

Fuel Economy Research on Series-Type HEV Intracity Buses with Different Traction Motor Capacity Combinations

Minjae Kim, Daebong Jung and Kyoungdoug Min
Seoul National Univ

ABSTRACT

Research on HEV (hybrid electric vehicle) intracity buses has become a topic of interest because the well-known service routes of intracity buses and the frequent stop/go pattern make the energy management of the vehicle straightforward. Thus, the energy flow and the energy management of the intracity bus have been studied extensively in order to improve fuel economy. However, the HEV buses that have been studied previously were equipped with a single traction motor or with dual motors with the same capacity for the convenience of the equipment without considering the motoring or generating efficiency of the traction motor. Therefore, the energy flow from the engine/generator unit to the traction motor that has been optimized by many kinds of energy distribution strategies could not be transferred to the wheels in the most efficient manner. This paper investigates this aspect of the energy flow. It studies the traction motor energy distribution by investigating combinations of the different traction motors with the different motoring/generating energy distribution methodology. The research suggests that instead of using a single traction motor or dual motors with the same capacity, dual motors with the different capacity combinations should be used to access the best efficiency distribution map. The different capacity combinations here not only refer to the physical capacity but also to the ratio of electrical energy distributed to the traction motors. Thus, the proposed approach distributes the required motoring/generating energy to the dual motors with the better efficiency. Therefore the system efficiency increases both for motoring and generating and the fuel economy of the system becomes better. The simulation of the proposed method was executed on the Simulink and AMESim co-simulation platform.

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INTRODUCTION

An intracity bus follows the same route each time that the energy usage is easily expected. Thus, the hybridization of the intracity bus is the urgent matter of concern [1, 2, 3]. Hybrid vehicle research generally focuses on increasing fuel economy or reducing emissions. Many strategies have been investigated to accomplish these two goals. The energy distribution control strategy is one of the most important issues to address because hybrid vehicles strongly depend on the supervisory control strategy. It influences each component of the vehicle. Even though the engine, the generator, the battery and the motor are very powerful, without an appropriate control strategy, the output performance may be no greater than that of an internal combustion engine vehicle.

There are several types of energy distribution control strategies-e.g., DP (Dynamic Programming), ECMS (Equivalent Consumption Minimization Strategy), and PMP (Pontryagin Minimum Principal) [4, 5, 6]. Energy distribution

research generally focuses on the energy flow from the engine/generator unit to the traction motor in [Figure 1](#). However, if the energy distribution at the traction motor is not efficient, even if a very effective or powerful methodology is used to supply the optimal energy from the engine/generator unit to the traction motors, the most efficient energy flow to the wheels cannot be achieved in the system.

This research focuses on the energy flow at the traction motors. Unlike the parallel-type HEV bus, in the series-type vehicle, dual traction motors are often used instead of just a single motor because the required traction motor capacity is much higher than that of the parallel-type vehicle. For example, the existing series-type HEV intracity bus is equipped with a 240 kW single traction motor or 120 kW dual motors [7, 8]. To raise the fuel economy of such series-type hybrid buses, using more efficient traction motors might be a solution. However, because a motor generally has a uniformly good efficiency and already has an efficiency of up

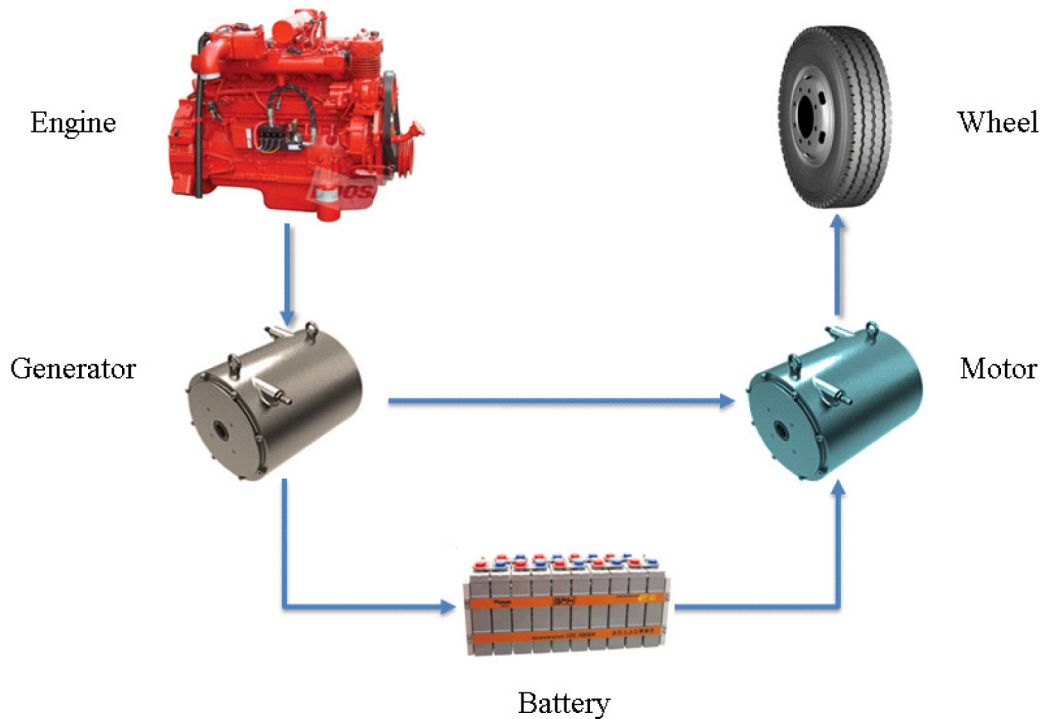


Figure 1. Series hybrid electric vehicle energy flow

to 95 %, raising the motor efficiency itself, even by 1 %, is very difficult. Therefore, determining which motor configuration to use and how to manage them can improve the system efficiency, even with the same hardware. In other words, in the past, the consideration given to choosing motor combinations was not sufficient. The decision was made based solely on convenience rather than by considering the motoring or generating efficiency of the traction motor. Therefore, the energy flow from the engine/generator unit to the traction motors cannot be transferred to the wheels in the most efficient manner. This paper studies the energy flow from the traction motors with the several kinds of traction motor combinations.

The energy distribution strategy from the engine/generator unit to the traction motors used the thermostat strategy which is well known for its robustness and the other variables in the simulation set, except for the gear ratio, were kept the same to facilitate an exact comparison. The methodology proposed in this paper provided an optimal efficiency at the traction motor because the energy that was efficiently transferred to the traction motor could be transferred to the wheel with the best efficiency, while leaving the energy distribution control strategies from the engine/generator unit to the traction motors unchanged.

The simulations in this paper were performed with the AMESim and Simulink co-simulation platform. AMESim served as the plant that implemented the dynamics of the series-type intracity bus and Simulink served as the controller that makes the command signals for the plant model.

BODY

1. TARGET MODEL

1.1. Hybrid Bus Specification

Table 1 shows the target series-type hybrid bus model specification used in this research. It is an intracity bus and has a 240 kW traction motor. The fuel type of the model is CNG and the engine, generator and motor's maximum power is limited to 180 kW, 180 kW and 240 kW, respectively. The battery used in the bus is a NiMH type and it provides a maximum power of 240 kW.

1.2. Bus Modeling

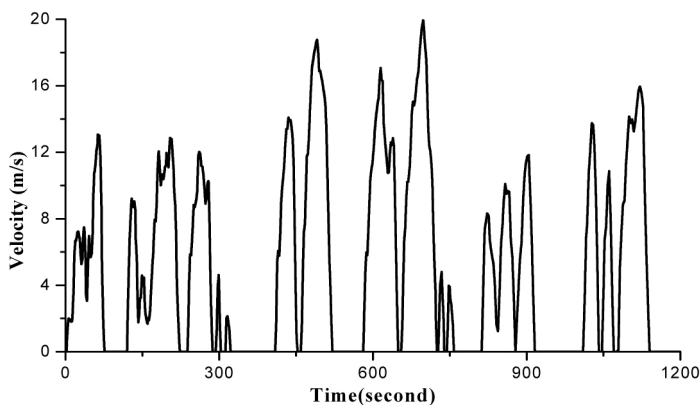
In the research, the forward simulation model of the hybrid bus was developed on the basis of the AMESim and Simulink Cosimulation platform. The plant model was designed by AMESim, which considers the inertia of the system, and the HCU (Hybrid Control Unit) logic was developed by Simulink. HCU obtains the information from each part and sends back the corresponding command. The motor choices for this modeling were 240 kW, 120 kW & 120 kW and 90 kW & 150 kW. And the assumption that all the summation gearboxes from the output of those motors to the wheels at different ratios have the same efficiency was used for the investigation of the different motor combination effects.

Table 1. Vehicle specification

Item	Parameter	Value
Vehicle	Type	Series Hybrid
	Total mass	15,000 kg
Engine	Fuel Type	CNG
	Maximum power	180 kW
	Maximum torque	883 N m
	Capacity	8,000 cc
Generator	Type	PM type
	Rated power	180 kW
	Maximum torque	912 N m
Motor	Type	PM type
	Maximum power	240 kW
Battery	Type	NiMH
	Maximum power	240 kW

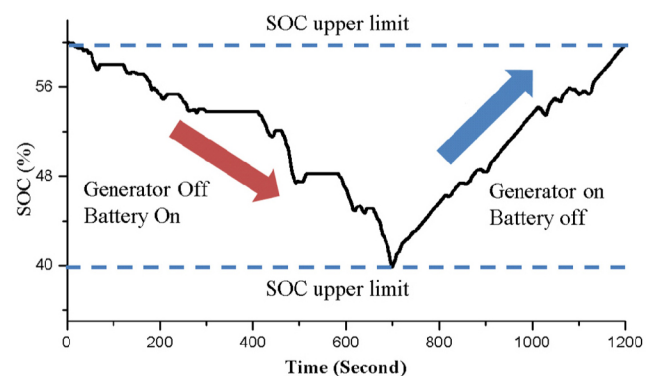
1.3. Speed Profile

The standard test cycles FTP, NEDC or US-06 are generally used for the evaluation of fuel economy for a passenger car. However, those speed profiles are not appropriate for testing and checking the relevance of the actual intracity bus fuel economy. The standard test cycles do not represent the real operating conditions because the intracity bus stops at each bus stop, and the driving load is much different from that of a real bus. Because this research is focused on the real buses that run in Seoul City, using the real speed profile is more appropriate [9, 10]. Figure 3 shows the bus speed profile that was used in this paper. It shows that the total time is 1150 s, and the average speed is 19.3 km/h, with a distance of 6.2 km, which has also been used often in other research studies [11, 12, 13]. The speed profile data were collected from a real Seoul city bus by Daewoo Bus Corporation.

**Figure 3. Speed profile of a Seoul city bus**

1.4. Power Distribution Strategy

The series-type HEV intracity bus was simulated with the thermostat strategy. The thermostat strategy is a rule-based strategy that considers the SOC limit of the battery. As shown in Figure 4, the strategy turns on the engine/generator unit when the battery SOC reaches the lower limit and turns off the engine when the battery SOC reaches to the SOC upper limit; thus, it is called an on/off control strategy. The strategy uses an engine/generator unit operation at the best bsfc point, so the efficiency is very high with relation to the engine. In Figure 4, the engine is turned on when the battery SOC goes down to 40 % and turned off when the battery SOC goes up to 60 %. Equation (1) shows the turn on/off standard of the thermostat strategy. The engine/generator unit generation power can be computed with (2) and (3). P_E is the generation power, and S_E is the engine on/off selection. P_B is the battery power burden for the motor traction, and P_R is the required power. P_E is the engine generation power.

**Figure 4. Thermostat strategy of a series-type HEV bus**

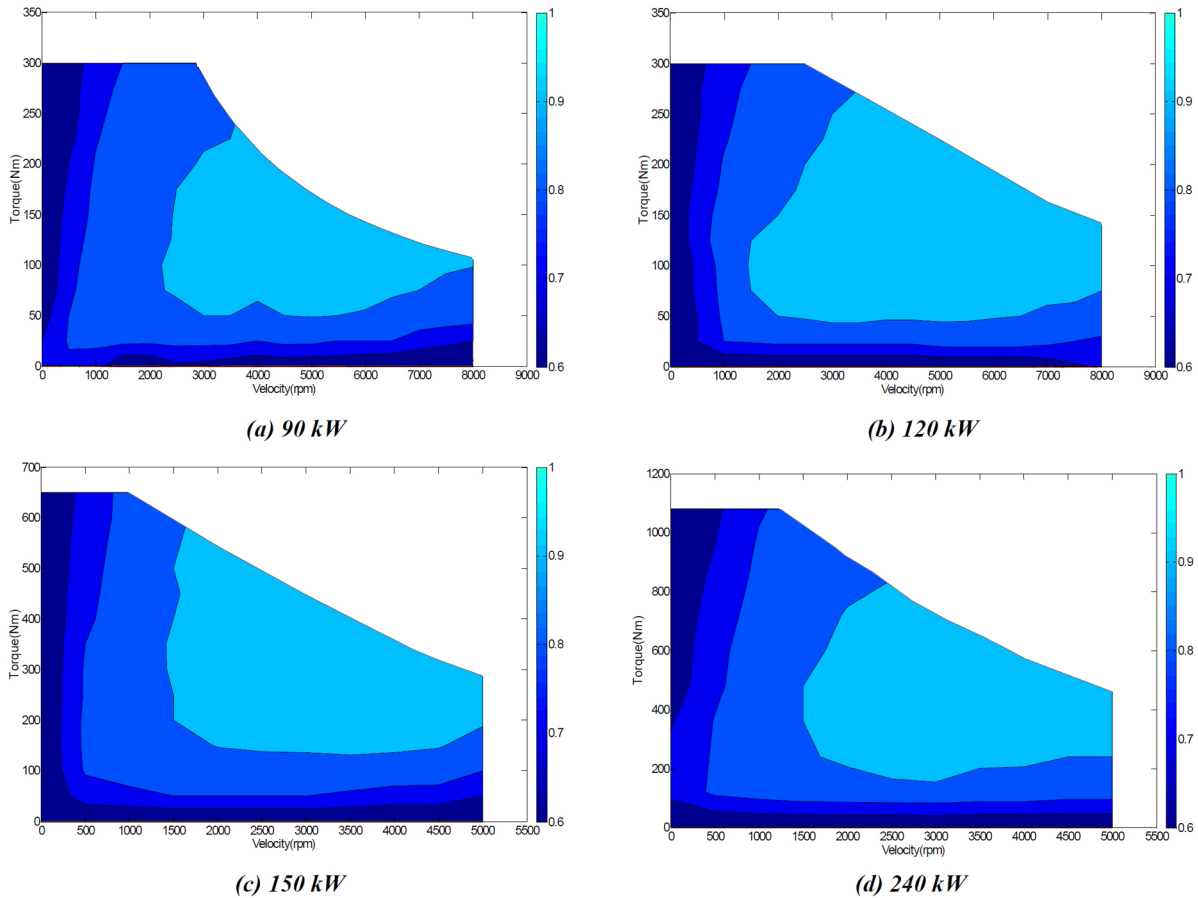


Figure 5. Motor TN curve and efficiency map

$$S_E = \begin{cases} 0 & \text{if } \begin{cases} SOC(t^-) \geq SOC_U \\ SOC(t^-) > SOC_L \text{ and } S_E(t^-) = 0 \end{cases} \\ 1 & \text{if } \begin{cases} SOC(t^-) \leq SOC_L \\ SOC(t^-) < SOC_U \text{ and } S_E(t^-) = 1 \end{cases} \end{cases} \quad (1)$$

$$P_E(t) = \begin{cases} 0 & \text{if } S_E(t) = 0 \\ P_{BB} & \text{if } S_E(t) = 1 \end{cases} \quad (2)$$

$$P_B(t) = \begin{cases} 0 & \text{if } SOC(t) < SOC_L \\ P_R(t) - P_E(t) & \text{if } SOC_L \leq SOC(t) \leq SOC_U \\ P_R(t) & \text{if } SOC(t) \geq SOC_U \end{cases} \quad (3)$$

As this strategy commands a single generation of the best bsfc operating point, the error caused by using thermostat strategy when evaluating the motor combination effects becomes only a few as it provides the power as much as it consumes in the traction motors with almost the same rate of the power generation per a gas consumption. The battery upper limit and lower limit of 60 % and 40 %, respectively,

was chosen as the internal resistance is nearly constant; thus, the effects of internal resistance also could be removed. The thermostat strategy generally maximizes the efficiency of the engine. However, when the engine is off, the only power source is the battery, so its capacity should be large. Therefore, the battery is heavy and this strategy could become more useful as improvements in battery technology occur [8][14].

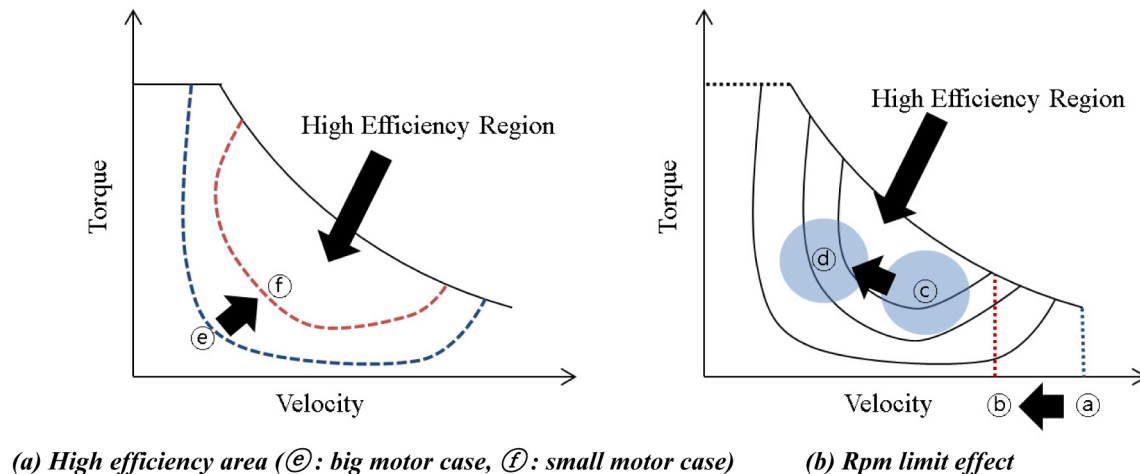
2. MOTOR CHARACTERISTIC

The motor combinations that were chosen in the research were 240 kW single, 120 kW & 120 kW dual, and 90 kW & 150 kW dual to meet the design specification of the bus, 240 kW. The map data for those motors are given in Figure 5. All of the motor information was provided by the same company, and the motors came from the same line-up; thus, the motor characteristic tendencies are expected to be consistent. The limitation information for the motors is provided in Table 2. The limitations are determined by the mechanical or electrical limitations. Because the rpm limits are different for each case, the reduction gear ratios were set to be different in order to use the full speed of each motor.

As shown in Figure 5, the high-efficiency area is the largest for the 120 kW case. Even though the efficiency of the 240 kW motor is generally expected to be very high and in

Table 2. Traction motor limit

Limit \ Capacity	90 kW	120 kW	150 kW	240 kW
Maximum Speed	8000 rpm	8000 rpm	5000 rpm	5000 rpm
Maximum Torque	300 N m	300 N m	650 N m	1080 N m

**Figure 6. Motor efficiency map tendency**

many cases the highest efficiency value of the largest motor might be the best, on the contrary the high efficiency region is expected relatively small when the capacity of the motor becomes small as shown in [Figure 5 - \(a\)](#) and [Figure 6 - \(a\)](#), the high-efficiency area cannot be fully used because of the rpm limit. As shown in [Figure 6 - \(b\)](#), as the motor rate capacity becomes much larger, the maximum rpm limit shows the tendency of rapid decrease from ⓐ to ⓑ. As a result, the portion over a 0.9 efficiency for 90 kW, 120 kW, 150 kW and 240 kW motors are 34 %, 51 %, 41 % and 38 %, respectively. Thus in [Figure 6 - \(b\)](#), the operating point in ⓐ that was used before would be in position ⓑ. Therefore, using the high-efficiency area is not easy and the motor will still work in the less efficient area in the motoring/generating mode. Even though the efficiency map of the motor has a nonlinear characteristic, such a tendency can be expected to apply to other motors of the same line-up.

3. POWER DISTRIBUTION STRATEGY IN THE TRACTION MOTORS

In the existing traction motor combinations, just a single 240 kW motor or 120 kW & 120 kW dual motors were equipped to provide the traction of a series-type HEV bus [7, 8]. However, those combinations were not enough, so the basic combination capacities of 90 kW & 150 kW, 120 kW & 120 kW or 240 kW single were chosen. Even though a motor capacity below 90 kW was considered, because of the traction torque problem, it was excluded from the analysis.

The different capacity combinations not only refer to the physical cases, as mentioned, but also the distributed electrical energies provided to the traction motor. For example, if 100 kW is required for the 120 kW & 120 kW combination, the power can be distributed as 50 kW to each motor, but it also can be distributed as 100 kW to one motor, and the other motor need not be involved.

When the simulation is run, for example, the operating points with the power distribution of the maximum power ratio are shown from [Figure 7, 8, Figure 9](#). In the figures, almost no operating points can be found below certain rpm as those cases happen when the vehicle speed is so low at the generating mode that the mechanical breaks were used instead of the traction motors for the safety. [Figure 10](#) shows the velocity errors between the simulation and the driver cycle when the start SOC of the simulation was 52.3 %. As in the figure, the simulation velocity follows the driving cycle very well that the bus can be expected to consume the energy as much as it requires equivalently according to the driving cycle load. That is because if the bus velocity cannot follow the driving cycle well then the fuel economy might be calculated better as the gas consumption cannot reflect the real driving cycle load. And this model uses thermostat strategy so the fuel economy interference as of the engine operating point scattering in the bsfc map could be ignored. That means if the other strategy like power follower strategy is adopted then the motor efficiency variation effects only cannot be considered as the variation of the engine operating points in the bsfc map also interferes the gas mileage [4].