On Key Issues in the Spread of Hybridized Heavy-duty Vehicles

Namio Yamaguchi [1], Kazuo Rokkaku [2], and Shigeyuki Minami [3]

[1] *Research Center for Artificial Photosynthesis, Osaka City University, yamaguchi-namio@hi-ho.ne.jp*
[2] *Research Center for Artificial Photosynthesis, Osaka City University, rokkaku@mx2.nisiq.net*
[3] *Research Center for Artificial Photosynthesis, Osaka City University, minami@elec.eng.osaka-cu.ac.jp*

Abstract

Improvements have made on the fuel efficiency and emission control of passenger cars, and the development of the hybridization of vehicles has been further assisting improvements. But great technological developments are required to see similar improvements to heavy-duty vehicles (HDV), including large city-buses and heavy-duty trucks, and the hybridization of vehicles is a vital method for resolving this problem. However, technology has not yet been developed far enough to achieve results in which performance is cost effective. As the mileage of HDV over their whole life cycle is approximately 10 times longer than that of passenger cars, designing a new system for HDV requires a different perspective. This paper clarifies the current problems occurring in the hybridization of HDV in order to improve fuel efficiency. This paper also proposes the effectiveness of installing a Fly Wheel system as a resolution for these problems.

Keywords

heavy-duty vehicle, bus and truck, hybridization, fly wheel, battery performance

1. INTRODUCTION

The need for the hybridization of HDV has been pointed out for a long time. A great deal of effort has been made regarding the hybridization of large city-buses and heavy-duty trucks [DOE/NREL, 2002], but this hybridization has not yet become popular [Nihon Bus Association, 2015]. This can be attributed to the fact that, though prices of vehicles increase due to hybridization, any progress on improving fuel efficiency remains low. For example, the selling price of an ERGA Hybrid from Isuzu Motors Limited is about 6 million yen higher than for diesel vehicles of the same grade, but the improvements made on fuel efficiency are small: a change from 4.8 km/L to 4.9 km/L [Japanese Ministry of Land, Infrastructure, Transport and Tourism, 2013]. This paper will clarify the technical reasons for why not much improvement has yet been made on the fuel efficiency of HEV large city-buses and will discuss strategies for improving fuel efficiency.

2. ANALYSIS OF THE ENERGY CONSUMPTION OF HEV LARGE CITY-BUSES

In Japan, an evaluation of an HDV's fuel consumption is made by using two methods. In the JE05 urban traffic mode, each vehicle is set to drive at an average speed of 27.3 km/h, simulating the situation when running on a highway, in a traffic jam, and in other urban conditions. In another traffic mode, each vehicle is set to drive at a constant speed of 80km/h, simulating the situation when running on outside the city [Nomoto, 2015]. Large city-buses are evaluated only by means of the JE05 mode, which is limited to the use of vehicles running in the urban city. In this section, an evaluation is made by using the JE05 mode on the energy recovery of an Isuzu ERGA Hybrid from Isuzu Motors Limited, the specifications of which have already been published.

The exterior of an Isuzu ERGA Hybrid is shown in Figure 1. Figure 2 shows the relation between time and velocity in terms of the JE05 mode. With the JE05 mode, vehicles are expected to run on a flat inner-city road and are to run approximately 14 km in 30 minutes. An analysis is made of the differences of energy consumption of HEV large city-buses set to the JE05 mode.

Table 1 shows the specifications of HEV and diesel large city-buses used for evaluation. The buses have similar specifications.

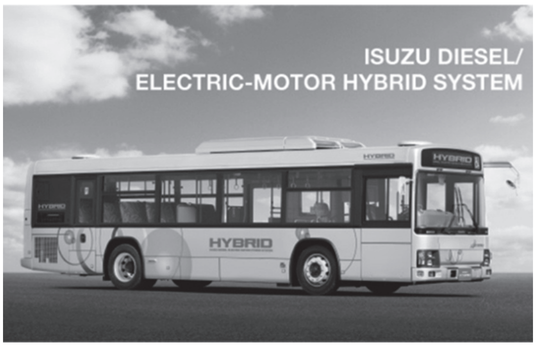

Fig. 1 Isuzu "ERGA Hybrid"

Calculations were made of running resistance (air resistance, rolling resistance, acceleration resistance, gradient resistance) based on the JE05 mode [Japanese Ministry of Land, Infrastructure, Transport and Tourism, 2008]. The analytic procedure is shown in Figure 3.

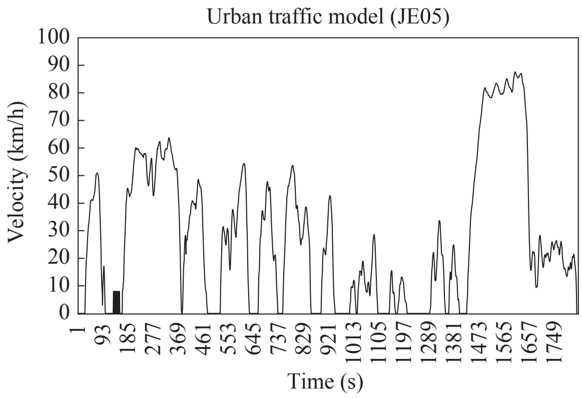

Fig. 2 Time and velocity in JE05 mode

Since the type and amount of fuel are known, running energy-consumption can be calculated if engine efficiency is determined. It is assumed that engine efficiency is similar between a large diesel bus, of which the specifications are similar to an Isuzu ERGA Hybrid (HEV large city-bus), and a hybrid-version bus. Each resistance loss and the total loss can be calculated from the specifications sheet and the JE05 driving mode. The difference between the running energy consumption and the total loss is the regenerative energy utilization. The regenerative energy utilization of the hybrid system is reinstated and reused. Table 2 shows the analytic results of running an HEV large city-bus calculated from this procedure.

Running energy consumption is 10.91 kWh, and regenerative energy utilization is 0.5442 kWh. As regenerative energy available is –6.006 kWh, the regenerative energy utilization ratio is 9.06 %.

This example shows that the fuel consumption value

Table 1 A comparison of the specification of HEV and diesel large city-buses

Specifications	Isuzu ERGA Hybrid (QQG-LV234L3)	Isuzu ERGA (QRG-LV290N1)
Vehicle curb weight (kg)	10,300	9,660
Riding capacity (persons)	73	79
Height (m)	2.965	3.045
Width (m)	2.490	2.485
A (m^2)	7.382	7.566
W (kg)	12307.5	11832.5
ΔW (kg) im = 1	1,030	966
Specific fuel consumption (km/L)	4.9	4.8
Engine	Inline-six diesel engine (191 kW)	Inline-four diesel engine (184 kW)
Maximum motor output (kW)	44	–

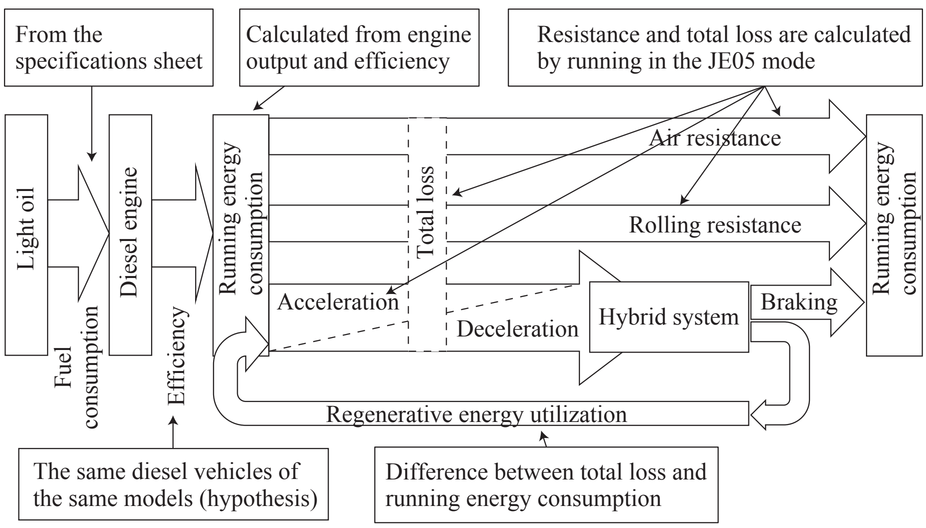

Fig. 3 Analytic procedure

Table 2 Calculation of running resistance of HEV large city-bus and diesel large city-bus (Calculated on the assumption that the efficiency of the two diesel engines is equal)

Items		HEV large city-bus	Diesel large city-bus
Inner-city running (JE05)	Running distance (km)	13.91	13.91
	Running time (h)	0.508	0.508
	Total loss (kWh)	11.45	11.13
	Regenerative energy available (kWh)	–6.006	—
	Regenerative availability/total loss ratio (%)	52.43	—
Engine-efficiency calculation	Total-loss equivalent diesel oil amount (L)	–	1.05
	Engine efficiency (%)	36.25 %	36.25
Running energy consumption (kWh)		10.91	11.13
Regenerative energy utilization (kWh)		0.5442	–
Regenerative energy utilization ratio (%)		9.06	–
Fuel consumption value on specifications (km/L)		4.9	4.8
Nb: Diesel oil energy density (kWh/L)		10.6	
Improvement of fuel consumption value		1.02 times	

improved by mere 1.02 times after hybridization. Meanwhile in general the fuel consumption value of hybrid passenger-cars today has improved by approximately 1.5 times. The poor improvement of fuel consumption of buses after hybridization can be attributed to the low regenerative energy utilization ratio, which is as low as 9 %. It is essential to improve energy efficiency by the effective use of the power generated by regenerative braking. In order to examine the impact of the regenerative energy unitization ratio on fuel consumption, the running resistance of an Isuzu ERGA Hybrid was calculated, and the details are shown in Figure 4.

According to Figure 4, the acceleration resistance loss accounts for over half of all loss and this shows clearly the necessity of increasing the regenerative energy utilization ratio. This result can be attributed to the characteristics of large city-buses, which operate by repeating running and stopping motions. Resistance loss during deceleration can be changed to re-acceleration energy by regeneration. Improving regeneration efficiency may improve fuel consumption to a large degree.

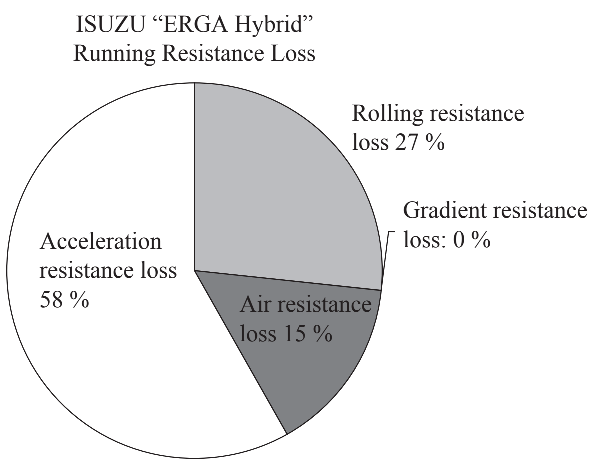

Fig. 4 Itemized running resistance loss of an Isuzu ERGA Hybrid

3. ANALYSIS OF INSTANTANEOUS REGENERATIVE POWER (ACCELERATION RESISTANCE LOSS)

Improving the regenerative energy utilization ratio requires an understanding of the content of the acceleration resistance loss of HEV large city-buses in detail. Samples of time variations in the acceleration resistance loss of HEV large city-buses are shown in Figures 5 and 6.

In Figure 5, the generated resistances of both acceleration and deceleration are well beyond 44 kW (the maximum power of the motor mounted in this bus), and the value is almost 300 kW at maximum on the negative side (during deceleration). However, Figure 6 shows that the pulse remains within 30 seconds. The key to problem-resolution is how to recover this short-lasting, high-powered pulse, and it is one of the most important factor in the useful hybrid system of HEV large city-buses.

To manage this, the average pulse width, the number of pulses, the maximum pulse width, and the total pulse power under set instantaneous regenerative power are calculated in relation to the amount of acceleration resistance loss (i.e. instantaneous regenerative power) on the negative side during one running in JE05 mode. The results are shown in Figure 7.

Figure 7 shows that when instantaneous regenerative

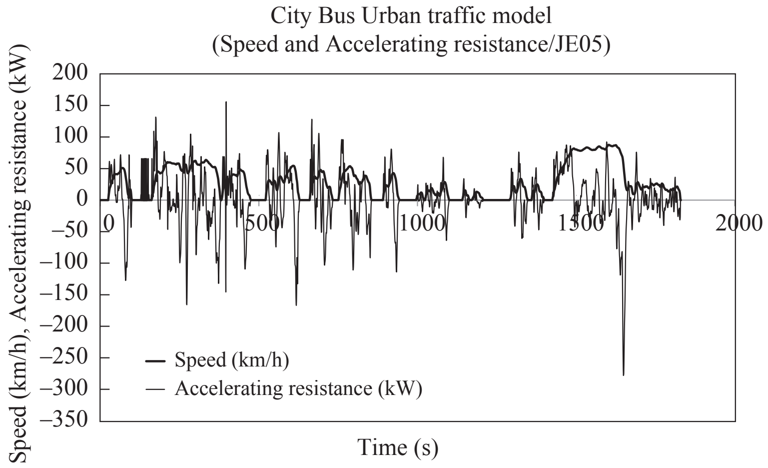

Fig. 5 Acceleration resistance loss from one running

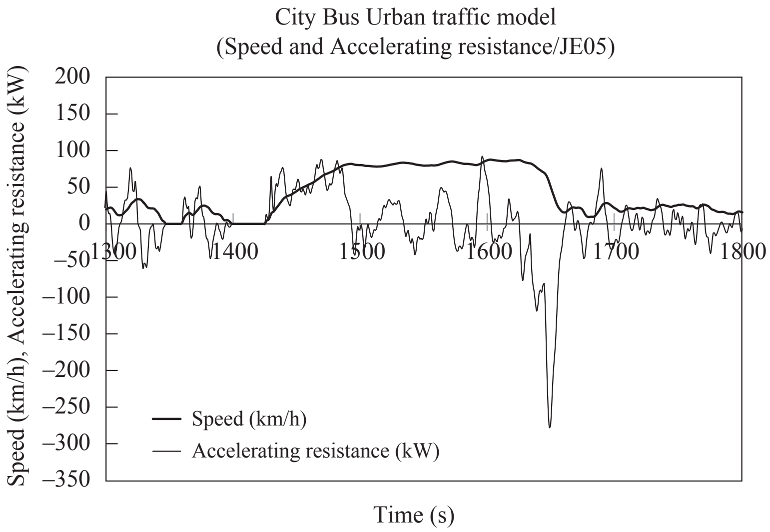

Fig. 6 Partly-enlarged view of acceleration resistance loss

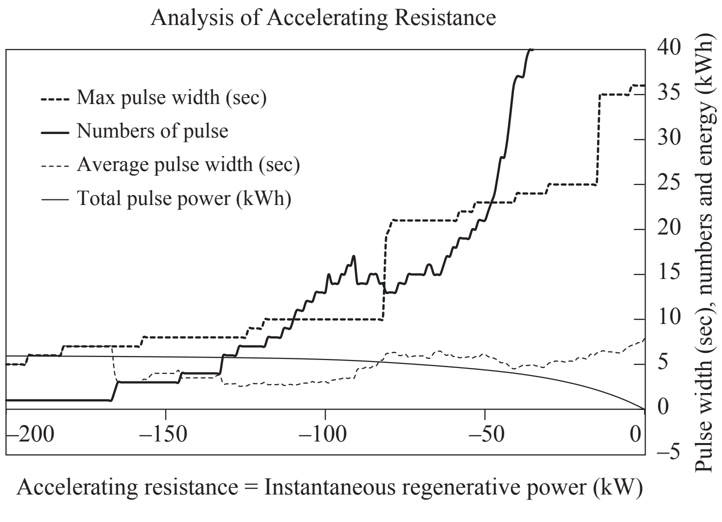

Fig. 7 Analysis of running an HEV large city-bus

power is set at 80 kW, the number of pulses available at one running decreases from 80 to 15 times and the maximum pulse width decreases from 35 to 10 seconds. When the instantaneous regenerative power is at 130 kW and over, the number of pulses decreases to 3 times and the maximum pulse width becomes 8 seconds. The average pulse width is about 5 seconds in this case. Meanwhile, the total pulse power is 6 kWh at maximum, but it is already 5kWh when instantaneous regenerative power is at 100 kW. This result indicates that in a hybrid system in which a pulse power is accumulated between 0 and 100 kW and changed to power again, approximately 90 % of the instantaneous regenerative power can be recovered. This indicates the features of acceleration resistance loss of large city-buses.

4. POWER RECOVERY BY REGENERATIVE COOPERATION BRAKING

In this section, discussion is conducted on how a hybrid system takes in instantaneous regenerative power. Regenerative cooperation braking is activated when HEV large city-buses decelerate. When brakes are applied in a hybrid system, the braking power of the motor operates and friction braking occurs when larger braking power is required. This is shown graphically in Figure 8 by using the acceleration resistance pulse as an example. Acceleration resistance is indicated with a bold line, vehicle speed is indicated with a broken line, and recovery power available is shown with a thin line on the negative side. The terms acceleration resistance and recovery power basically share the same meaning though the terms are different as output and recovery. The maximum output of the motor is listed as 44 kW. The maximum recovery power is 44 kW. The rotation number of the maximum output is not listed. In a hybrid system, the rotation number is presumed set near to the low-side rotation number, where a diesel engine indicates maximum torque. As the maximum torque of the engine is listed as 761 Nm/1450-2200 rpm in the specifications sheet, the speed of the maximum output is calculated as 37km/

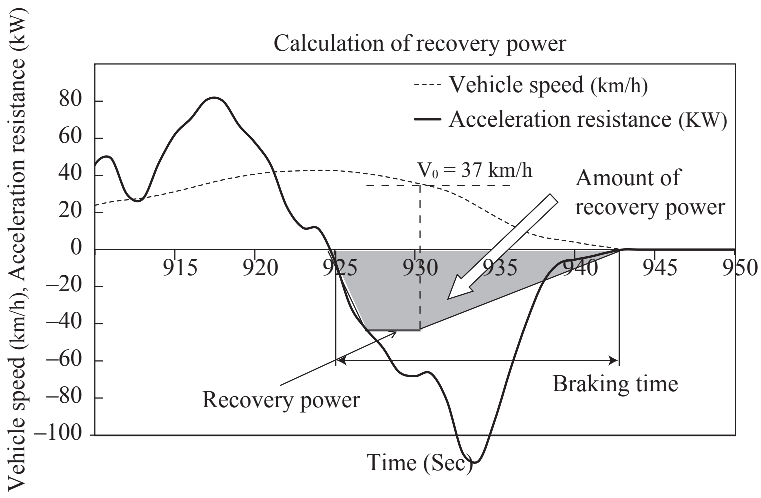

Fig. 8 Regenerative cooperation braking

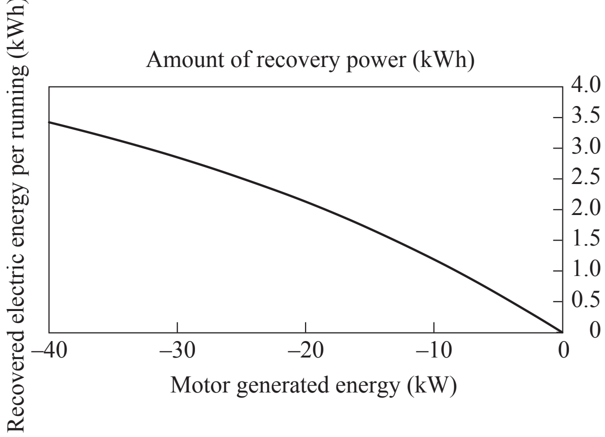

Fig. 9 Amount of recovered electric energy per running in JE05 mode

h, based on the tire standards. Recovery power is set constant at 37 km/h and more, and for speeds under this the power decreases as speed decreases. Thus the thin line's trapezoid is the amount of recovery power, and the recovery power of the motor is calculated based on this. The results are shown in Figure 9.

The increase in the amount of recovered power in relation to the motor generated energy in the neighborhood of the origin in Figure 9 is gradual compared to the increase in the amount of recovered power in relation to instantaneous regenerative power in Figure 7.

The power generated in the motor is sent to the battery through a converter, and it is restricted here again. This is affected greatly by the charging capability of the battery in particular. The regenerative energy utilization of HEV large city-buses is 0.54 kWh for one running according to Table 2. It can be inferred from Figure 9 that the motor generated energy is about 5 kW, of which the amount of recovered power is 0.54 kWh. Though the maximum output of the motor is listed as 44 kW in the specifications sheet for this bus, the motor generated energy is only 5 kW. The poor improvement in fuel efficiency can be attributed to an insufficiency in the charging capability of the battery. It is possible greatly to increase the amount of recovered power and energy efficiency if the maximum charging capability of batteries in HEV large city-buses is increased.

5. INCREASE OF CHARGING POWER DURING THE REGENERATION OF BATTERIES FOR HEV

5.1 Increasing the output of the entire hybrid system

In 2016 Hino Motors Ltd. began selling Blue Ribbon Hybrid HEV large-city buses [Hamai, 2016]. The improvements in fuel efficiency can be compared with Hino's other hybrid models produced in earlier years, and they are summarized in Table 3.

The output of the motor, inverter and battery were increased, and the fuel consumption was improved by 12 % in comparison to the fuel consumption of diesel vehicles. For this, water cooling was applied to cool off the motor and inverter, and the battery was installed in the upper part of the vehicle body to improve cooling efficiency. Fuel consumption was improved as result, but the degree of improvement is not as great as that seen with HEV passenger cars. Regenerative energy utilization was 1.2 kWh when calculated in the same way as for Table 2 and based on a comparison of fuel consumption with the 2016 model. The regenerative energy utilization ratio improved to 20 %. Based on this, motor generated energy (the maximum charging power of the battery) can be inferred as approximately 11kW in Figure 9. The maximum output of the motor is 90 kW, but unfortunately the performance is limited by the charging power of the battery (approximately 11 kW). This paper's discussion of the charging power and the improvement in fuel consumption, as well as this calculation, is summarized in Table 4.

5.2 An effective application of increasing pulse power recovery

The duration for instantaneous regenerative power is short even if the power is in bulk, as is shown in Figure 7. A possible effective method is to use a system to charge the bulk power over short period in the

Table 3 Improvements in fuel consumption of Hino's Blue Ribbon Hybrid buses

	2009 model Maximum output/rated output (kW)	2016 model Maximum output/rated output (kW)	Improvements in new model
Motor	41/6	90/30	From air cooling to oil cooling
Inverter	41/6	90/30	From air cooling to oil cooling
Battery	4.8 kWh (rated)	7.5kWh (rated)	Cooling by installation in the ceiling
Fuel consumption (km/L)	4.25(4.25)	5.5 (4.9)	(Fuel consumption values of diesel vehicles are shown in brackets)

Table 4 Relationship between charging power of battery and improvement in fuel consumption

Maximum charging power of battery (kW)	Regenerative energy utilization per running (kWh)	Regenerative energy utilization ratio (%)	Improvement in fuel consumption compared to diesel vehicles (%)
5	0.54	9	2
11	1.2	20	12
30	3.0	50	40

battery slowly after it hits a peak, after accumulating the power in a device other than the battery temporarily while avoiding charging the power in the battery suddenly. It is shown in Figure 9 that when the maximum charging power of a battery is set to 30 kW, the amount of recovered power becomes approximately 3kWh. In this case, the regenerative energy utilization ratio becomes 50 % and fuel consumption goes from 5.5 km/L to 6.89 km/L, as is found in Table 4. This results in a 40 % improvement through hybridization in comparison to uncomplicated diesel vehicles. It shows that the charging power of the battery and fuel consumption are heavily related.

An average pulse power can be examined in order to lower the maximum charging power of the battery. The duration time when instantaneous regenerative power reaches 30 kW is calculated when running for 30 minutes in JE05 mode, using Figure 7.

- Maximum duration: 24 seconds
  In this case, the maximum power amount of 1 pulse: 30 kW × 24 sec / 3600 = 0.2 kWh
- Average duration: 5.1 seconds
  In this case, the average power amount of 1 pulse: 30 kW × 5.1 sec / 3600 = 0.0425 kWh
- The number of pulses: 46 times
  In this case, the average interval: 30 × 60 / 46 = 39 sec.

The average power after pulse power is smoothed is calculated by dividing the average pulse power amount by the average interval. The result is 0.0425 × 3600 / 39 = 3.9 kW, and the battery is charged by this smoothed power. This calculation is a simple average value, but this is likely to decrease the charged power expected for the battery to a great extent.

A capacitor and Fly Wheel could possibly be used as a temporary energy storage device for this purpose.

A Ragone Plot is a convenient method for selecting a device. This is a plot separating the features of a storage device into energy density and outcome density. The values of typical devices are calculated by using a Ragone Plot and shown in Table 5 [Bogdan, 2005].

A Fly Wheel is an appropriate choice when the maximum duration is taken to consideration. When this is used, the average power-amount is 0.0425 kWh, output is 30 kW, and thus weight is calculated as approximately 40 kg, and the cost becomes $12,000.

The total running distance of HDV over their lifetime is 10 times longer than that of passenger cars.

Table 5 Ragone plot

	Energy density (Wh/kg)	Power density (kW/kg)	Run time	Cost ($/kg)
Li-ion battery	100	0.1	hour	3,000
Fly wheel (carbon-fiber)	10	1	< min	300
Super capacitor	1	10	sec	100

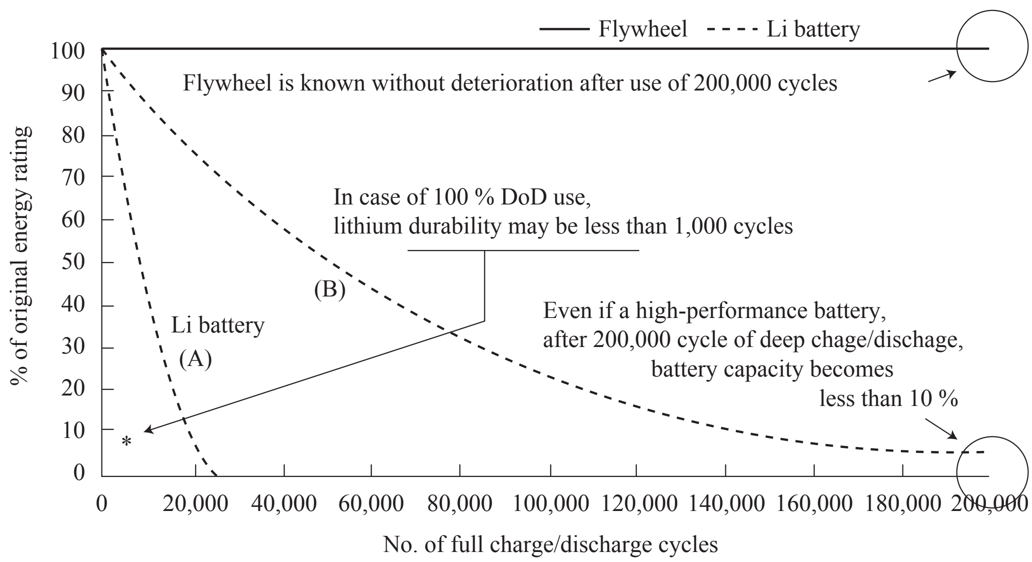

Fig. 10 Performance of fly wheel versus li-ion battery for full charge/discharge cycles

Note: Altered by the author from a Temporal Power Ltd pamphlet.

Thus any system's duration should be designed differently than for HEV. A Fly Wheel is expected to last 20 years, and it has a much higher durability for full charge/discharge cycles than a battery. Figure 10 shows the performances of a Fly Wheel versus a Li-ion battery for full charge/discharge cycles. In the case of 100 % DOD use, the durability of a Li-ion battery is less than 1,000 cycles, while Fly Wheel makes it possible to run more than 200,000 cycles. If mass-production can lower the costs, hybridized heavy-duty vehicles (HDV) with a Fly Wheel can play a key role in the increase of fuel efficiency.

6. CONCLUSION

The levels of exhaust fumes and fuel consumption in small vehicles are at satisfactory levels without electric power, but most heavy-duty vehicles are run by diesel, and improvements in fuel consumption and NOx and other exhaust fumes are necessary. With today's technology, running heavy-duty vehicles only by means of a battery is not possible in respect to cost and life-span, and thus hybridization is necessary as a way to resolve this problem. Hybrid large city-buses and trucks have been produced and sold experimentally, but they have not yet become popular. The main cause of this is that the improvement of fuel efficiency is poor even though cost increases as the result of hybridization. This paper has pointed out that the cause of this situation is due to an insufficiency in charging capability of batteries for regenerating power, and this is shown by calculations using the example of commercially-sold large city-buses. Using the results of analysis based on this running model, a solution is proposed regarding the possibility of installing a Fly Wheel system which complements the charging capability of the battery.

References

Bogdan, T., Energy storage technologies for all-electric combat vehicles, AECV, 2005.

Cao, E., New battery/ultra-capacitor hybrid energy storage system for electric, hybrid and plug-in hybrid electric vehicles, *IEEE Transactions on Power Electronics*, 2012.

DOE/NREL Transit Bus Evaluation Project. https://www.afdc.energy.gov/pdfs/nyct_diesel_hybrid_final.pdf, 2002.

Hamai, S., Development of new units for heavy-duty hybrid city buses, *EVS29*, 2016.

Japanese Ministry of Land, Infrastructure, Transport and Tourism, Jidosha nenpi ichiranI (A list of vehicle fuel-consumption), 2013.

Japanese Ministry of Land, Infrastructure, Transport and Tourism, Juryousha haishutu gasu no sokuteihouhou (Methods for measuring exhaust fumes from heavy-duty vehicles), Exhibit 41, 2008.

Nihon Bus Association., Nihon no bus jigyo to Nihon no bus kyoukai no gaiyo (Bus business and a brief summary of the bus association in Japan), Booklet of Nihon Bus Association, 2015.

Nomoto, S., https://www.jsae.or.jp/~dat1/mr/motor27/mr2706.pdf, 2015.

Shogo Nishikawa, https://www.jsae.or.jp/~dat1/mr/motor14/mr200209.pdf, 2002.

(Received April 15, 2017; accepted May 19, 2017)