AISD Plug-in Hybrid School Bus Project

Progress Report

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by

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This report is a summary of the research performed thus far on behalf of the Department of Transportation of the Austin Independent School District (AISD). The goal of this continuing project is to compare the emissions and fuel consumption of AISD's plug-in hybrid school bus and a conventional diesel school bus.

Section 1 is a brief overview of this project. The standard AISD school bus driving cycle that was developed for this project is presented in Section 2. The results obtained to-date regarding fuel economy and emissions of the oxides of nitrogen (NOx) are summarized in Section 3. Of course, the plug-in hybrid school bus consumes energy while plugged in to recharge the batteries, and this energy along with the energy consumed and emissions from the electric power plant(s) must also be accounted for, as discussed in Section 4. The tasks that still remain to be performed in order to complete this project are discussed in Section 5. The aid that we need from AISD in order to complete this project is discussed in Section 6.

1. Introduction

During April and May of 2009, four days worth of data were collected from the plug-in hybrid school bus (bus #0728) and three days worth of data were collected from the conventional diesel school bus (bus #0702)). Our research team also tried to test a 2001 diesel school bus (bus #1001). However, because the older bus uses a different computer communication protocol (the SAE J1708 protocol, whereas the newer buses use the SAE J1939 protocol), it was not possible to log the required fuel injection rate and vehicle speed data. Therefore, we could not obtain a complete set of data for the #1001 bus. All tests were conducted by Kyung Jin Kim with assistance from Michael Smith of Emerald Electronic Design and Ralph Cearly of AISD.

Additionally, Claire Florette, another graduate student on this project, is responsible for accounting for the electricity used to charge the battery pack on the plug-in hybrid school bus and then analyzing the emissions from Austin Energy's power plants associated with this recharging process, so that the overall energy costs and overall emissions associated with the plug-in bus can be analyzed.

One of the primary goals of this project was to use, for the first time anywhere, a new technique for quantitatively comparing two vehicles that are used for the same type of service, such as two school buses. Normally, to compare the fuel economy and/or emissions of two vehicles, in-use driving data (for several days or weeks of normal service) is used to generate a standardized driving cycle (vehicle speed versus time). The intent of the standard driving cycle is to compress the dominant features of a typical day's driving pattern into a half-hour or less. This is accomplished by selecting "microtrips" (vehicle stationary with engine idling, followed by an acceleration transient, a cruise, and then a deceleration back to stationary idle) such that the sum of the microtrips is quantitatively representative of an entire day's worth of activities. Then, the two vehicles are both tested using this driving cycle either by using a chassis dynamometer or via "track testing" using an SAE standard test procedure (J 1312). Emissions and fuel economy data is acquired during these tests, allowing the eventual comparison of emissions (in grams/mile) and fuel economy (in miles/gallon) for the two vehicles.

An additional requirement for developing a standard driving cycle for a hybrid is that microtrips must be selected that represent activities while the vehicle is both in "hybrid mode" and in "non-hybrid mode".

However, because these tests are expensive and the present project was unfunded, our research team decided to apply a new technique that we had been theoretically developing for several months, in conjunction with Eastern Research Group's Austin personnel. This new technique involves collecting in-use data regarding not only vehicle speed as a function of time but also emissions and fuel consumption as functions of time, with all data acquired simultaneously. One then uses the in-use data to generate the standard driving cycle, as usual. However, one then interrogates the data to extract the emissions and fuel economy data that correspond to the "microtrips" that constitute the standard driving cycle and extracts the emissions and fuel economy data for all of the microtrips that are included in the standard driving cycle. Thus, our new technique requires less time, fewer resources, and is much less costly.

2. The Standard AISD School Bus Driving Cycle

The standard AISD School Bus Driving Cycle, for the "Giraffe" route in the southwest region of the City of Austin, is illustrated in Figure 1. The standard driving cycle is composed of micro-trips representing highway and local road driving, including representative periods of idling. This driving schedule is ~6.4 miles long and has a duration of ~28 minutes, but represents an entire typical day of school bus operations.

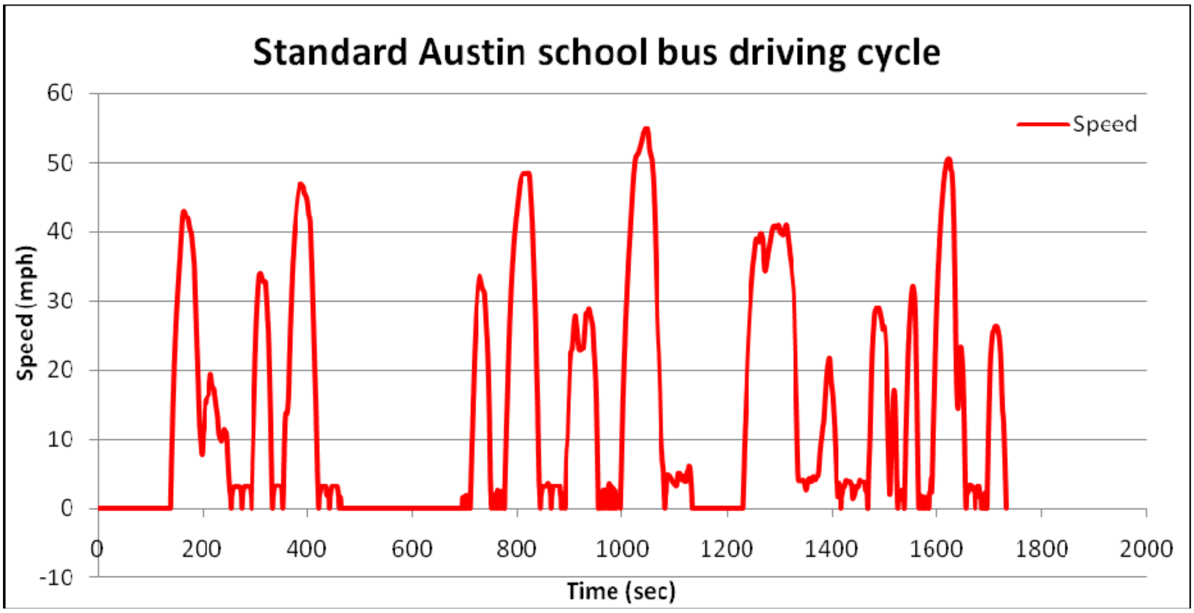

Figure 1: The Standard AISD School Bus Driving Cycle.

Because of the need to ensure that the Standard AISD School Bus Driving Cycle incorporated the appropriate number of representative microtrips in both hybrid mode and non-hybrid mode for AISD's plug-in hybrid school bus, the vehicle speed versus time data used to generate this cycle were all obtained from the plug-in hybrid school bus. Thus, it was not surprising that when interrogating the overall data set for the plug-in hybrid school bus to extract the fuel economy and emission data, we could regenerate the AISD cycle with 99.81% accuracy. However, because we acquired data from the conventional school bus for only three days, extraction of the representative microtrips to regenerate the AISD cyle was only 94.41 %

accurate. While this is quite good, our research team would like to take additional data to allow an even more precise match.

3. Fuel Economy and NOx Emissions Comparisons

As illustrated in Figure 2, the NOx emissions rate from the plug-in hybrid school bus is ~3.4 grams/mile, compared to ~4.6 grams/mile for the conventional diesel school bus. That is, the plug-in hybrid school bus is emitting approximately 25% less NOx than the conventional diesel school bus.

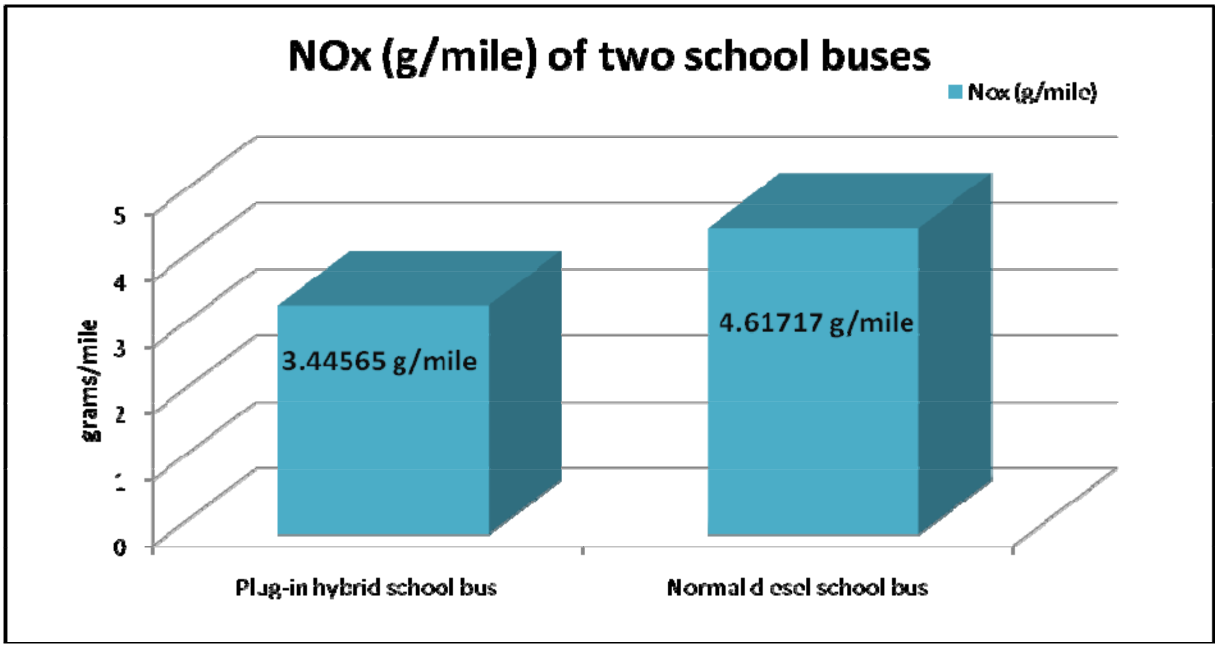

Figure 2: Comparison of the NOx emissions rate (g/mile).

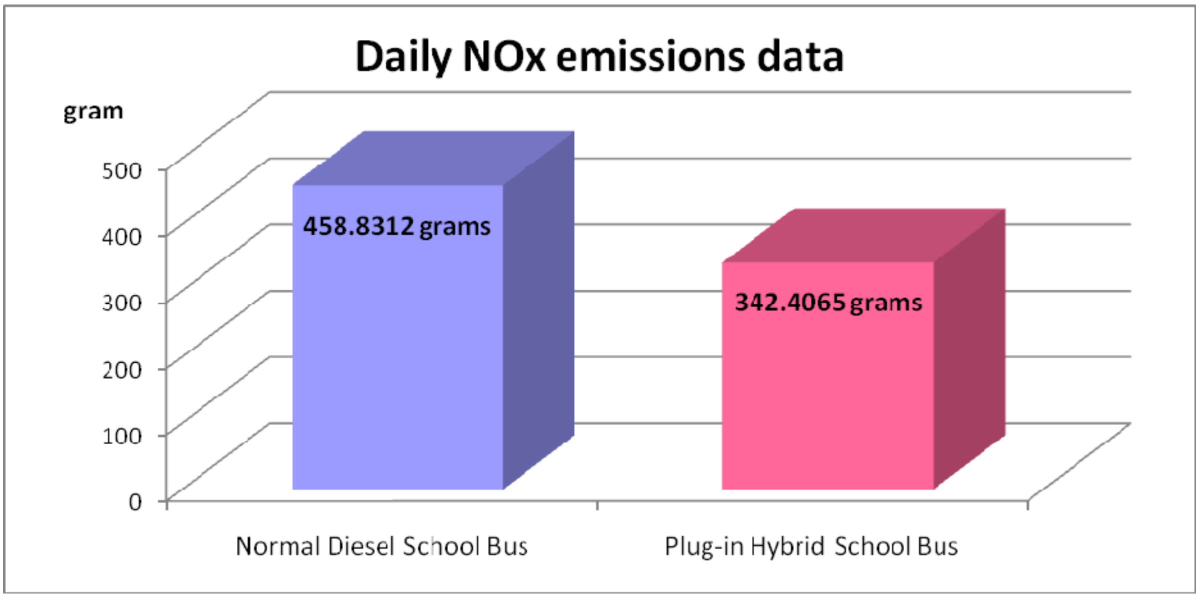

Figure 3: Daily NOx emissions from the two school buses.

One of the several advantages of having a representative driving cycle, and having the fuel economy and emissions data that correspond with this cycle, is that one can easily extrapolate to determine the emissions and fuel consumption for a typical day's operations. Specifically, one simply needs to multiply the emissions in g/mile and the fuel consumption in gallons/mile by the total miles traveled per day. The results of this calculation for the two buses are shown in Figure 3. The plug-in hybrid school bus emits ~342 grams of NOx per day versus ~459 grams/day from the conventional diesel school bus. Although, as explained earlier, we could not compare the NOx emissions from AISD's older school buses, it is expected that the older buses emit much more NOx due to the less stringent emissions standards at the time of their manufacture.

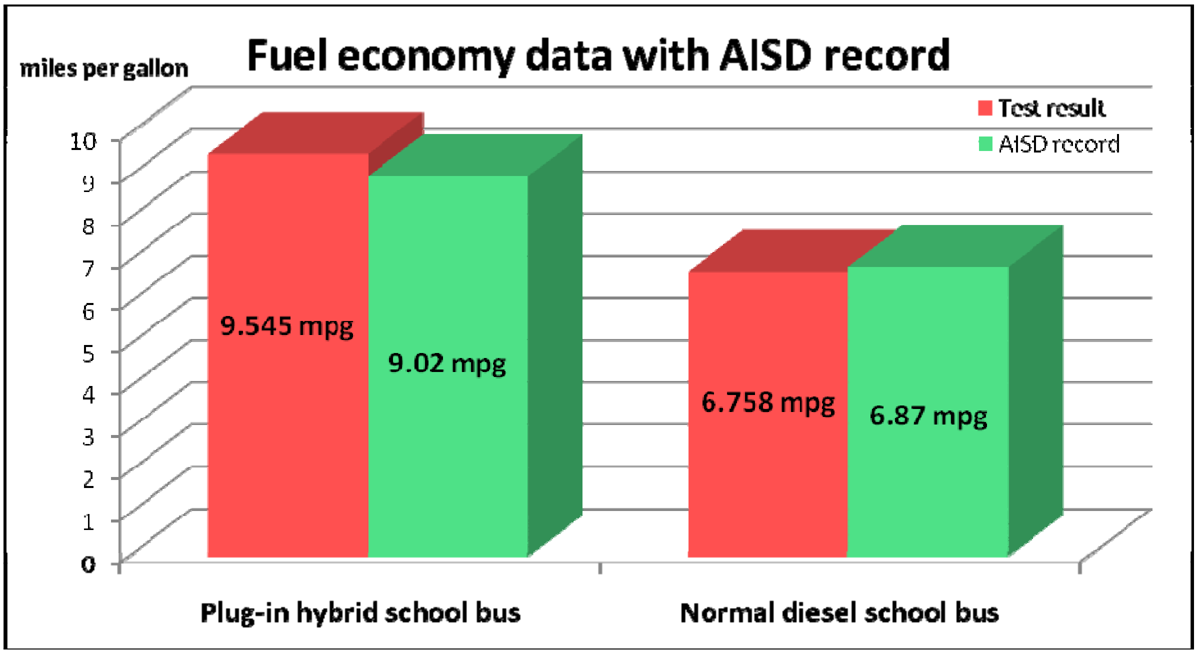

Figure 4: Fuel economy comparison for the two school buses during operation over the Standard AISD Driving Cycle. These results show excellent agreement with AISD records.

The fuel economy during operation over the Standard AISD School Bus Driving Cycle for the plug-in hybrid school bus is compared to the fuel economy for the conventional bus in Figure 4. The plug-in hybrid school bus' fuel economy was ~9.5 mpg, which is ~41% higher than the ~6.8 mpg for the conventional diesel school bus. One reason that the plug-in school bus produces this benefit is that the plug-in hybrid uses the electric motor for "torque assist" during low speed accelerations, thus requiring less fuel for the same acceleration rate as the conventional bus.

As also illustrated in Figure 4, our fuel economy comparison using our new experimental technique agrees extremely well with AISD's cumulative records for the past two years.

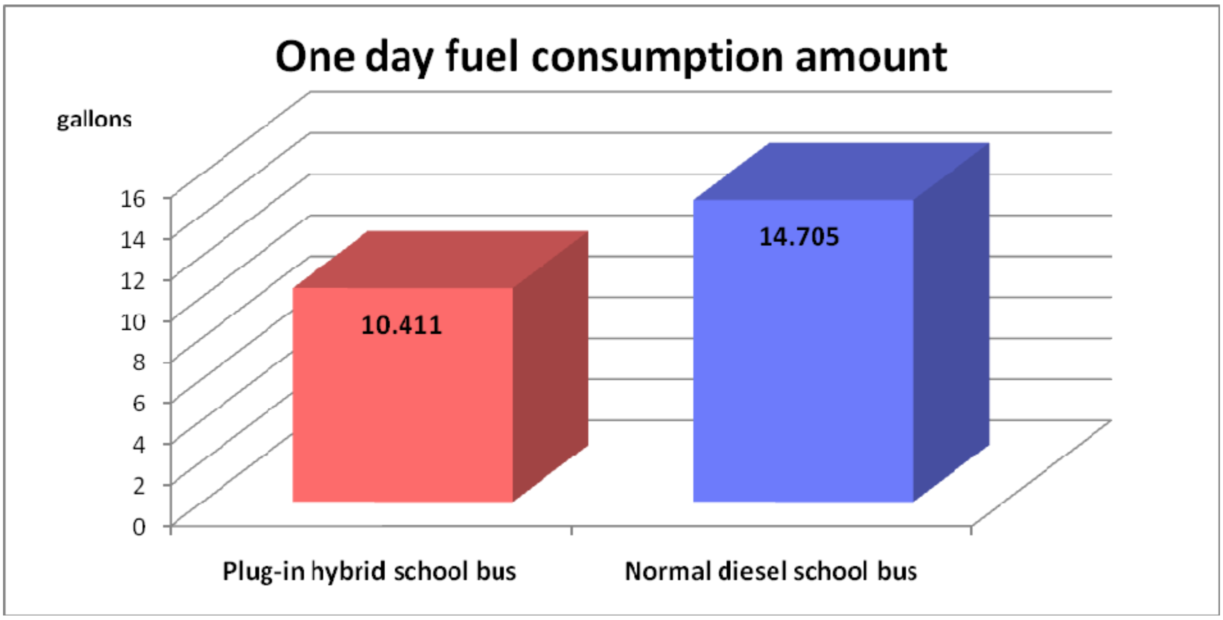

Figure 5: Daily fuel consumption data for the two school buses.

The daily fuel consumption for each bus is illustrated in Figure 5. The plug-in hybrid school bus consumes ~10.4 gallons of fuel per day, compared to ~14.7 gallons/day for the conventional diesel school bus. However, one should also consider the daily electricity used for charging the battery pack in the plug-in hybrid school bus, as discussed in Section 4.

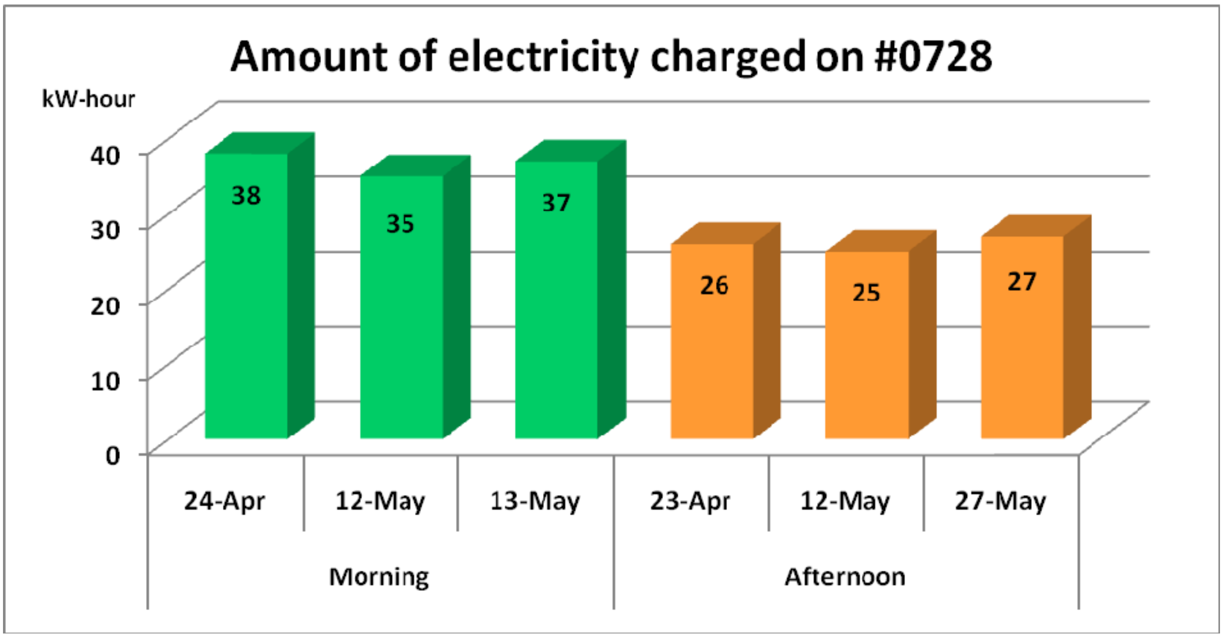

Figure 6: Daily electricity used for charging the Li-ion battery pack.

4. Overall Energy Cost and Overall Emissions Comparisons Including the Electric Power Plants

As illustrated in Figure 6, the plug-in hybrid school bus used ~62.7 kW-hours of electricity per day to charge the battery pack, on average.

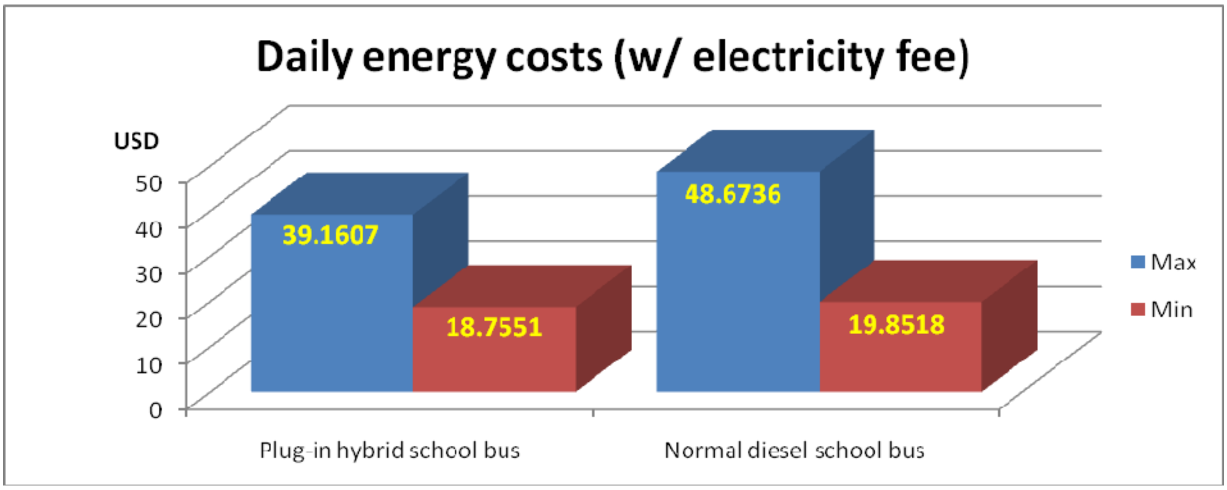

Figure 7: Daily energy cost comparison for the two school buses.

AISD pays ~7.4 cents per kW-hour for electricity and, as noted above, ~62.7 kW-hours of electricity are used each day, for an average daily electric power cost of $4.64. However, the maximum energy cost is due to the diesel fuel consumed each day. The diesel fuel price hit a peak of $3.31/gallon in September 2008 whereas the minimum diesel price occurred in January 2009 at $1.35/gallon. Thus, as illustrated in Figure 7, the daily overall energy cost ranged from $18.76-$39.16 per day for the plug-in school bus compared to $19.85-$48.67 for the conventional school bus. This yields a daily energy cost savings in the range from $1.09 to $9.51 neglecting other operating costs, such as maintenance and battery pack replacement.

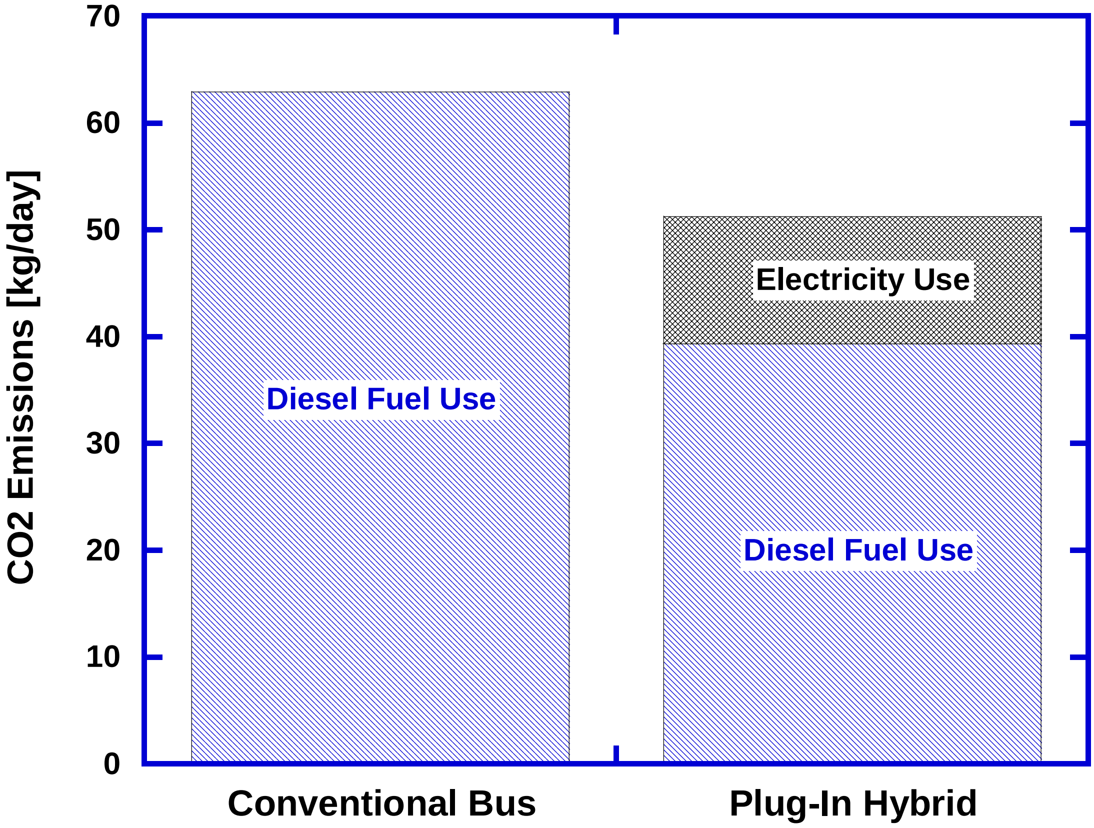

Figure 8: Daily energy greenhouse gas (CO_2) emissions comparison for the two school buses.

The greenhouse gas (CO_2) emissions from the two buses are illustrated in Figure 8. To generate this figure, accounting for the emissions from Austin Energy's power plants, we used the electricity mix data from Austin Energy for the times of day that corresponded to when the plug-in hybrid school bus recharges off the power grid. The conventional school bus emits about ~63 kg/day whereas the plug-in hybrid emits CO_2 at a rate of ~51 kg/day.

We will perform similar analyses of the NO_x and PM emission for the two buses once we obtain the PM data, as discussed in Section 5.

5. Remaining Tasks

For heavy-duty diesel powered vehicles, the only pollutants of interest are NOx and particulate matter (PM). With funding from the US DOE, our research group has been developing a real-time diesel PM sensor. We had originally planned to install this PM sensor on the AISD buses to log data simultaneously with the NOx and fuel economy data. However, this was delayed by development issues, which have since been resolved. Thus, we need to install the PM sensor on the two AISD buses so that we will have a complete set of data. Publication of the results we currently have, without PM emissions comparisons, will be impossible.

While taking the PM data, we should retake all data for at least two weeks per bus. During these tests, we also need to log temporal data regarding barometric pressure, fuel temperature, and oil temperature.

Once we have the new data set, we can complete our comparison of the conventional diesel school bus and the plug-in hybrid bus, in the latter case accounting for the energy consumed and NOx and PM emissions from Austin Energy's power plants when recharging the battery pack.

We also need to acquire more data regarding recharging of the plug-in hybrid's battery pack.

6. Requested Aid from AISD

To allow completion of our study of the benefits of the plug-in hybrid school bus, we need aid from the AISD Department of Transportation. Specifically:

1) We need to acquire more data regarding recharging the battery pack in the plug-in hybrid school bus twice per day. We need AISD's assistance in allowing Claire to get 7-10 days worth of data.
2) We need AISD's patience and assistance in allowing Kyung Jin to get two school weeks' worth of data for each of the two buses. To accomplish this, we need to install our data logger again, connecting only to a 12 V battery source, a ground, and the computer diagnostic interconnect port. We will also need to install our mass air flow instrument and, for the first time, drop a thermocouple down the dipstick hole and another down the fuel fill tube.

Once we have completed our study, we plan to publish a technical paper through the SAE, and will be pleased to list the appropriate personnel at the AISD DOT as co-authors.