

Fuel Economy Analysis of Alternator with Kinetic Energy Storage for a Conventional Vehicle

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ABSTRACT

This paper evaluates the effect of our new alternator concept for a conventional vehicle, which is able to generate electricity by storing kinetic energy of the vehicle in the high speed flywheel as rotation energy under deceleration. The alternator constructs a planetary gear device and multiple clutch-brakes perform CVT, alternator and high speed flywheel without an expensive electric device, mechanical CVT and vacuum pump. So it has high cost performance.

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INTRODUCTION

Fuel economy regulations have been increasingly tight due to, among other things, global warming and soaring crude oil prices. Europe, which has the strictest regulations, requires CO₂ emissions to be reduced by 30% from 2011 levels by 2020 and afterward (see Fig. 1).

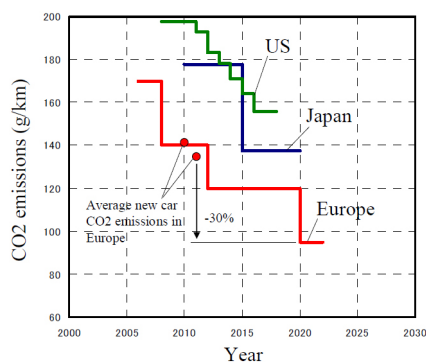


Figure 1. CO₂ emissions standard

This trend is expected to accelerate since energy demand will rise each year based on future population increases and growth of emerging economies. To meet the fuel economy regulations, vehicle electrification has been expanding, as seen with HVs and EVs. However, it is forecast that internal combustion engine (ICE) vehicles (especially compact cars) will remain dominant even in 2020 (see Fig. 2) because of

such problems that include expensive HV and EV prices and infrastructure deployment. Consequently, it is necessary to improve the fuel efficiency of compact ICE cars, which will remain the mainstream. However, since integration of existing fuel-saving technologies currently studied in the world is, on its own, not enough, it is vital that additional measures are devised.

In the search for measures to improve the fuel efficiency of ICE cars, the current state was analyzed through measurement of the energy balance in actual ICE vehicles. Figure 3 shows the energy balance for a range encompassing from the heat value of the gasoline up to the driving of the wheels in Japanese in-use fuel economy mode. Fuel economy improvement perspectives were identified according to the magnitude of energy lost, including ① Improvements in engine thermal efficiency, ② Improvement in power transmission, ③ Waste heat recovery, ④ Reductions in auxiliary losses, and ⑤ Braking energy recovery. Among these factors, ① through ④ have seen technological development to the point where there are few feasible improvements left. In contrast, ⑤ braking energy recovery was assessed as promising for the following reasons.

(1). ⑤ generates a larger amount of energy than ② or ④. Braking during deceleration dissipates 1.5 MJ, sufficient energy to drive the alternator, which requires 1.2 MJ.

(2). ⑤ provides better quality energy than ③. Since ⑤ generates power in the form of torque multiplied by rotational

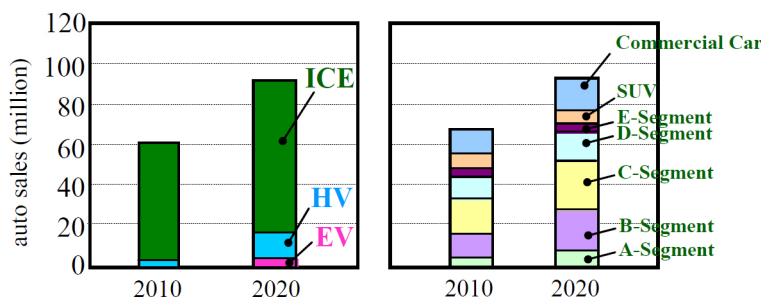


Figure 2. Automotive Powertrain & Segment Outlook

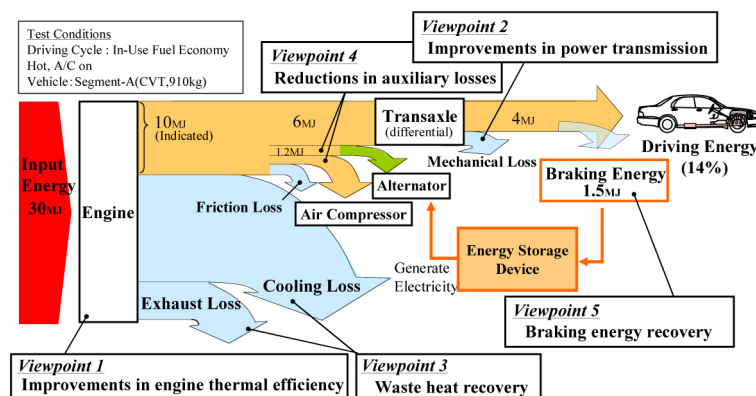


Figure 3. Energy flow in conventional vehicle

speed, the system configuration would highly probably be simple and with low losses.

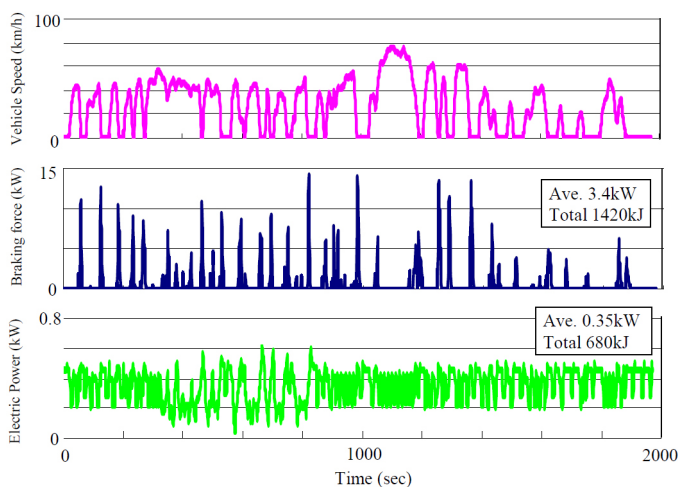


Figure 4. Braking energy and electrical power in in-use fuel economy cycle

Electricity requirements and braking energy of a B-segment car were measured to identify problems in regenerating braking energy and using it as electricity. Regarding auxiliaries, only the air-conditioning system was operated during the test. The navigation, proximity sensor, rear view camera, and EPS systems were not operated. Figure 4 shows a time-series graph of braking energy and electricity

requirements in the in-use fuel economy mode drive cycle. The graph reveals that the total electricity requirements of the vehicle amount to 680 kJ, which is about one half of the total braking energy (1420 kJ). Meanwhile, electricity consumption is constantly 0.35 kW (on average), while braking energy of 3.4 kW (on average) is generated intermittently. In other words, although the braking energy meets the electricity requirements in terms of the total amount of energy, it does not continuously cover the requirements. Moreover, the current on-board lead acid battery has a low maximum input capacity of a few hundred watts, resulting in regeneration of only a fraction of the braking energy. Consequently, to use braking energy as electricity, it is necessary to use an energy storage device that temporarily stores a large amount of energy.

Energy storage devices currently considered promising are categorized into three types according to energy storage form (Table 1): power generated by a generator and stored as electricity; fluid pressure increased by a pump or the like and stored as pressure; and the speed of a rotating body of significant inertial mass increased by reduction gear or the like and stored as kinetic energy. These present their respective challenges in implementation. Efforts are underway to meet these challenges. Flywheel (FW) systems fall into types that store energy as kinetic energy. Compared with other devices, the FW system has the following advantages:

- Changes in characteristics caused by ambient temperature changes are small plus excellent durability since the system is entirely composed of mechanical parts
- High cost reduction potential since no minor metals are used
- Can be highly efficient due to the absence of energy conversion
- Handles large amounts of energy with ease since the maximum input is determined largely by mechanical parts such as gears and bearings

The FW system is considered promising for use in conventional vehicles specifically due to few restrictive conditions (temperature and durability) in application and cost reduction potential. We have designed a system, combining an existing alternator and an FW, to temporarily store a large amount of braking energy as rotational energy in the FW and to operate the alternator to generate power when electricity is needed. For installation in mass-produced vehicles, however, it was necessary to address challenges such as simplified reduction gear and generator designs, avoiding the use of a vacuum pump, and use of a low-cost FW material. This paper details these challenges and presents ideas as solutions to them.

Table 1. Comparison of energy storage methods

□ advantageous item

Form of Energy	Electricity		Pressure	Kinetic Energy
means	Battery (Li-Ion)	Ultra Capacitor	Accumulator	High Speed Flywheel
Self Discharge Rate	1 %/year	5 %/month	small in quantity	2 %/min
Specific Power Density	0.5 kW/kg	2 kW/kg	1 kW/kg	1.5kW/kg
Durability	1,000 Cycles	200,000 Cycles	Semipermanent	Semipermanent
Operating Temperature Range	0-60	-25-70	-35-80	-30-120
Understanding Charging Energy	difficult	possible by voltage	possible by pressure	possible by flywheel revolution
Mountability	comparative ease	comparative ease	need a large accumulator	need to integrate into a powertrain
Cost	go down in price by mass-production	expensive capacitor & convertor	expensive accumulator	availability of commodity materials

CONCEPT OF AN ALTERNATOR WITH KINETIC ENERGY STORAGE

Challenges

1. Simplified Reduction Gear and Generator Designs -

Storing energy in a FW system increases the FW speed. To this end, it is necessary to change the rotational speed on the part of the vehicle to a higher speed than the FW speed with a device that provides continuous speed variation. The following three systems are used for continuous speed variation. High cost is an issue with all these systems because of the need for expensive equipment such as CVT and motor inverter.

(i). Electrical conversion system: Converts braking energy into electrical energy via a generator. The electrical energy is used to increase the speed of a motor coupled to a FW to store the energy. For power generation, the motor coupled to the FW is used as a generator.

(ii). CVT system: The input shaft on the vehicle is coupled to the input shaft of a toroidal or belted continuously variable transmission. The output shaft is coupled to a FW. This system changes the speed input from the vehicle to increase the FW speed. For power generation, a generator coupled to the FW is used.

(iii). Electric CVT system (Prius THS system): Three shafts of planetary gear are used as an input shaft (input shaft on vehicle), output shaft (coupled to the FW), and speed change shaft (coupled to the motor) to change the speed input from the vehicle to increase the FW speed. Power is generated by a motor inverter coupled to the speed change shaft.

2. Avoiding the Use of a Vacuum Pump - At high FW speeds, losses (windage losses) are produced by friction between the FW and the air. The magnitude of the loss is roughly proportional to the ambient pressure. In some cases with our competitors, this problem is addressed by installing a vacuum pump, which is costly.

3. Use of a Low-Cost FW Material - Flywheels rotating at high speeds are associated with a failure mode involving breakage caused by the centrifugal force. Centrifugal forces are determined by the following equation: $F = m\omega^2$ (m : mass; ω : rotational speed). The amount of stored energy is determined by the following equation: $E = 1/2 I \omega^2$ (I : moment of inertia $\approx m$; ω : rotational speed). Consequently, the use of a light and low-speed FW with the aim of increasing the material strength reduces the amount of stored energy and translates to reduced effectiveness of the FW in improving the fuel economy. One solution to this tradeoff is the use, at high speeds, of a high specific strength material (CFRP or magnesium alloy) that has a high strength to weight ratio. However, this solution is costly.

Solutions

Our solutions to these challenges are shown in Fig. 5. To reduce the cost, this system incorporates an electric CVT, the already installed alternator as motor coupled to the speed change shaft, negative engine pressure (intake) instead of a vacuum pump, and a FW constructed of steel. The system has three components, which work as explained below.

1. Power Split Device: planetary gear (simplified reduction gear and generator designs) - Provides functions to change the axle rotational speed to match the FW speed. In the present system, the carrier, sun gear, and ring gear are used respectively as input shaft, output shaft, and speed change shaft. The ring gear and the wet electromagnetic brake are coupled. The braking torque of the wet electromagnetic brake controls the torque transmitted to the ring gear to