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Improve fuel efficiency in hybrid bus applications using a high-power servo motor

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Introduction

There has been a significant shift in the bussing industry from pure diesel traction systems to a hybrid traction system. The reasons are economic.

This paper will present a simple model for hybrid bus traction application. The energy consumed by the bus as a result of velocity changes, e.g., speed correction and start/stop cycles, will be calculated for a traditional diesel bus and a hybrid bus.

The size, weight and efficiency of the traction servo motor will be examined at a high level to determine if further efficiency improvements can be made.

In a series hybrid, there are additional gains in fuel efficiency that are due to running the diesel engine at a constant speed at the peak efficiency point. This is done by running the engine at a constant speed into a very efficient generator. This additional efficiency gain is beyond the scope of this paper. The main challenge with including the added efficiency of the series generator is tied to the difficulty in obtaining reliable numbers for the difference in efficiency of the diesel engine between running the engine at a constant speed and running the engine at varying speeds and therefore the saving represented by the series generator are not included in the calculations in this paper.

Overview

In this paper, a mathematical model is developed for a bus. The bus that is modeled does not represent any particular make or model. The parameters for the bus model are based on various sources of information. The range of values for a given bus parameters for the bus model was determined by choosing a reasonable value in the range of information discovered.

Table 1 provides a range of parameters that resulted from the information search.

Table 1

Parameter	Range
Bus Gross Weight	12 – 23 Tons
Fuel Economy	1.7-3.5 mpg
Diesel Engine Efficiency	20%-30%
Energy Content of Fuel	142000 BTU/gal

This information will be use to create a simple fuel consumption model for the bus. The model will be use to answer some question about optimizing the servo motor for maximum fuel and dollar savings. The paper will introduce a few concepts before pulling the full bus model together. Conclusions will be drawn based on what the model tells us.

Hybrid bus overview

The momentum of a bus changes constantly as the bus travels on its route, picking up and discarding passengers. The momentum of the bus increases as the bus accelerates between a low speed and a high speed. The increase in momentum of the bus is a result of work done by the diesel engine. The diesel engine consumes fuel at some rate while it converts the fuel energy into mechanical energy.

When the bus decelerates between a high speed and a low speed, the momentum change of the bus is converted to heat by application of the brake. Any normal speed corrections that result from turning a corner, starting and stopping, or simply adjusting to traffic flow speed, will result in a momentum change of the bus. Every momentum cycle from low speed to high speed and back results in fuel being burned to accelerate the bus, and then the bus momentum being converted to waste heat in the brake pads. In other words, every speed adjustment consumes fuel and therefore costs money.

In a hybrid bus platform, a traction servo motor is used to accelerate the bus from battery power. In series hybrid, the servo motor undertakes the entire task of accelerating the bus. In a parallel hybrid the servo motor assists the diesel engine in accelerating the bus. The main difference between the traditional diesel-only platform and the hybrid platform is that the traction servo motor is also used to slow the bus momentum during changes in speed. The energy captured during deceleration is stored in a capacitor bank or a battery. During the next acceleration cycle, the energy, previously captured and stored in the battery, is converted back into momentum of the bus.

Energy re-capture concept

The energy re-capture process using the servo motor system appears simple and efficient. However, effective re-capture rate is lower than one might imagine. Consider the component average efficiencies provided in Table 2. Note that the average efficiency can vary considerably from the "peak" efficiency often provided from the component manufacturer. For example, a servo motor has a low efficiency if it is commanded to produce high torque at low speed, and an amplifier consumes watts of energy even if the commanded current to the motor is zero. Therefore, the motor efficiency in Table 2 is not the peak motor efficiency; it is the average efficiency of the motor over the range of operation that includes operating the motor at low speed high torque points.

Table 2

Device	Average Efficiency
Servo Motor, ε_{motor}	85%
Amplifier, ε_{Amp}	95%
Storage Device, $\varepsilon_{storage}$	99%
Wheel drive train, $\varepsilon_{DriveTrain}$	97%

Let's assume that the bus slows from a high speed of V_{high} to a lower speed of V_{low} due to a change of traffic flow. During the speed adjustment, the energy contained in the bus' momentum changes. The change of kinetic energy can be calculated from the bus velocity and mass, as indicated by equation (1.1). However, if the bus ends up at a different elevation, one may also need to include the bus potential energy; however, we are not going to include potential energy in order to simplify concepts.

$$\Delta E = \frac{1}{2} m (V_{high}^2 - V_{low}^2) \qquad (1.1)$$

The traction servo motor system is going to attempt to recapture this change in energy as the bus slows. At some later time the bus will re-adjust it speed from the low velocity back to the high velocity. The traction system will reuse the captured energy to bring the bus back up to the original speed. Figure 1 contains a simple schematic of the system.

Using a very simple model the energy recaptured, E_r, is given in equation (1.2).

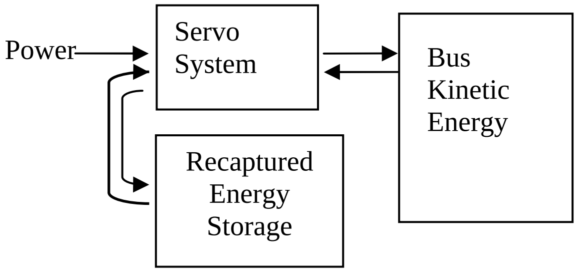
$$E_r = \varepsilon_{motor}\varepsilon_{amp}\varepsilon_{storage}\varepsilon_{driveTrain}\Delta E = \varepsilon\Delta E \quad (1.2)$$

If we consider the efficiencies in Table 2, the recaptured energy, E_r, will calculate as indicated in equation (1.3). Note that only 77.5% of the energy was recovered. If we then send the energy back to the bus momentum at the same efficiency level as we captured it, the amount of energy converted back into momentum is only 60% (60% = 0.775*0.775*100%).

$$E_r = 0.85*0.95*0.99*0.97 = 0.775\Delta E \quad (1.3)$$

Since the efficiency during capturing and reuse of the energy is not 100%, some external power needs to be supplied during acceleration in order to retain the original speed. This is depicted by the power input in Figure 1.

Figure 1



The efficiency of our servo system is important. Having an easy method of measuring efficiency can provide some valuable insight. By knowing the mass of the bus, the velocity of the bus, and measuring the additional input power during acceleration, one can determine the efficiency of the entire system without ever knowing how much energy was recaptured and recycled. We don't even need to known what the individual component efficiencies are. A derivation will follow.

Measuring system efficiency

Assume that ε is the efficiency of converting electrical energy to bus kinetic energy, this includes the efficiency of the motor, the amplifier, the storage device and the drive train. The external power supplied to the servo system over time, plus the contribution of the recovered energy E_r times the efficiency, ε, will equal the change in Bus momentum. This relationship is presented in equation (1.4). The equation holds over one full momentum change cycle from high speed to low speed then returning to the initial high speed.

$$\varepsilon\oint P_{in}dt + \varepsilon E_R = \Delta E \quad (1.4)$$

Also note that during the energy recapture cycle the power input from the outside is zero and that the energy recapture from the bus momentum to electrical energy occurs at an efficiency of ε. This results in that equation (1.4) can be rewritten as equation (1.5). The assumption that power in is zero during the recapture is actually not necessary; it was done to simplify the math; the result of equation (1.5) is the same even it power is non-zero re-capture.

$$\varepsilon\oint P_{in}dt + \varepsilon^2\Delta E = \Delta E \quad (1.5)$$

Re-arranging equation (1.5) yields equation (1.6).

$$\frac{\Delta E}{\oint P_{in}\,dt} = \frac{\varepsilon}{1-\varepsilon^2} \equiv L_v \quad (1.6)$$

The parameter L_v is defined as the energy leverage. The energy leverage is a number greater than one for a system that is effectively recapturing and reusing energy. The energy leverage is the change in kinetic (and potential) energy of the bus divided by the net energy input over a compete energy cycle. An energy cycle is defined as a change in velocity from V_1 to V_2 and then back to V_1. If one thinks about the structure of the equation, it appears that we have a system where we are getting more energy out, ΔE, then we are putting in, $\oint P_{in} dt$. In fact, we are, because we are recapturing and reusing a portion of the input energy. A pendulum is a good example: it has a very high energy leverage number, a small amount of input energy over one cycle and it used to maintain a much larger kinetic energy change over the same cycle.

Another implication of equation (1.6) is that the efficiency of a complicated system can be determined by parameters that are easily measured. An integrating power meter can measure the input power, Pin, and determine the energy used per cycle, $\oint P_{in} dt$. The velocity and weight of the bus can be easily measured as well.

The process of measuring the system efficiency would be quite simple: Run the bus through several velocity cycles on a level surface while monitoring and recording the energy going into the servo motor drive from the external power source; this is equal to P_{in}. (However, this would only be only feasible on a series hybrid because the engine is decoupled.) The energy leverage is calculated from the left side of equation (1.6). The right side of equation (1.6) is solved for ε, as show in equation (1.7). The efficiency is calculation from equation (1.7).

$$\varepsilon = \frac{\sqrt{\left(4L_v^2+1\right)}-1}{2L_v} \qquad (1.7)$$

The efficiency of the servo system will be very important. It ultimately will be responsible for a significant proportion of the overall fuel savings. Equations (1.6) and (1.7) can also be used to determine the theoretical efficiency for the same system. Later in this paper, the average efficiency is determined for a servo motor; the energy leverage method is used to determine the theoretical efficiency.

A simple bus fuel consumption model

Next a simple model will be developed that will be used as a tool to determine the dollar value of an efficiency point. The values in table 1 are used as a starting point. The assumptions that were selected for our bus are presented in Table 2. Our bus will weigh 40,000 lbs (20 tons), will have a diesel engine with an average efficiency of 20%, and a fuel economy of 2.4 mpg highway (1.7 mpg city).

Table 2

Bus Model Selected Parameters	
Bus Gross Weight	20 Tons
Fuel Economy (@35mph)	3 mpg
Diesel Engine Efficiency	20%
Energy Content of Fuel	142000 BTU/gal
Life of Bus	300,000 mi
Cost of Diesel (Future)	$6/gal

The bus model in this paper is assumed to be used primarily in the city to pick and drop off customers very frequently. Without having an actual move profile of a city bus over its 300,000-mile journey, some simplifying assumptions will be made. The bus motion profile is provided in the following paragraph.

The bus travels constantly at 35 mph. Every 2 mi the bus comes to a complete stop to pick up passengers. Every 0.5 miles the bus needs to make a speed correction of 35 mph to 20 mph back to 35 mph to turn a corner. Every 0.25 miles the bus needs to make a speed correction of 35 mph to 30 mph back to 35 mph to adjust to traffic.

In order to simply the calculations, the drag on the bus caused by wind drag and wheel friction was constant at all times. Given the bus weighs 40,000 lbs, gets 3 mpg at 35 mph and has an engine efficiency of 20%, the drag on the bus calculates to 1394 lbs (6201N).

The fuel used to overcome this drag force on the bus is 100,000 gallons over it 300,000 mi journey.

Additional fuel is required to adjust the speed of the bus. The amount of fuel required to change speed is different for the hybrid as compared to the all diesel bus.

As an example, the calculations will be shown for the 35 mph to 30 mph back to 35mph speed correction. According to the motion profile the bus will under go 300,000mi/0.25mi per correction which calculates to 1.2 million such corrections. The kinetic energy of the bus is 2.22 mega joules at 35 mph and 1.63 mega joules at 30 mph. The amount of energy wasted by starting and stopping is 1.2 million corrections * (2.22MJ - 1.63MJ) = 708GJ. The fuel required to supply this level of energy = 708GJ / 149 MJ/Gal / 20% eff = 23646 gallons.

Table 3 contains the gallons of fuel used for each of the three simulated corrections for the diesel only bus. The bus used a total of 164,798 gallons and obtained and overall fuel usage of 1.8 mi/gal.

Table 3

Fuel Usage for Diesel Only Bus	
35 MPH for 300K Mi	100,000 Gals
Stop every 2 miles	11,141 Gals
35-30 MPH correction	23,646 Gals
35-20 MPH correction	30,0012 Gals
Total Gallons	**164,798 Gals**
Total Dollars	**$988000**

Table 4 contains the gallons of fuel used by the hybrid bus. The calculations for fuel consumption are the same, however, for the hybrid version the fuel consumption is reduced by the recaptured energy as indicated by equation (1.3). Since the recaptured energy must past through the servo system twice, the effective amount of recaptured energy is 0.775*0.775*100% = 60%.

Table 4

Fuel Usage for Hybrid Bus	
35 MPH for 300K Mi	100,000 Gals
Stop every 2 miles	4,475 Gals
35-30 MPH correction	9,498 Gals
35-20 MPH correction	12,056 Gals
Total	**126,029 Gals**
Total Dollars	**$756,000**

The hybrid bus attained an overall fuel economy of 2.4 mpg. This is 30% increase in fuel efficiency and represents an overall savings of $232,000 over the life of the bus, if we assume diesel is $6 per gallon.

Here is some added food for thought. If the bus were to be run entirely from the power grid with a cost of electricity assumed to be $0.105 per kWhr, the cost of the moving the bus through our motion profile is $121,000 total. This represents a savings of $867,000 over the diesel bus. I will ask why don't we plug the bus into the power grid at every bus stop? If every bus stop had a pug-in station that could supply 200 amps to the batteries for the 2 minutes while the customers got on/off the bus the total cost of the motion profile would be $397,000 for the combined cost of diesel and the grid power.

The cost of inefficiency and weight

The fuel consumption model was rerun assuming the motor had an overall efficiency of 86% percent instead of 85%, and the model was re-run assuming the servo motor weighed 100 lbs more. Table 5 presents the results of fuel savings for the three different scenarios.

Table 5

Cost of fuel for different Scenarios of Bus weight and Servo motor efficiency	
40,000 lbs and 85%	$232,613
40,000 lbs and 86%	$238,118
40,100 lbs and 85%	$233,194

Table 6 contains the fuels savings per efficiency point and the fuel cost per lb of weight. These numbers are for the full life of the bus and assume the bus has traveled 300,000 miles.

Table 6

Simulation Results	
Saving per 1% eff	$5505
Cost per 1 lb of Weight	$5.81
Weight break even point	947 lbs/%

For every percentage point of efficiency gained, it will result in the bus consuming $5505 less fuel. The cost of hauling around and extra lb of weight is only $5.81. This means that if we can increase the efficiency of the servo motor and it results in less than 947 lbs of additional weight it may be worth carrying the extra weight; maybe it is not worth carrying the full 947 lbs but some additional weight that is less than 947lbs may provide benefit.

Bigger and colder is better

In the next section an investigation will be made in order to determine if it is better to make the motor smaller or bigger and to look at the effect of servo motor temperature on fuel consumption.

A few assumptions where made in order to simplify the analysis: The torque constant of the servo motor was fixed at 75 volts per KRPM. The motor winding temperature was fixed at either 50°C or 150 °C, and therefore adequate cooling was assumed such that the selected winding temperature was achieved. The analysis was based on the MPP270 servomotor manufactured by Parker Hannifin. The torque produced by each of the servo motors was selected at 400 N*m. This is a torque level that will allow the bus to acceleration to 35 MPH in 15 seconds. The bus was assumed to have no gears. The servo motor directly drives the tires of the bus such that the bus reaches 70 mph at 4000 rpm servo motor speed. The size and power rating of the amplifier was the same for all of the scenarios.

The baseline motor was an MPP2708 that was cooled using engine coolant at 100°C and had a 150°C winding temperature. The MPP270G motor is the same frame size; however, it has a lamination stack that is two times longer and weighs an additional 160lbs. The motors with a 50 °C winding temperature are assumed to be cooled with a cooling loop that is independent from the engine cooling loop.

Table 7

Motor average efficiency			
Motor	Temp	Weight	Efficiency
MPP2708	150 °C	207	85.0%
MPP2708	50 °C	207	87.5%
MPP270G	150 °C	367	91.1%
MPP270G	50 °C	367	92.5%

Table 7 contains the average efficiency of four different motor scenarios that were simulated. It needs to be reiterated that the efficiencies in Table 7 are the average efficiencies. These values where calculated by the energy level method as indicated in equations (1.6) and (1.7). These efficiencies are not to be confused with the peak motor efficiency. The peak motor efficiency is much higher because the peak efficiency is run at a constant speed that is much higher than this motor will typically run in this bus application.

The longer motor runs more efficiently than short motor because it has a lower resistance for the given torque constant. This means that the I^2R losses are much less. The cooler motors ran more efficiently than the hot motor because the resistance of copper is a strong function of temperature.

If we take a look at the incremental savings of the four motor scenarios one can see that an addition amount of savings is possible. The savings indicated in table 8 indicate the cost savings of the added motor efficiency minus the cost of carrying the extra weight minus the estimated material cost of the longer motor. The savings are based on a fuel cost of $6/gal.

Table 8

Savings in addition to $233,613	
Motor	Savings
MPP2708 @ 150 °C	$0
MPP2708 @ 50 °C	$ 13,570
MPP270G @ 150 °C	$ 21,880
MPP270G @ 50 °C	$ 29,480

There is one more scenario to consider. Since a servo motor has higher efficiency at high speed, why not run the motor at high speed for more time during the move profile? This can be achieved by adding a two-speed transmission. In this case the motor would spin at 4000 RPM at 35mph and would shift to high gear for speeds above 35 mph.

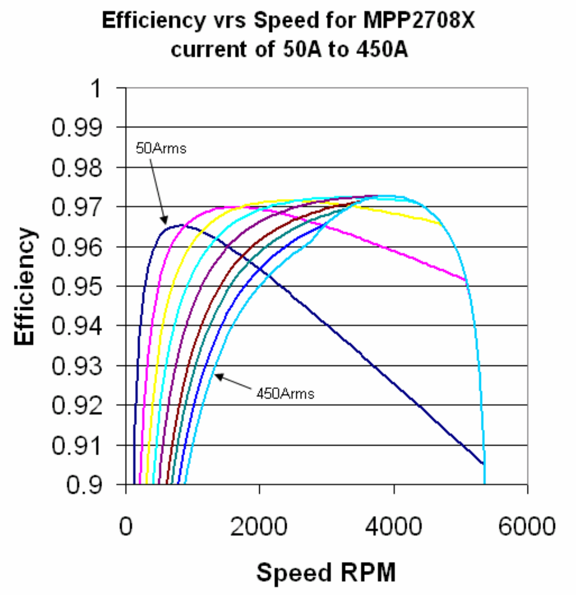
Table 9 considers the last scenario where the motor drives the tires though a two speed gearbox. The savings calculation includes: an increase in efficiency as a result of running the motor at high speed, a decrease in efficiency due to gearbox losses (98% gearbox efficiency was assumed), a penalty due to carrying the extra motor and/or gearbox weight, and a penalty in the cost of the extra motor and/or gearbox.

Table 9

Savings using a two speed gearbox.		
Motor	Savings over Table 8	Total Savings
MPP2708,150 °C	$ 26,282	$ 26,282
MPP2708, 50 °C	$ 19,096	$ 32,667
MPP270G, 150 °C	$ 7,139	$ 29,028
MPP270G, 50 °C	$ 2,739	$ 32,220

Table 9 shows some interesting results. If the smaller motor is used, the two speed transmission presents a savings. If the large motor is used the additional savings of the transmission is very small. The reason for this is that the gearbox presents another source of in-efficiency. The efficiency loss of the gearbox was more than the efficiency gain achieved by running the large motor at the higher speed. There is a torque value at every speed point for the servo motor where the efficiency is a maximum. The large motor with the gearbox actually ran at a torque level that was less than optimum for the speed. This phenomenon is caused by the friction losses, as a proportion of the torque produced by the motor, became significant because the motor is oversized. Figure 1 contains an efficiency map of the MPP2708 motor; at low values of current and torque the friction and spinning losses reduce the high-speed efficiency.

Figure 1



Conclusions

Additional fuel savings can be obtained by using one or more of the following:

1) Over sizing the motor
2) Separate motor cooling loop
3) Using a gearbox

The largest gain was seen by using the small motor with the two-speed transmission and keeping it cool. There is another advantage to the two-speed transmission: The MPP2708 can only produce 400 N*m peak torque. With the two-speed transmission, the motor can produce 800 N*m of low-speed torque. This would have the advantage of better responsiveness for the bus driver.

The second biggest gain was seen in using the over-sized motor with the two-speed gearbox. However, this solution can be disqualified because the gains are not big enough to justify using both the big motor and the gearbox. The overall package would be larger and heavier and would represent no additional savings.

Using a separate cooling loop in either the small motor or the large motor would represent good value. One possibility for achieving this would be to not use the engine coolant loop for motor cooling. Use a separate radiator loop. The motor would only need about 1000 to 2000 watts of cooling power to achieve an additional 10% fuel savings.

Additional investigation is needed in order to look at using the efficiency map in order to achieve additional savings by adjusting the torque produced by the motor as a function of speed the motor is going. This could be done in software and therefore could represent "free" fuel savings.