

Development of the World's First Engine/Battery Hybrid Forklift Truck



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The demand for vehicles with reduced environmental impact is rapidly increasing in the industrial vehicle market. In order to meet this demand, a 4.0–5.0-ton engine hybrid forklift truck was developed and is being sold for the first time. The vehicle makes use of existing and proven components of both battery and engine forklift trucks, utilizes our innovative lithium-ion battery, and achieves reliability and economic efficiency, with a 39% improvement in fuel efficiency and reduced CO₂ emissions.

1. Introduction

In light of the recent increase in global environmental awareness, the demand for reduced environmental impact and lower carbon emissions is rapidly increasing, even in the industrial vehicle market. Battery-operated vehicles now dominate over half the domestic market for forklift trucks. However, for mid-to-large-size forklift trucks with longer operating hours and heavier operation loads, the market share of traditional engine-powered forklift trucks is still overwhelmingly high.

Figure 1 shows the main models available in the forklift truck market with rated capacity and load in operation. The electrification of small models has steadily progressed, but the electrification of mid-to-large models requires further innovation in battery technology. Engineers are increasingly considering the use of lithium-ion batteries instead of lead-acid and nickel-metal hydride batteries to power these vehicles.

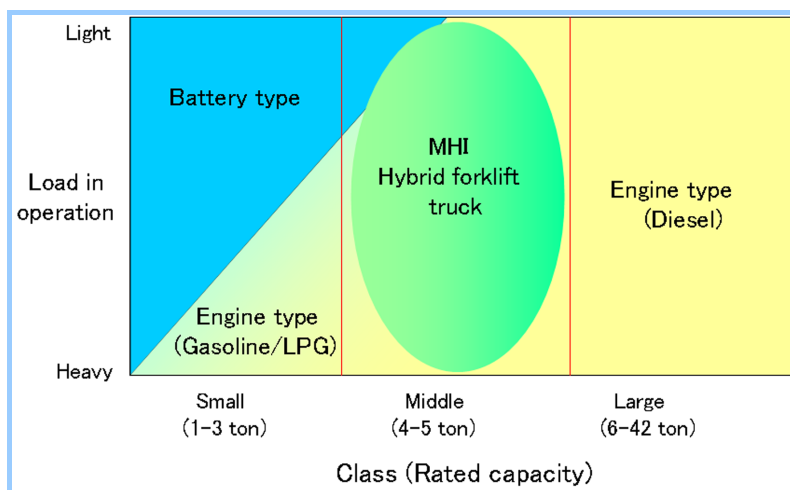


Figure 1
Forklift market and
our hybridization
principle

Based on market trends, we developed a 4.0–5.0-ton hybrid engine forklift truck utilizing our powertrain / power electronics technology and lithium-ion technology to fill the void in the market for a mid-sized forklift truck with a reduced environmental impact. The vehicle became available for purchase in October 2009.

This paper outlines the characteristics of our forklift hybrid system.

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2. Forklift hybrid system

A forklift truck is a service vehicle used for transport that is equipped with a load-handling device that an ordinary automobile does not have. In the hybridization of a forklift truck, both traveling and load handling functions must be considered. In general, hybrid vehicle configurations consist of series, parallel, and series-parallel arrangements. We chose to adopt a series-parallel configuration for traveling and parallel configuration for load handling after designing the hybrid system power management and considering the component arrangement, engine and motor capacity, and energy converting efficiency.

2.1 Traveling system (series-parallel configuration)

Due to the engine and torque converter characteristics of traditional forklift trucks, the engines are efficient for high-speed travel, but less efficient at low speeds. In addition, a large amount of fuel is consumed during starting. However, an electric motor can generate high torque at low speeds with no major decrease in efficiency. Through sophisticated power management, making use of both the engine and motor characteristics, improvements in efficiency can be realized.

The motor is primarily used when starting and at low speeds; at mid-range speeds and above, the vehicle switches to the engine. If the operator quickly depresses the accelerator pedal in a sudden start, both motor and engine power are applied, regardless of the vehicle speed, to generate the maximum system power (Figure 2).

During inertial travel and deceleration, the motor works as a generator, and the vehicle kinetic energy is converted to electric power and stored in the lithium-ion battery (Figure 2).

2.2 Load handling system (parallel configuration)

For small loads, the engine powers the hydraulic pump. For large loads, the motor assists in driving the hydraulic pump (Figure 3).

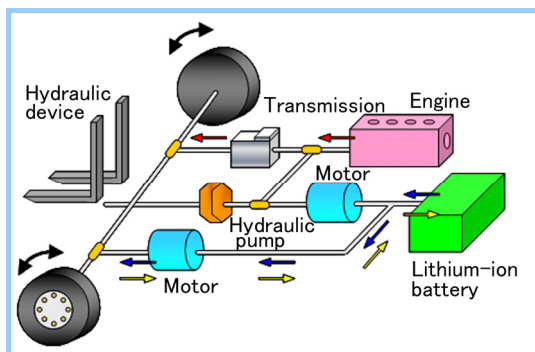


Figure 2 Traveling: series-parallel configuration

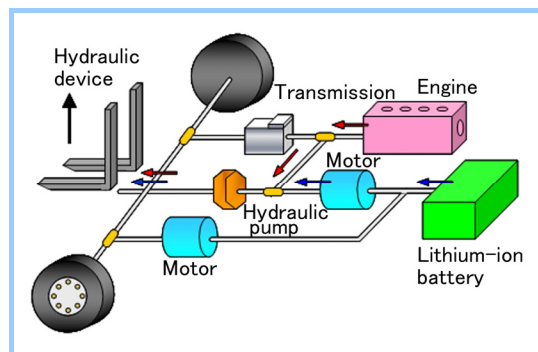


Figure 3 Load handling: parallel configuration

2.3 Idling stop function

In order to verify the effect of not idling the engine, known as an idling stop function, which is now used in automobiles, the actual operating conditions of an engine forklift truck were investigated. The investigation showed that the idling rate varied from 0% to more than 40%, demonstrating a wide variability (Figure 4). Taking this idling rate as a parameter, the fuel consumption was calculated for various combinations of driving modes, loads, and other factors. These calculations revealed that the idling stop function improved the fuel efficiency by up to 10% (Figure 5). This led us adopt the idling stop function.

For an effective idling stop function, the time required for the engine start and the vibration and noise when the engine starts and stops are important factors. To meet the necessary requirements, the power line mounting arrangement, gear train, oil pressure circuit, and motor control were improved. The result was an idling stop function that was stress-free to the vehicle operator.

2.4 Lift-tilt anti-relief function

In most load-handling systems, if the hydraulic lever is held after the hydraulic lift cylinder or tilt cylinder reaches the end of its stroke, the oil pressure circuit enters a state of relief. This is one factor that increases fuel consumption. In our new system, a lift-tilt anti-relief function was

adopted, which controls unnecessary pressure relief at the end of the cylinder stroke by monitoring the hydraulic circuit pressure.

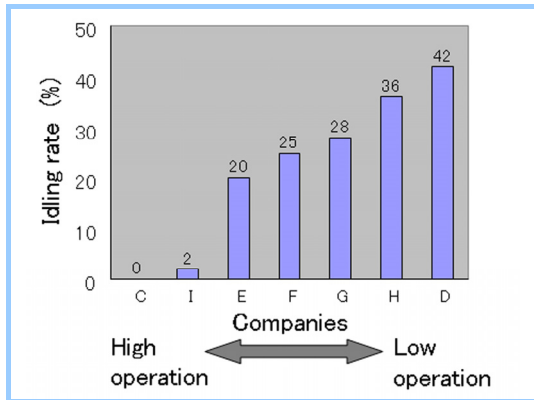


Figure 4 Vehicle idling rate during operation

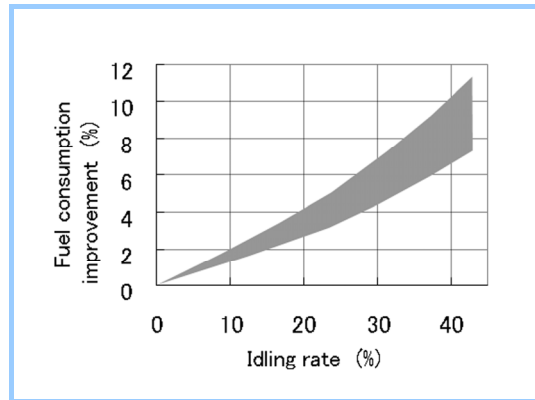


Figure 5 Calculated reduction in fuel consumption by using an idling stop function

3. Specifications and hybrid component design

The specifications of our hybrid forklift truck with a series-parallel traveling system and parallel load-handling system are shown in Table 1.

Table 1 Specifications

		FD40 Hybrid	FD45 Hybrid	FD50 Hybrid
Rated capacity	(kg)	4 000	4 500	5 000
Overall length / width / height	(mm)	4200 / 1460 / 2250	4240 / 1460 / 2250	4530 / 1460 / 2250
Maximum lift speed	(mm/s)	610	530	530
Maximum travel speed	(km/h)	21		
Hybrid system				
Traveling		Series-parallel		
Load handling		Parallel		
Engine				
Model		Mitsubishi Diesel S4S		
Displacement volume	(cc)	3331		
Rated power	(kW)	38		
Emission regulations compliance		2007 Japanese Domestic Exhaust Gas Emission Regulations		
Inverter				
Control method		Vector control		
Maximum current	(Amps)	400 (continuous)		
Maximum output voltage	(Vrms)	66		
Motor				
Type		3-phase AC induction motor		
Rated power	(kW)	10		
Number	(Units)	2		
Battery				
Type		Lithium-ion battery		
Rated power	(V)	90		
Capacity	(Ah)	45		

3.1 Engine

To achieve downsizing, a 3.3 L (38 kW) diesel engine was adopted instead of the 5.0 L (57 kW) diesel engine commonly used in 4.0–5.0 ton engine forklifts. As the result of the downsizing, the engine load use area on the fuel-consumption map was shifted higher, enabling higher operational efficiency (Figure 6).

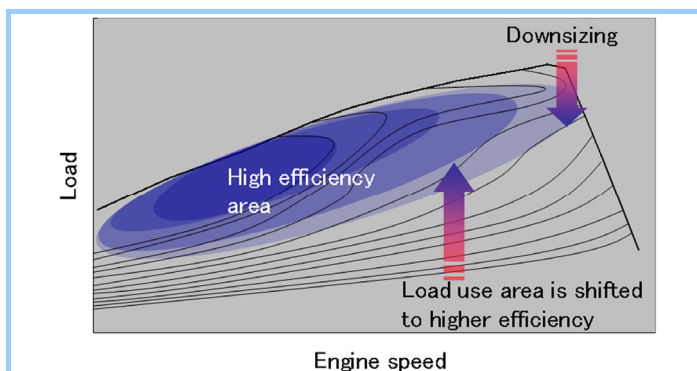


Figure 6
Engine fuel-consumption map

3.1 Motor

The brake energy regeneration capability of the motor has a strong effect on the vehicle fuel consumption and is a key component of the design. A high-output motor is required to generate a strong deceleration force. However, braking operation varies according to driving practices and operators. Therefore, to determine the motor specifications based on the deceleration rate, and on the braking operation and frequency, real operating practices at customer sites were investigated.

Figure 7 was generated by measuring the vehicle speed during real operating practices at customer sites and plotting the deceleration rates at 0.5-second intervals. The figure indicates that weak deceleration by engine braking was dominant at high speeds, but the strong deceleration by braking was more common at medium and low speeds.

Our hybrid forklift truck brake system has both a mechanical brake and a motor regeneration brake. The mechanical brake is activated for braking needs beyond the deceleration force generated by the regeneration brake. The motor specifications cover 50% of the deceleration that commonly occurs during the operation of forklift trucks, with motor regeneration achieving high energy absorption.

3.3 Lithium-ion battery

High rate charge and discharge capability are important characteristics of a secondary battery in a hybrid system. One problem with extant lead-acid batteries is that increasing the current per battery capacity results in deteriorating charge and discharge efficiency. In contrast, a lithium-ion battery has stable charge and discharge efficiency even when the current is increased; this characteristic is favorable for application in hybrid systems (**Figure 8**). In addition, lithium-ion batteries have far longer service lives than lead-acid batteries. We adopted a lithium-ion battery made by Mitsubishi (co-developed with Kyushu Electric Power Co., Inc.), which is superior to lead-acid batteries in terms of both performance and service life.

The lithium-ion battery is surrounded and protected by a counterweight to improve crashworthiness. Precautions were taken to insure that heat from high-temperature components in the engine room is not be transmitted to the battery. For battery temperature control, the temperature of each cell is monitored by a dedicated controller (BMU) and forced cooling is performed by the engine cooling fan. In addition, the BMU also monitors voltage and current to prevent overcharge and overdischarge.

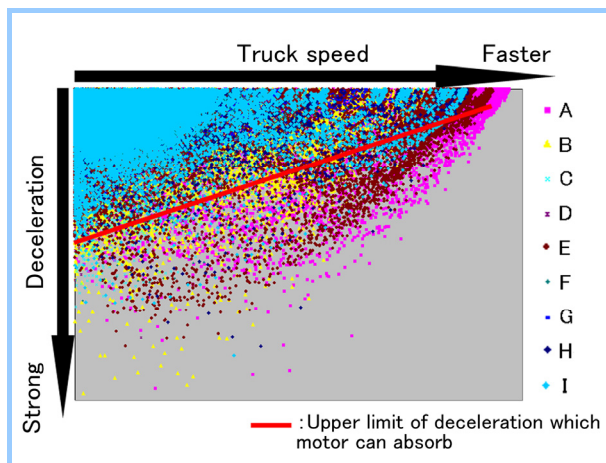


Figure 7 Forklift deceleration frequency map

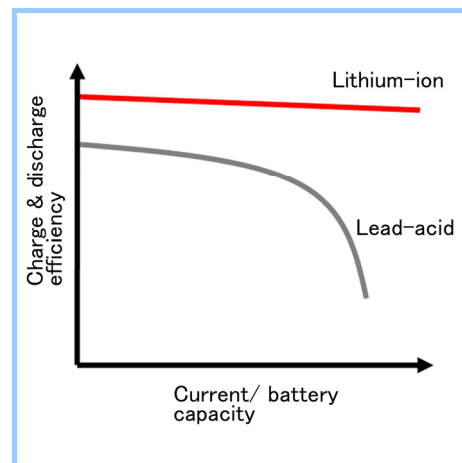


Figure 8 Current charge and discharge capability

4. Performance evaluation

4.1 Fuel consumption

To evaluate fuel consumption, the JIS D6202 test (**Figure 9**), a method widely used to observe forklift truck fuel consumption, was applied. The results indicate a 39% reduction in fuel consumption compared to our 5-ton engine forklift truck.

Assuming 300 annual operating days and 8 daily operating hours, and converting the reduction in fuel consumption to CO₂ emissions, 14.6 tons of CO₂ emissions are eliminated per forklift truck per year. This calculation does not account for the time when the vehicle is stopped; we anticipate that the idling stop function facilitates further reductions in fuel consumption.

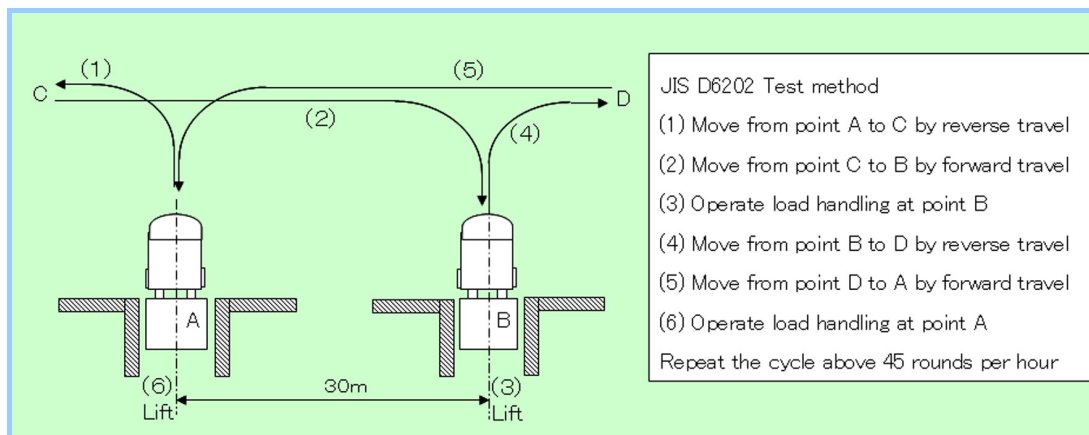


Figure 9 Fuel consumption patterns

4.2 Other evaluations

Regarding traveling and load handling, we confirmed that the performance of the hybrid forklift truck is equivalent to the performance of our engine forklift truck in the same class. In addition, the newly installed hybridization components passed all evaluation tests for strength, durability, and environment resistance.

5. Conclusion

By applying hybrid technology and lithium-ion battery technology to reduce environmental impact, we developed a 4.0–5.0-ton hybrid forklift truck. A 39% reduction in fuel consumption was achieved while maintaining traveling and load handling performance equivalent to an engine forklift truck.