COMPARISON OF PARALLEL AND SERIES HYBRID POWERTRAINS FOR TRANSIT BUS APPLICATIONS

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ABSTRACT
The fuel economy and emissions of both conventional and hybrid buses equipped with emissions aftertreatment were evaluated via computational simulation for six representative city bus drive cycles. Both series and parallel configurations for the hybrid case were studied. The simulation results indicate that series hybrid buses have the greatest overall advantage in fuel economy. The series and parallel hybrid buses were predicted to produce similar CO and HC tailpipe emissions but were also predicted to have reduced NOx tailpipe emissions compared to the conventional bus in higher speed cycles. For the New York bus cycle (NYBC), which has the lowest average speed among the cycles evaluated, the series bus tailpipe emissions were somewhat higher than they were for the conventional bus, while the parallel hybrid bus had significantly lower tailpipe emissions. All three bus powertrains were found to require periodic active DPF regeneration to maintain PM control. Plug-in operation of series hybrid buses appears to offer significant fuel economy benefits and is easily employed due to the relatively large battery capacity that is typical of the series hybrid configuration.
INTRODUCTION
The city transit bus is an important mode of public transportation that is undergoing rapid change in terms of the vehicles employed in active service. There are nearly 70,000 buses operating in the U.S. today. In 1996, more than 95% were powered by conventional diesel powertrains, but by the end of 2014 about 40% had been replaced with buses using alternative emerging power sources [1-2]. By 2008, hybrid buses already represented 18% of the city transit bus market [2], and this market share has increased significantly since then. A recent report released by the business intelligence survey firm IDTechEx projects that the emerging global market for hybrid and pure electric buses will be worth $100 billion by 2025 [3]. This is mainly attributed to the excellent fuel savings and emissions reductions offered by hybridization for the city transit bus application, due to their high frequency of stop-and-go and idle operation [4].

Hybrid powertrains used in city bus applications are generally either series or parallel configurations [5]. In a series configuration, the wheels are driven directly by an electric motor, while the engine drives a generator that converts its mechanical power into the electricity that powers the electric motor or is stored in a battery. The primary electrical components - the motor, generator and the battery - of a series hybrid must provide or accept power levels approaching or even exceeding what is required to propel the vehicle, resulting in rather significant costs. A primary advantage of the series hybrid is that the battery is able to accommodate most of the transient power fluctuations associated with stop-and-go driving. Thus, the engine for a series hybrid can be downsized to provide only the average power needed by the vehicle, and the engine is able to operate near its peak efficiency most of the time. A downside to this scenario is the efficiency penalty associated with the dual-step conversion of energy (i.e., mechanical to electric to mechanical). In parallel configurations the bus can be propelled separately by the engine or electric motor, or by both at the same time. The option of having two power sources makes it possible to keep the electric motor and battery smaller, thus reducing costs [5]. Although favorable results have been reported in the literature for the fuel consumption and emissions of hybrid transit buses [6-13], many issues related to the combined fuel efficiency and emissions control of series and parallel hybrid powertrain configurations, particularly when integrated with emerging aftertreatment systems required to meet new emissions regulations, remain unresolved. This is particularly true when the effects of different urban drive cycles are considered [14].

The objective of the present paper is to develop a consistent simulation methodology that can account for rapidly evolving diesel hybrid and aftertreatment technologies and the increasing constraints imposed by the current emissions regulations. By evaluating and comparing the fuel economy and emissions of conventional and hybrid city transit buses equipped with aftertreatment devices, the authors aim to identify potential advantages and technical barriers that can be expected when applying hybrid technologies in city bus applications. The software platform used in this study is Autonomie, an open architecture powertrain and vehicle systems simulation tool developed by Argonne National Laboratory [15]. In addition to components included in the default bus configuration specified in Autonomie, the authors added engine, aftertreatment, and battery models developed at Oak Ridge National Laboratory (ORNL) that account for the transient fuel consumption, battery energy, engine-out emissions, and aftertreatment component performance of comparable conventional and hybrid buses operating over representative city bus drive cycles.

LITERATURE REVIEW OF HYBRID BUSES
A wide range of experimental results have reported that hybrid powertrain technologies increase fuel savings for city transit buses [7-13], as summarized in Table 1. The tested hybrids include both series and parallel buses, and the data were measured for both on-road city driving or chassis dynamometer testing conditions. In general, these results show that the fuel consumption benefits of hybrid buses are most significant for slow- and medium-speed drive cycles (i.e. <18 mph) [13]. Transit Authorities have quantified the fuel savings by direct comparison of hybrid and conventional diesel bus fuel consumption [16]. However, the fuel savings reported vary considerably even for the same drive cycle or similar
conditions of on-road city testing. This variation is likely the result of multiple factors, including low
measurement precision and lack of consistent methodologies for comparing different hybrid concepts
used in bus applications [7-8]. For example, in the on-road evaluations, most reported results include only
a statistical analysis of the overall fuel economy of a small sample of tested hybrid and conventional
buses [7-12]. For the chassis dynamometer measurements, many studies focused on a specific series or
parallel hybrid configuration compared to a conventional bus [7-8, 11-13]. Thus the results did not
evaluate the difference in fuel saving between series and parallel powertrain configurations.

**TABLE 1 Literature Summary for Fuel Economy and Emissions Reduction.**

<table>
<thead>
<tr>
<th>Testing Cycle</th>
<th>Fuel Economy</th>
<th>CO</th>
<th>HC</th>
<th>NOx</th>
<th>PM</th>
<th>Samples &amp; model-year of hybrid &amp; conventional bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBD</td>
<td>-23%~59%</td>
<td>-97%~38%</td>
<td>-43%~450%</td>
<td>-36%~49%</td>
<td>-93%~50%</td>
<td>2S (1999) : 2C (1998) [7]</td>
</tr>
<tr>
<td></td>
<td>-54%~59%</td>
<td>-94%~38%</td>
<td>+120%~450%</td>
<td>-49%</td>
<td>-93%~60%</td>
<td>1S (1999) : 2C (1999) [12]</td>
</tr>
<tr>
<td>NYBC</td>
<td>-44%~22%</td>
<td>-51%~25%</td>
<td>-88%~0%</td>
<td>-47%~56%</td>
<td>-78%~0%</td>
<td>1P &amp; 1S (2010) : 2C (2011/2012) [13]</td>
</tr>
<tr>
<td>KCM</td>
<td>-36%~14%</td>
<td>-50%~650%</td>
<td>-25%~460%</td>
<td>-31%~11%</td>
<td>-94%~33%</td>
<td>1P &amp; 1S (2010) : 2C (2011/2012) [13]</td>
</tr>
<tr>
<td>UDDS</td>
<td>-14%~0%</td>
<td>+120%~300%</td>
<td>-70%~0%</td>
<td>-7%~2%</td>
<td>0%~150%</td>
<td>1P &amp; 1S (2010) : 2C (2011/2012) [13]</td>
</tr>
<tr>
<td>New York City</td>
<td>-19%~22%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>10S (1999) : 10C (1998) [7]</td>
</tr>
<tr>
<td>King County</td>
<td>-27%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>2S (2004) : 30C (2004) [8]</td>
</tr>
<tr>
<td>15 dies c°  b</td>
<td>-21%~40%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>35P (&lt;200) [9]</td>
</tr>
<tr>
<td>New York City</td>
<td>-28%~38%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>20S (2002/2004) : 10C (1994/1998) [10]</td>
</tr>
<tr>
<td>Ames, Iowa</td>
<td>-12%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>10P (2010) : 7C (2008/2010) [11]</td>
</tr>
</tbody>
</table>

C: conventional; P: parallel; S: series; ° on-road city testing; Including DC, New York, Seattle etc.; ° unknown.

Table 1 also reveals a considerable range of results in the available experimental emissions measurements for hybrid vs. conventional buses in city driving [7-8, 11-13]. The results reported before 2007 demonstrate that hybrids achieved significant emissions reductions (with the exception of HC emissions in some cases). However, the data appearing after 2010 show a complex mix of results with less clear emissions differences between hybrid and conventional diesel buses. One possible explanation for this ambiguity could be changes in emission controls that have taken place due to rapidly evolving aftertreatment technologies and regulations [3, 17]. For example, in 2004, the U.S. EPA emissions standard was 2.4 g/bhp-hr for NOx and 0.1 g/bhp-hr for PM emissions; in 2007-2010, a new standard was phased-in that restricts emissions to 0.2 g/bhp-hr for NOx and 0.01 g/bhp-hr for PM, as well as 0.14 g/bhp-hr for HC [17]. The new emissions regulation requires buses to be equipped with a full exhaust aftertreatment system that typically consists of a diesel oxidation catalyst (DOC), a diesel particulate filter (DPF), and urea-selective catalytic NOx reduction (urea-SCR) in order to minimize tailpipe emissions [4]. Here, the DPF is generally based on a wall-flow substrate and can be catalyzed or non-catalyzed specific to application and design. The 2002-2004 and earlier bus models were often either equipped with a DOC only or no aftertreatment system was employed at all [7, 12], and SCR was rarely used.

As a consequence of the rapidly changing technology and regulatory environment described above, it is very challenging to make consistent, comprehensive comparisons between the various hybridization options for buses utilizing existing published data and reports. Thus, developing a flexible, consistent, and well-defined approach for simulating comprehensive hybrid bus systems under realistic operating conditions will be important for making informed decisions about commercialization and deployment of the next generation of urban public transit systems.
METHODOLOGY

Bus Powertrain Model

To establish a reference point for comparisons, a conventional (non-hybrid) transit bus configuration was
initially specified using Autonomie based on a 2005 Optima LF-34 bus, which is powered by a 5.9-L
Cummins ISB diesel engine and equipped with a 5-speed automatic transmission [18]. Table 2 lists the
key specifications of the modeled bus. To confirm that this bus model provides reasonable simulation
results, the predictions were validated with on-road measurements made by ORNL and the Knoxville
Area Transit (KAT) Authority for the same bus [18]. For a travel distance and time of 28.6 miles and
7200s, respectively, the predicted and measured trip fuel consumptions were 6.68 gallon and 6.56 gallon,
respectively. This difference is within acceptable measurement accuracy, indicating that the basic
simulation assumptions concerning the powertrain configuration were reasonable. The measured fuel
consumption results were collected from the engine control unit (ECU) via the vehicle’s SAE J1939 data
port.

For the hybrid transit bus simulations, two hybrid powertrain configurations were developed,
including a series configuration without a transmission and a pre-transmission parallel configuration with
a single motor. In the modeled series hybrid bus, a 12kWhr Li-Ion battery is considered together with a
191 kW diesel engine, a 202 kW permanent magnet electric motor, and a 208kW generator. This design
allows the electric drivetrain to be used extensively and the engine is employed only to maintain the
battery state of charge (SOC). For modeling of the parallel hybrid, the authors specified a pre-
transmission parallel configuration with a single motor between the clutch and gearbox. The electric
motor and battery in the parallel hybrid were rated at 60 kW peak power and 4.5kWh capacity,
respectively. Table 2 lists the key electrical system features for the series and parallel hybrid buses. Other
powertrain components (including the engine) and parameters are the same as those used in the
conventional bus configuration. In addition, 400kg and 120kg, respectively, were added to the overall
masses of the series and parallel hybrid bus configurations to account for the additional electric
components. Charge sustaining control strategies, modified from the default Autonomie strategies, were
utilized to manage the power transfers among the primary powertrain components (engine, electric motor
and transmission) and maximize fuel consumption, as described in previous studies by the authors [14-
15].

<table>
<thead>
<tr>
<th>Powertrain Component</th>
<th>Parameter</th>
<th>Conventional</th>
<th>Parallel</th>
<th>Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>Max torque</td>
<td>1024 Nm@1450rpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max power</td>
<td>191 kW@2200rpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Idle speed</td>
<td>845 rpm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Drive</td>
<td>Final ratio</td>
<td>3.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheel</td>
<td>Wheel radius</td>
<td>0.45 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chassis</td>
<td>Frontal area</td>
<td>8.5 m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aerodyn drag coeff</td>
<td>0.0098</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bus mass</td>
<td>11,636 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>Model</td>
<td>5-speed manual</td>
<td>5-speed manual</td>
<td>Fixed gear ratio</td>
</tr>
<tr>
<td>Traction Motor</td>
<td>Max power</td>
<td>N/A</td>
<td>60 kW</td>
<td>202 kW</td>
</tr>
<tr>
<td></td>
<td>Max torque</td>
<td>N/A</td>
<td>460 Nm</td>
<td>1540 NM</td>
</tr>
<tr>
<td>Generator Motor</td>
<td>Peak power</td>
<td>N/A</td>
<td>na</td>
<td>208 kW</td>
</tr>
<tr>
<td>Battery</td>
<td>Capacity</td>
<td>N/A</td>
<td>4.5 kWh</td>
<td>12 kWh</td>
</tr>
<tr>
<td>Mass penalty</td>
<td>Hybrid components</td>
<td>0</td>
<td>120 kg</td>
<td>400 kg</td>
</tr>
<tr>
<td>Accessories</td>
<td>Electrical power</td>
<td>360 W</td>
<td>2490 W</td>
<td>2490 W</td>
</tr>
<tr>
<td></td>
<td>Mechanical power</td>
<td>6790 W</td>
<td>1580 W</td>
<td>1580 W</td>
</tr>
</tbody>
</table>
Engine Model and Map

The engine model was developed based on static steady-state maps to predict fuel consumption and exhaust properties solely on the instantaneous speed and load. However, to accurately estimate fuel economy and tailpipe emissions, it is important to accurately model the transient fuel consumption and engine-out exhaust properties, since these can change dramatically from their steady-state values. The engine model addresses this issue by utilizing dynamic correction factors to the steady-state maps that account for recent engine history to provide more accurate estimates of engine fuel consumption and engine-out exhaust properties. These correction factors model the dynamic engine response as first-order lags associated with heat-up or cool-down of major engine components and the rate at which excess heat is added to the engine from combustion or lost to the surroundings. The lag parameters are calibrated with transient engine data and/or known engine characteristics. Details of this approach are explained more fully in a previous publication [19]. The engine model was developed using Matlab/Simulink. In the present study, transient engine-out emissions and fuel consumption data were not available for the simulated 5.9-L Cummins ISB engine. Thus the engine map was estimated by downsizing a map derived from measurements of a Caterpillar 3126E 7.2-L diesel engine [15], while keeping the brake specific fuel consumption (bsfc) and the emissions at the same brake mean effective pressure (bmep) unchanged. The steady-state exhaust temperatures were also assumed to remain unchanged. Although this is admittedly an approximation, the authors believe it is suitably adequate to provide the correct general trends. This same engine scaling methodology has been employed in several other vehicle simulations studies [14, 20, 21]. The detailed engine map was already reported in the authors’ earlier publication [4].

Aftreatment System Model

A full aftertreatment system model was developed to account for CO/HC/NOx/PM emission controls required by U.S. EPA regulation standards. The model aftertreatment system consists of a DOC, a catalyzed DPF, and urea-SCR. DOCs are used to catalytically oxidize unburned HC and CO, as well as to promote NO oxidation to NO2 for improving the efficiency of downstream NOx and particulate removal. Urea-SCR is specifically designed to remove NOx from lean engine exhaust and requires urea injection into the exhaust at a rate proportional to the engine out NOx emissions such that a 1:1 stoichiometry of NH3:NOx is produced on the SCR for the NOx reduction reaction. Catalyzed diesel particulate filters remove particulate matter from the engine exhaust by mechanical filtration; the trapped solid carbon including adsorbed residual HCs are subsequently oxidized. The particulate oxidation can occur during normal operation via oxidation by NO2 at moderate exhaust temperatures (~300-350°C) or by oxidation with O2 when appropriate exhaust temperatures occur (>500°C); such oxidation and cleaning of the DPF is known as “passive” regeneration. If particulate builds up significantly, the exhaust back pressure will rise and affect engine efficiency thereby requiring “active” regeneration of the DPF. During active regeneration, the DPF temperature is increased to temperatures where oxidation of the PM will occur (>500°C). Additional fuel is required for active regeneration which penalizes system fuel efficiency. Due to the driving cycle for transit buses, active DPF regeneration is typically required and impacts total fuel economy significantly.

The DOC kinetic mechanism and parameters have been calibrated using experimental dynamometer measurements over a range of engine load conditions for a DOC catalyst provided by Johnson Matthey [22, 23]. The SCR model was fitted to laboratory bench-reactor measurements of a commercial chabazite Cu-zelite SCR catalyst (commonly sold on diesel vehicles) [14]. The catalytic DPF model was validated with experimental dynamometer measurements using a Corning EX-80 cordierite DPF equipped on a heavy-duty engine [20, 24]. The computational models developed at ORNL are not available in the public version of Autonomie, but additional details and calibration information for each of the ORNL component models have been published previously [4, 14, 20, 22-24]. To account for required emissions controls, both the conventional and hybrid buses were assumed to be equipped with a 2.3-L DOC, 9.7-L catalyzed DPF, and 7.7-L SCR catalyst, positioned as shown in Figure 1. By locating
the DPF upstream of the SCR catalyst, chances for passive regeneration of the DPF are increased, potentially reducing the need to expend extra fuel for active DPF regeneration.

![Diagram](image_url)

**FIGURE 1** Configuration of the simulated DOC/CDPF/SCR aftertreatment system.

**Li-ion Battery Model**

To utilize appropriate engine-battery control strategies, an equivalent-circuit battery dynamic model was developed, based on data available in the open literature [25], to account for additional battery physics using electrical circuit analog components. These components include voltage sources, variable resistors, and capacitors. More specifically, the equivalent-circuit model accounts for open-circuit voltage, ohmic resistances in the connector, electrodes and electrolyte, and two sets of parallel resistor-capacitor combinations to reproduce the effects of mass transport and the electric double layer, respectively. The model is capable of effectively simulating both the steady-state and transient battery responses that are observed in Li-ion batteries. The model has been validated with experimental measurements [25]. Simulated voltage profiles generated with the model for a Li-Ion battery subjected to periodic pulse discharges and charges matched experimental measurements to within 1% except when the accumulated charge level was below 5% (which does not commonly occur in real-world operation).

**Transient Driving Cycles**

Since city transit buses can experience very different operating conditions depending on the routes followed and traffic conditions in a particular city, many different bus drive cycles have been developed. To represent a broad range of potential uses, five separate drive cycles, covering average cycle speeds ranging from 3.57 m/s to 12.73 m/s, were selected for our analysis. These include the Central Business District (CBD) cycle, Manhattan bus cycle (MAN), New York bus (NYBC) cycle, Orange County Transit Authority (OCTA) bus cycle, and Washington Metropolitan Area Transit Authority (WMATA) cycle. Table 3 summarizes the characteristics of these bus drive cycles. Since the drive cycles were developed without consideration of real road grades, which can considerably change the engine’s operating conditions [4], an additional drive cycle including moderate road grades was also developed and is referred to as the Knoxville Area Transit (KAT) cycle. This new transit bus cycle was constructed using data from an ORNL database of MD trucks [18], which includes one year of measurements from three Class-7 buses (all with a conventional diesel powertrain), operated by KAT in Knoxville, TN. The KAT cycle consists of two distinct types of operating conditions: frequent stop-and-go during the first 4000s, and an extended idling period for the remainder of the drive cycle. These operations were found to be very typical of the Knoxville data. The stop-and-go periods were observed to be dominated by relatively low accelerations and decelerations. Extended engine idling occurred roughly 50% of the time (much of it at single stops). The KAT cycle exhibits speed, acceleration and grade profiles representative of the conditions experienced by all three buses, and also captures idle operation [4].

**TABLE 3** Details of Selected Bus Drive Cycles, including the ORNL-Developed KAT Drive Cycle.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>CBD</th>
<th>KAT</th>
<th>MAN</th>
<th>NYBC</th>
<th>OCTA</th>
<th>WMATA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (s)</td>
<td>567</td>
<td>7200</td>
<td>2178</td>
<td>620</td>
<td>1909</td>
<td>1839</td>
</tr>
<tr>
<td>Distance (mile)</td>
<td>2.01</td>
<td>17.15</td>
<td>4.13</td>
<td>0.61</td>
<td>6.54</td>
<td>4.26</td>
</tr>
<tr>
<td>Avg. Speed (mph)</td>
<td>12.73</td>
<td>8.57</td>
<td>6.83</td>
<td>3.57</td>
<td>12.33</td>
<td>8.34</td>
</tr>
<tr>
<td>Max Speed (mph)</td>
<td>20.00</td>
<td>39.06</td>
<td>25.30</td>
<td>30.70</td>
<td>40.63</td>
<td>47.50</td>
</tr>
<tr>
<td>% Idle Time</td>
<td>20.6%</td>
<td>54.5%</td>
<td>39.2%</td>
<td>68.9%</td>
<td>26.9%</td>
<td>43.8%</td>
</tr>
<tr>
<td>Max Accel (m/s²)</td>
<td>2.30</td>
<td>2.12</td>
<td>4.60</td>
<td>6.10</td>
<td>4.06</td>
<td>3.00</td>
</tr>
<tr>
<td>Max Decel (m/s²)</td>
<td>-4.70</td>
<td>-2.28</td>
<td>-5.60</td>
<td>-4.30</td>
<td>-5.13</td>
<td>-4.50</td>
</tr>
</tbody>
</table>

**RESULTS**

To investigate the impact of hybrid technology on fuel savings and emissions control, conventional and hybrid city buses were simulated by repeating each cycle until reaching a total duration of 7200s (i.e. 2 hours). Each case was simulated using an initial cold start of 20°C. The predicted tailpipe emissions, on a g/mile basis, were used to directly compare the emissions from the conventional and hybrid buses.

**Fuel Economy**

Figure 2 compares the fuel economy of conventional, series hybrid, and parallel hybrid buses over the six selected bus drive cycles. As expected, both hybrid bus configurations are predicted to have better fuel economy than the conventional bus. The main factors responsible for these savings are: (1) a boost in the engine efficiency by operating at more favorable engine speeds and loads, (2) reduction of idling and accessory loads as a result of engine shutdown during stops, and (3) brake energy recovery. A summary of the fuel economy improvements for the series and parallel hybrid buses is shown as a function of the average speed of each drive cycle, and a nearly linear relationship is evident. This trend indicates that hybridization may be most beneficial for buses operating on low-speed routes. Cycles with lower average speeds usually have longer idling times and higher braking energy losses, which can be recovered in hybrids. This feature could be particularly valuable to bus fleets, enabling them to make appropriate decisions in purchasing hybrid buses to reduce operating costs based on characteristics of their specific usage. Measured data from hybrid buses, including a combination of series and parallel hybrid configurations, are also plotted in Figure 2 as a benchmark. The simulated fuel savings are generally seen to fall within the range of the available measurements. It is observed that the series powertrain achieves a 4%-16% better fuel economy than the parallel powertrain (resulting in a 5%-24% improvement relative to the conventional bus fuel economy), and the series hybrid advantage is greatest at lower average cycle speeds. However, when one considers the overall life-cycle for a techno-economic analysis, the greater initial battery cost and potential for additional battery maintenance must be evaluated along with the fuel economy benefit.

It is useful to recast the fuel consumption results in terms of thermodynamic engine efficiencies as illustrated in Figure 3. This figure compares the cycle-averaged engine thermal efficiencies of conventional, series and parallel hybrid buses. The series hybrid bus achieves substantially higher engine efficiency than the comparable parallel hybrid bus. This is instructive because it reveals how the availability of the electric drive makes it possible to operate the engine at speeds and loads where it has higher efficiency, thus reducing both fuel consumption and the emission of greenhouse gases (GHGs). The series hybrid bus does better than the parallel hybrid bus because the series hybrid bus can make more extensive use of its larger battery to keep the engine operating near its point of maximum efficiency more often.

Another factor that distinguishes hybrid from conventional buses is their relative energy losses associated with braking and accessory loads, as illustrated in Figure 4 for the KAT cycle. Each energy loss graph has been normalized to the conventional bus fuel energy budget to facilitate comparisons and highlight the overall energy savings. One major difference between the performance of the simulated hybrid buses is that the series hybrid is predicted to achieve an 80% kinetic energy recovery, compared to a 45% kinetic energy recovery for the parallel hybrid. This improvement is due to regenerative braking performance and is again a consequence of the larger battery and motor used in the series hybrid bus.
FIGURE 2 Comparison of fuel economy improvements for hybrid buses over the representative city drive cycles extended to a duration of 2 hours. The test data for hybrid buses are from references [7-13] and include both series and parallel hybrid configurations. The hybrid FE improvement is relative to the baseline conventional bus fuel economy level.

FIGURE 3 Comparison of the cycle-averaged engine efficiency among conventional and hybrid buses over the representative city drive cycles extended to a period of 2 hours.
The two types of hybrid buses employ very different modes of energy transfer, which results in significant differences in their internal energy losses. In the series hybrid, energy must always be transferred from a mechanical form (engine out to generator) to an electric form (generator out to battery) and then back to a mechanical form (battery to motor). Figure 4 reveals that the inefficiencies involved in these energy transfers generate losses of 8.6% in the series hybrid over the KAT cycle. Conversely, there is less energy transfer in the parallel hybrid, resulting in a more modest 1.5% loss for the KAT cycle.

Emissions

Figure 5(a) illustrates a considerable reduction in the hybrid engine-out CO, HC, and NOx emissions for all drive cycles, with the exception of the NOx emissions on the CBD cycle. The series hybrid generates lower engine-out HC and NOx emissions than the parallel hybrid, although the magnitude of the difference appears to be rather cycle dependent. Although there is a clear trend for the engine-out emissions, the situation for tailpipe emissions (i.e. post-aftertreatment) is more complex (see Figure 5(b)) because of the different responses of each of the aftertreatment components. Both the series and parallel hybrid buses achieve similar CO and HC—but lower NOx—tailpipe emissions compared to the conventional bus over drive cycles having higher average speeds, such as CBD, OCTA, and WMATA (the KAT cycle is an exception). The KAT cycle includes a single period of idling that lasts nearly 3200s. The hybrid buses will shut off their engine during this period, which dramatically reduces the CO/HC tailpipe emissions for this cycle [4]. For the lowest average-speed drive cycle (NYBC), the series hybrid powertrain has an adverse effect on tailpipe emissions, while the parallel hybrid powertrain can achieve lower tailpipe emissions since a higher exhaust temperature is maintained. This is further confirmed by the data in Figure 5(c), which is the reduction in emissions that the aftertreatment system achieves—engine-out to tailpipe—for each vehicle configuration. It is apparent that aftertreatment for the series and parallel hybrid buses achieve similar emissions reductions, relative to the conventional bus for the higher average-speed drive cycles. For the NYBC cycle, however, the series hybrid configuration has much lower catalyst efficiency since the series hybrid powertrain generates relatively low temperature exhaust due to reduced engine operating time in response to significant idle time and low tractive loads. This leads to the aftertreatment catalysts operating at temperatures below suitable activity (i.e. <200°C) while following the NYBC. 200°C is a typical light-off temperature for aftertreatment catalysts in achieving efficient emissions reduction.
The predicted trends for PM emissions indicate that hybrid bus engine-out PM emissions should be less than those for conventional buses, except for very low-speed drive cycles, such as the NYBC (see Figure 6(a)). The high PM emissions during the NYBC cycle is another consequence of the low engine exhaust temperatures present during the low speed city drive cycle. In any event, both the conventional and hybrid buses will continue to accumulate PM in the DPF during all of the drive cycles, as illustrated in Figure 6(b) for the OCTA cycle. Ultimately, this PM accumulation in the DPF results in increased back pressure and a need to implement active regeneration which consumes extra fuel. The increased back pressure alone will translate to a small level of additional fuel consumption (0.3%-0.5%), and active regeneration (burning of the accumulated soot) typically occurs every 300-400 miles, which generates a fuel penalty of 1%-2% [14, 26].

FIGURE 5 Comparison of (a) engine-out and (b) tailpipe CO/HC/NOx emissions from conventional and hybrid buses over the representative city drive cycles extended to a period of 2 hours. The bars included on the conventional bus results show a 30% variation level for reference. (c) shows emissions reduction efficiencies.
DISCUSSION

For bus applications, the series hybrid powertrain achieves higher engine efficiency and kinetic energy recovery, but it has a relatively high cost for the larger sized electrical components needed. In addition, an energy penalty is incurred from the dual-step energy conversions in the series hybrid. Figure 7(a) shows the battery state of charge (SOC) vs. power trajectory for the series hybrid bus during the KAT drive cycle. This graph demonstrates that only a rather limited range of the battery capacity is utilized during the drive cycle, which is typical of series hybrid operation. Although it may appear that the large battery size is unnecessary, if too small a battery is used for the series hybrid powertrain, its power characteristics can significantly limit the level of kinetic energy recovery that can be achieved, and the battery may also be inefficient in storing the energy generated from the engine operating at peak efficiency. Under-sizing the battery for the series hybrid bus can therefore result in inadequate energy savings, and energy losses associated with the dual-step energy conversions inherent in the series hybrid operation may not be offset by the increased efficiencies that the series hybrid is designed to exploit. With currently available battery technology, sizing is primarily constrained by battery power limits, and excess energy storage capacity is generally available when the power needs are satisfied. It is therefore desirable to consider alternatives that may allow more effective use of the available battery capacity in series hybrids.
FIGURE 7 Simulated Li-Ion battery power vs. SOC trajectories of the regular series hybrid and plug-in series hybrid buses over a KAT cycle. The spots represent the second-by-second Li-Ion battery power.

Figure 8 Impact of plug-in hybrid technology on the fuel economy of series hybrid buses over the representative city drive cycles extended to a period of 2 hours.

The authors repeated the series hybrid bus simulations for all the drive cycles using a control strategy similar to that employed for light duty plug-in hybrid vehicles. Specifically, the battery power utilization was modified so that the battery SOC is permitted to decrease to a threshold of 25% before switching to a charge sustaining control mode, and it is assumed that the battery would be charged before the bus is put into service each day. The details of this plug-in series hybrid control strategy can be found in [26]. Two different sized batteries (12 and 24 kWh) were considered to see how this would change the performance. In the simulations, the initial battery charge was assumed to be 92% to be consistent with the modeling of the conventional and regular hybrid buses, although a full initial battery charge would provide even greater benefits. As was also done in the initial analysis, each simulation was run from an initial cold start of 20°C and for a total duration of 7200s (i.e. 2 hours). Figure 7(b) illustrates how the KAT cycle SOC pattern changes due to the modified control strategy for the bus with the 12kWh-battery. The additional energy stored in the battery initially is used to provide the majority of the energy needed to power the bus.
for an extended period at the beginning of the drive cycle. Compared to the regular series hybrid bus, the plug-in series hybrid SOC management strategy allows a much broader band of the battery storage capacity—between 25% and 92% of SOC—to be utilized, and the fuel economy result is improved considerably. Figure 8 demonstrates the fuel economy benefits of the plug-in series hybrid bus compared to the regular hybrid buses. Notably, by utilizing the electrical energy stored in the 12kWh battery, the plug-in control approach increases the fuel economy by an additional 30%-50% compared to the regular series hybrid (still using the conventional case as the basis to allow comparisons with data from the previous figures). As seen in Figure 8, the simulations indicate that the plug-in series hybrid can achieve more than 7 mpg for most of the city bus drive cycles. By replacing the 12kWh-battery with a 24kWh battery, the plug-in series hybrid can achieve nearly 10 mpg. It is well known that electricity—at an average price of $1.29 per gasoline gallon equivalent (GGE) in the U.S.—is much cheaper than the equivalent energy derived from a combustion engine using liquid fuel (e.g. $2.63 per GGE) [27]. This indicates that plug-in operation of a series hybrid powertrain, particularly with a larger battery, offers a significant energy cost savings potential in transit city bus applications by maximizing electric energy use and reducing petroleum consumption.

In the drive cycle simulations, additional plug-in recharging events were not considered. It is clear that maximizing the fuel economy of a plug-in hybrid bus is strongly related to the charging strategy employed, including how long and how often charging is performed. Since city transit buses typically operate repeatedly over planned local routes, an optimized charging strategy and the use of additional charging stations along the route could further maximize the fuel consumption of plug-in hybrid buses. Such optimization is beyond the scope of this study, but additional research on this topic is well warranted for future studies.

CONCLUSION

Bus simulation models were developed to compare the fuel economy and emissions between series and parallel hybrid buses. The models provide consistent and meaningful comparisons between hybrid bus technology options by identifying energy efficiency and emissions trends, performance-limiting drivetrain and aftertreatment factors, and opportunities for future R&D.

For the hybrid bus options considered here, both series and parallel hybrid buses improve fuel economy significantly. Compared to the comparable parallel bus, the series hybrid bus achieves substantially higher engine efficiency while achieving more kinetic energy recovery. However, the efficiency penalty due to the dual-step energy conversion in the series hybrid offsets a significant portion of these energy savings. Nonetheless, the series hybrid powertrain achieves a 4%-16% higher fuel economy than the parallel hybrid powertrain.

Results from the emissions estimates indicate that the series and parallel hybrid buses achieve similar CO and HC, but lower NOx, tailpipe emissions compared to the conventional bus for drive cycles with higher average-speeds. For the lower average-speed drive cycle evaluated (NYBC), the series hybrid powertrain has a negative effect on tailpipe emissions while the parallel hybrid powertrain can still lower tailpipe emissions significantly. For PM emissions, all of the configurations evaluated (conventional and hybrid buses) accumulate PM continuously over all of the drive cycles and require periodic active DPF regeneration which consumes additional fuel.

A charge-depleting SOC management strategy corresponding to plug-in hybrid vehicles is an effective approach for maximizing the utilization of the large battery capacity typically used in series hybrids. Operating the series hybrid bus as a plug-in hybrid can boost fuel economy more than 30%-50%. If an even larger battery is employed in the vehicle, the plug-in hybrid control strategy is capable of achieving nearly 10 mpg. This research demonstrates that plug-in operation of series hybrid buses offers a significant potential for energy cost savings by maximizing electric energy use and reducing petroleum consumption. This research topic clearly deserves further consideration in the future.
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REFERENCE


