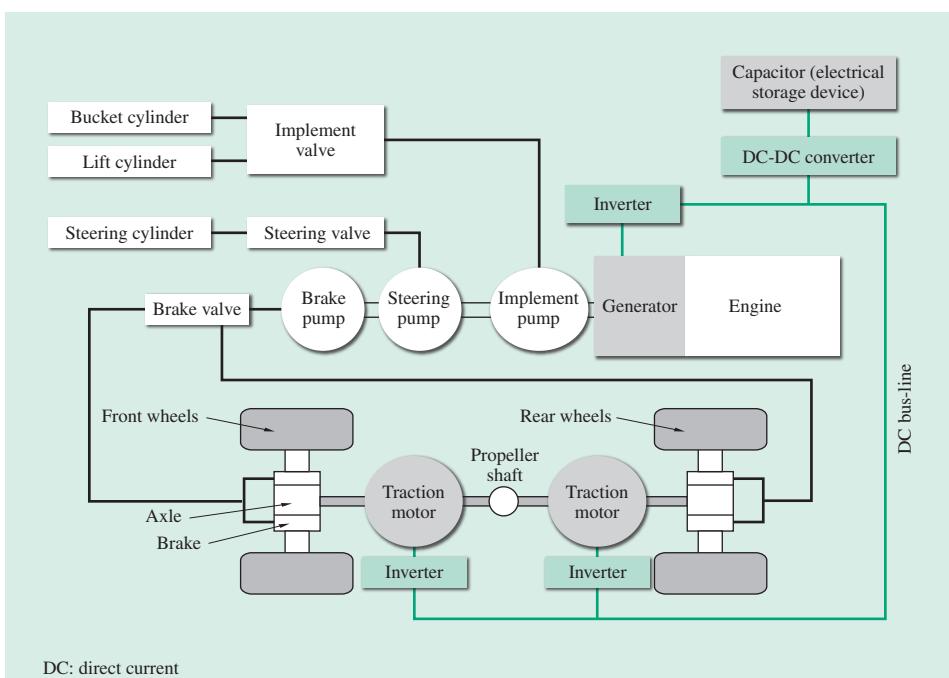


Fig. 3—Block Diagram of ZW220HYB-5B Hybrid System. Two traction motors are driven by electric power from the generator, which in turn is driven by the engine. The traction motors are used as generators during deceleration to store the regenerative energy as electrical energy in the capacitor so that it can be re-used when accelerating.

generator and the electric power from the generator drives the traction motors, a major feature of the power train is that there is no mechanical power transmission coupling between the engine and axles.

The system uses two traction motors located on the propeller shaft that provides electric drive to the axles. The two traction motors have different characteristics, one with low torque and high speed and the other with high torque and low speed, and the system incorporates a control function that operates each motor at the appropriate efficiency based on the work being performed at the time, whether it be driving at speed or digging and so on.

The capacitor is connected to the direct current (DC) bus-line via a DC-DC converter. It is designed to charge with regenerative energy during deceleration and discharge during acceleration to return this energy to the traction motor.

The hydraulics operate in the same way as on a conventional vehicle, with the engine providing mechanical drive to the hydraulic pump. For safety, the vehicle uses an existing highly reliable hydraulics system for the steering and brakes to ensure that these functions are not lost in the event of a fault in the hybrid system.

Techniques for Using Hybrid Drive to Reduce Fuel Consumption

The following three considerations apply to techniques for reducing fuel consumption by using hybrid drive. (1) Not having a mechanical power transmission mechanism between the engine and axle improves the efficiency with which engine power is transmitted because it reduces mechanical power losses such as those that occur in conventional torque converters, clutches, and gears.

(2) Because previous wheel loaders have transmitted traction power via the torque converter and transmission, delivering the required driving speed and power is subject to engine speed restrictions. A series hybrid, on the other hand, can alleviate these restrictions, and is designed to improve fuel consumption by having the vehicle controller operate the engine at low revolutions (revs) whenever possible and automatically avoid operating at speeds where its fuel efficiency is poor.

(3) Because the system includes a capacitor, it can efficiently store regenerative energy by operating the traction motors as generators when decelerating and reuse this energy when accelerating. As a result, it is possible to use a smaller engine with a lower output and better fuel consumption than would have been required

in the past. As this smaller engine is operated at low revs wherever possible, it also reduces acoustic noise.

Issues with Hybrid Drive

While the adoption of hybrid drive is a major technical development for improving the energy efficiency of construction machinery, it also faces issues with the cost of electrical components, whether their shape and size are appropriate for fitting into existing vehicle bodies, and their reliability and durability.

Because of the significant cost reductions that come from producing electrical components in high volumes, the construction machinery sector is at a major disadvantage because of the small market size compared to the automotive industry⁽²⁾. While an advantage of the series hybrid configuration is that it reduces the component count by eliminating the need for a transmission, it also requires heavy-duty inverters, motors, and other components to transmit enough power to drive a vehicle with an operating weight of 18 t or so at high speed. This means that developing drive system equipment that has high output and energy density while still keeping costs down is a major challenge. While Hitachi Construction Machinery has adopted a two-motor design for its traction motors, shifting to a single motor for wheel loaders (which need a large drive torque for digging) would require a motor with an extremely high capacity and a high-output inverter to control it. Because this means high production costs due to an inability to use off-the-shelf components, and because the required components would be too large to fit in the vehicle body, a two-motor design, despite its higher component count, provides a way to balance costs and the ability to fit the system into the vehicle.

Because construction machinery operates in harsh environments, the reliability and durability of electrical equipment is also an issue. Components such as drive motors and inverters need to be at least as reliable as the transmissions used in existing vehicles, with airtight housings designed to be water and dust proof. Hitachi Construction Machinery has also made detailed structural reinforcements to ensure components have the durability to withstand the vibrations that are characteristic of construction machinery.

Hitachi Construction Machinery has also given special consideration to safety. Because the drive train is a fully electric system, Hitachi Construction Machinery has incorporated a variety of features into the control system (including duplicate inputs for device signals, having controllers monitor each

other, and the use of monitoring microcontrollers) to ensure that the drive power can be turned off quickly if a problem is detected to prevent it from operating incorrectly. That is, the control system is designed in such a way that dangerous situations will not occur.

ZW220HYB-5B FUEL SAVINGS AND FEATURES

The following sections describe the fuel savings achieved by the ZW220HYB-5B wheel loader using the hybrid system described above, and its product features (see Fig. 4).

Fuel Savings

In addition to the greater power transmission efficiency achieved by adopting a hybrid drive train, the ZW220HYB-5B also reduces energy losses in the hydraulics and delivers a more appropriate output when digging. As a result, the new model achieved a 31% reduction in fuel consumption compared to the previous ZW220 model (which uses a torque converter) in fuel economy testing conducted using in-house test criteria.

However, because wheel loaders are general-purpose machines used in a wide range of applications (including quarrying, agriculture, industrial waste processing, snow clearing, and cargo handling), their fuel consumption can vary widely depending on operating conditions. The ZW220HYB-5B has a hybrid drive train and generally tends to achieve higher fuel savings the more frequently it is driven. As applications that do not involve a lot of driving or where the vehicle spends a lot of time idling may not deliver worthwhile fuel savings, it is important that it be marketed for use at sites where the work is of a nature that will benefit from its fuel consumption characteristics.

Product Characteristics

In addition to lower fuel consumption, the ZW220HYB-5B also has the following features.

(1) Quieter operation

The smaller engine made possible by use of hybrid drive significantly reduces noise levels in the vicinity of the vehicle.

(2) Continuously variable speed provides stress-free driving

Eliminating the transmission and using an electric motor enables continuously variable speed. Because there is no need for gear changes when digging or



Fig. 4—Cutaway Diagram of ZW220HYB-5B Power Train. Despite incorporating the hybrid system, the ZW220HYB-5B has the same vehicle appearance and dimensions as the previous model.

driving uphill, for example, and because there is no gear-change shock, this helps reduce driver fatigue. (3) Potential for energy-efficient operation through independent control of driving and non-driving operations

Whereas the driving speed and implement speed were coupled on previous non-hybrid models where engine revs were controlled by the driver operating the accelerator pedal, on the ZW220HYB-5B this has been replaced by a system based on independent control, where the accelerator pedal controls the driving speed and the implement levers control the implement speed. In the case of loading material onto a dump truck, for example, there are situations in which the driver wants to raise the implement (bucket) quickly at the same time as reducing the vehicle speed as it approaches the truck. On previous models where the driving speed and implement speed were coupled via the accelerator pedal, this would result in drive power losses because it required use of full accelerator at the same time as pressing the brake pedal to slow the vehicle down.

Because the ZW220HYB-5B can control the implement and driving speeds independently, the driver can take his foot off the accelerator pedal to slow down at the same time as maintaining the desired implement speed. This reduces power losses because it enables loading to be performed with the minimum amount of braking, while also helping to reduce driver fatigue by requiring less use of the brake pedal.

CONCLUSIONS

This article has provided an overview of the hybrid system in the ZW220HYB-5B and described the results of fuel economy testing and product features.

As evident in the automotive industry, the use of electric drive is a major trend in the area of energy efficiency technologies for vehicles powered by fossil fuels. Hybrid systems that use electric drive technology are expected to achieve even greater fuel savings in the future as batteries achieve higher energy storage densities and enable greater use to be made of lost energy. In the ZW220HYB-5B system, the engine could be replaced by a fuel cell and there is a potential to achieve zero emissions in the future in consideration of the environment.

Hitachi Construction Machinery Co., Ltd. intends to continue supplying construction machinery that has even greater energy efficiency by making full use of the power electronics technologies of Hitachi.

REFERENCES

- (1) N. Mihori, "Introduction to Hybrid Cars," Gijutsu-Hyohron (Nov. 2009) in Japanese.
- (2) M. Edamura et al., "Adoption of Electrification and Hybrid Drive for More Energy-efficient Construction Machinery," Hitachi Review **62**, pp. 118–122 (Mar. 2013).

ABOUT THE AUTHORS



Kazuo Ishida

Development Center, Construction Vehicle Equipment Division, Development & Production Group, Hitachi Construction Machinery Co., Ltd. He is currently engaged in the development of a hybrid wheel loader.



Masaki Higurashi

Design Department, Control System Center, Development & Production Group, Hitachi Construction Machinery Co., Ltd. He is currently engaged in the development of a hybrid wheel loader control system.