Tier 4 Genset Dominant Hybrid Rebuild/Repower Package for Switcher Locomotives

Tasks 4 and 5 Reports

And

Final Report

for:

New Technology Research and Development Program

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Submitted by:

Alternative Motive Power Systems, LLC

Principal Investigators:

Dan Frederick

Brian Couchene

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Abstract/Executive Summary

The primary problem addressed in this project is emissions from switching and road switching locomotives including current genset offerings. Our approach is to create a “mild” hybrid power and control system, in modular form/package, that will totally eliminate idle emissions and minimize emissions with cleaner Tier 4I engines that will be controlled in a way that will allow them to operate at maximum efficiency. Smokeless start and the ability to move the locomotive or “index” railcars without starting an engine will contribute to further emissions reduction. The availability of this technology will enable clients to quickly incorporate this technology into existing locomotives. Overall contribution will be lower fuel consumption, reduced emissions, improved low speed tractive effort, and greatly enhanced diagnostics.
Introduction/Background

Locomotives used in switching and low speed short line applications are typically purchased from larger railroads once the locomotives are no longer suitable for Regional or Class 1 use. There are currently several genset options available; some even in kit form. To our knowledge no one has implemented a practical hybrid solution to date. Rising fuel prices, tightening emissions standards, and diminishing qualified maintenance personnel for aging fleets make the development of this kind of solution practical and significant.

Attempted solutions so far have been implemented, primarily, by engineers and manufacturers with a locomotive background rather than experience with locomotives and experience implementing the development of control schemes for a variety of hybrid vehicles. In some instances, poor battery technology was chosen. Hybrid technology is not the answer for every locomotive application.

Alternative Motive Power Systems’ (AMPS) approach differs from other attempted solutions because of our ongoing experience and the development of new technologies that have finally matured. Our modular approach allows us and potential users of this equipment to choose a variety of engine and alternative fuel options depending on operational requirements. It also affords the option of incorporating more efficient and mature technologies as they are developed.

Project Objectives/Technical Approach

AMPS will finalize the design of a modular package for converting a conventional switcher locomotive into a hybrid genset switcher locomotive. AMPS will build a prototype modular package and contract with Railserve to install it and do performance testing on the resulting prototype locomotive. AMPS will work with Railserve to partner with a rail yard in Longview, Texas, to demonstrate the locomotive in a representative working environment and to complete load and emissions testing of the prototype in comparison to a conventional switcher locomotive.

Project Objectives included in the Grant Activities (Scope of Work) are:

- To demonstrate that repowering of an in-use conventionally powered road switcher locomotive with a multiple genset/hybrid genset package reduces NOx emissions from a conventionally powered diesel locomotive by up to 98% and by 25% compared to a non-hybrid genset package.
- To demonstrate the commercial viability and cost effectiveness of the modular approach to the design and installation of the multiple genset/hybrid genset package.

In order to achieve these objectives AMPS will:

- Refine the genset package modules in order to make system integration into the locomotive chassis as quick and simple as possible.
- Undertake in-use measurement of the emissions before and after the installation of the multiple genset/hybrid genset dominant package.
- Determine the fuel consumption before and after repowering with the genset package.
• Assess operator acceptance of use of the installed system.

The prototype multiple genset/hybrid genset package will be installed on a GP9 road switcher locomotive purchased by AMPS from Railserve. The gensets will be provided by a contractor to meet AMPS specifications and AMPS will provide any interface components required. The gensets will be installed in the road switcher by Railserve at the Union Tank Car Repair Shop in Longview, Texas.

The energy source for the initial commercial version will be two generator sets installed in parallel in the road switcher locomotive in place of the original 1,500 to 2,000 horsepower (hp) diesel engine, one of which will be a battery hybrid module with a 150 kilowatt (kw) diesel generator and, the other a 400 kw diesel generator set. Both engines in the gensets will be Tier 4 certified engines (as allowed under 40 CFR section 1033.150 Interim provisions). In the hybrid module, in addition to the 150 kw diesel engine, there will be a battery pack module.

Where the induction generator is coupled to an engine in the more conventional diesel engine gensets, AMPS uses an induction generator electrically connected to an alternating current (AC) inverter. This inverter, by varying the electrical slip in the generator, generates a constant direct current (DC) bus voltage. This voltage is then fed to either a set of storage batteries or to individual traction motor controllers, or to both.

In the hybrid genset, the electricity will flow directly to the DC bus on the traction motor propulsion drives. The batteries will be charged by the smaller genset once a predetermined state of charge is sensed. This will allow the smaller genset to run at peak efficiency almost 100% of the time. If the full capacity of the larger genset is not required for locomotive propulsion, it will be used for additional battery charging. If required the locomotive can operate on batteries alone.

The genset modules will be assembled by a supplier designated by AMPS. Both the operator control stand and the locomotive will be equipped with quick connectors to the control cabinet and the traction motor propulsion drive skid respectively. This will allow for major systems testing to assure proper function and quick, on-site assembly.
**Tasks**

Tasks included in the Grant Activities (Scope of Work) are:

- Task 1: Finalize design of genset package modules
- Task 2: Control and power system design, assembly, and programming
- Task 3: Locomotive systems installation and performance testing
- Task 4: Emissions and fuel economy testing of conventional and prototype locomotive, and
- Task 5: Evaluate operator acceptance of prototype locomotive

**Task 4: Emissions and Fuel Economy Testing of Conventional and Prototype Locomotive**

From the Grant Activities (Scope of Work):

> **Task 4: Emissions and Fuel Economy Testing of Conventional and Prototype Locomotive**

2.4. **Task Statement:** The PERFORMING PARTY will test the emissions and fuel use of the assembled prototype locomotive against a comparable conventional locomotive in field use.

AMPS contracted infoWedge to perform the emissions and fuel economy testing to compare the conventional and prototype locomotives in actual revenue service. The tests occurred as the locomotives were actually used at the Eastman Chemical facility in Longview, Texas. This approach allowed a more realistic comparison of emissions and fuel consumption than would be provided by the conventional way of testing locomotive emissions (which is a steady-state test used for certification to federal emissions standards).

The prototype hybrid switcher was compared to a conventional switch locomotive that could reasonably be replaced by the prototype when it becomes commercially available. The prototype was powered by two, non-road type diesel engines, each turning an induction motor/generator. It also had a significant amount of electrical energy storage capacity in a bank of batteries. The traction motors independently drew power from all of these “sources” on a common DC electrical bus. The conventional switcher was a General Motors’ Electro-Motive Division (EMD) model SW1200. It was powered by a single, 1200 HP diesel “prime mover” (EMD model 12-567C) turning a DC generator, which sent power to the two sets of traction motors in the front and rear trucks. It was last remanufactured “as new” in 1979 at EMD’s Paducah, Kentucky facility. It was well maintained, in good working order, and in daily use by Railserve at the Eastman Chemical facility.

In-use emissions tests were made possible by primarily using portable emissions measurement systems (PEMS) that are approved by EPA for in-use compliance tests of most types of engines (see 40 CFR 1065 Subpart J). Since the prototype hybrid switcher uses readily available, non-road diesel engines (as are found in construction equipment like bulldozers), the PEMS were easily adapted to that locomotive. However, in-use testing the conventional locomotive required significant fabrication and adaptations to allow an “apples-to-apples” in-use comparison with the hybrid prototype. For example, the exhaust pipes on the conventional locomotive are much larger than the hybrid’s. Therefore, the normal PEMS exhaust flow meters could not be used and an alternative method, that is similar to that for measuring flow from a
stationary diesel generator, was used instead. As allowed in 40 CFR 1065.655, an accurate measure of second-by-second fuel flow was determined from the results of the exhaust measurements. Power outputs of the various motive power sources on the locomotives were determined by measuring their voltage and current outputs and calculating the appropriate power (with the use of efficiency factors in some cases).

Since the tests occurred during actual revenue service, the tested duty cycles of the two locomotives were not identical, but they did cover the same range of loads since they were used for similar service with similar hopper cars carrying similar materials. Therefore, the test data were analyzed to allow a fair comparison by splitting the results into power “bins,” yielding an average emission factor for each of the idle, low, medium, and high power modes. Then cycle-average emissions were calculated by recombining the mode-average results according to a reasonable mix of these power modes for switcher service as observed at the Eastman facility.

After data collection was completed, the data were quality assured, reduced and analyzed. This process is described in a report delivered to AMPS by infoWedge. In the following sections we give a summary of how the test contractor prepared for and conducted the tests. We also summarize how the resulting data were analyzed and we give the final results.

**Preparation for Emissions and Fuel Use Testing**

AMPS’ emissions test contractor, infoWedge prepared for emissions and fuel consumption testing by visiting the fabrication and test locations, researching various options for in-use testing switch locomotives in actual service, and having an adaptation of the conventional locomotive prepared for installation. The following sections summarize these activities.

From the Grant Activities (Scope of Work):

2.4.1. Preparation for emissions and fuel use testing

2.4.1.1. The PERFORMING PARTY will visit Railserve in Longview, Texas, as the prototype hybrid genset switcher is being fabricated and determine that the system control data are compatible with data required for performance and emissions testing and that the exhaust ducting and fuel system modifications necessary for in-use emissions tests are installed.

InfoWedge traveled to Longview, Texas in early February 2013 to formalize testing plans and determine whether the control data to be recorded by the prototype hybrid would provide the data necessary for the required testing. Personnel from AMPS were also there and they were able to provide introductions to the Railserve personnel, to explain the prototype, and to learn the testing process.

At the Railserve location where the prototype fabrication took place AMPS provided infoWedge with the data that would be available on the CAN network of the hybrid locomotive. It included all data necessary for tracking engine speed, condition, load and total power output from the engines (according to the engine control unit). Power output from the induction generators and the batteries would also be available, providing a redundant measure of total power output.

During research on the test protocols it was determined that fuel system modifications would not be required for the prototype locomotive. This is because the engine layout in the prototype allowed the use of EPA approved, in-use exhaust flow measurement systems to determine mass flow through the engines
(as allowed for in-use testing under 40 CFR 1065.655). Therefore, no fuel system modifications were necessary.

From the Grant Activities (Scope of Work):

2.4.1.2. The PERFORMING PARTY will visit the Longview working railyard selected in Task 2.2.5. to fabricate the exhaust ducting and fuel system modification on the working conventional road switcher which will be used for side by side emissions comparison with the prototype hybrid genset switcher locomotive

AMPS and infoWedge personnel also visited the test site to make sure testing could occur there and to view the switch locomotive that would most likely be used for testing. The Eastman Chemical facility in Longview had a high level of security and strict safety rules. For example, no photography was allowed and contractors who had not taken a day long safety course could not visit without an approved escort. So it was necessary to establish how these and other significant restrictions would impact test schedule and how they could best be accommodated during testing

As was the case for the prototype locomotive, it was determined that fuel system modifications would not be required for the conventional locomotive either. In the case of the conventional switcher infoWedge was able to design a way to manifold together the exhaust stacks of the SW1200 locomotive and configure the single duct to allow direct measurement of exhaust velocity from the engine. This was essentially an adaptation of EPA Method 2 for measuring stack velocity in stationary source emissions testing. The sketch in the figure below shows the essentials of the duct manifold design.

![Figure 1. Sketch of switcher with exhaust velocity measurement duct in place.](image)

By directing the single duct backward, over the cab of the locomotive, it would be possible to have a long enough section of pipe to take accurate gas velocity measurements. By using a primary standard technique for measuring the gas velocity, such as a Pitot tube, it would be possible to accurately
determine exhaust mass flow in essentially the same way it is determined using the standard PEMS setup. Therefore, no fuel system modifications were necessary for the conventional switcher either.

From the Grant Activities (Scope of Work):

2.4.1.3. The PERFORMING PARTY will finalize the Portable Emissions Measurement System (PEMS) testing protocols based on 40 CFR 1065 regarding in-use testing of mobile source diesel engines in general and 40 CFR 92 regarding locomotive engines.

The final test protocol was designed to enable a fair comparison of the emissions and fuel consumption of locomotives used in switching operations at the Eastman facility. Where possible, all emissions related data would be collected following the relevant guidelines from 40 CFR 1065 Subpart J, where the use of Portable Emissions Measurement Systems (PEMS) for in-use measurement is described. Wherever not possible (for example, exhaust velocity measurement on the conventional switcher), primary standard methods and best engineering practices would be used. Below we summarize the measurement methods, the test duty cycle, and the data analysis methods.

Measurement Methods

Gaseous exhaust constituents were to be measured using a gaseous PEMS manufactured by Sensors, Inc. The SEMTECH-DS model of PEMS measures carbon dioxide (CO₂), carbon monoxide (CO), nitrogen dioxide (NO₂), nitrogen oxide (NO), total hydrocarbons (THC), and oxygen (O₂) according to requirements for PEMS in 40 CFR 1065 Subpart J. It is one of the PEMS pre-approved by EPA for in-use compliance testing.

Particulate matter was to be measured using the Siris system manufactured by ProcessMetrix. The Siris uses a method of dual-angle detection of laser light scattering. For ultra low-sulfur diesel (and other fuels) it has been shown by Caterpillar and others to correlate extremely well with gravimetric lab methods and the pre-approved PEMS method of photo-acoustic detection.

Exhaust flow was to be measured using two methods, both based upon the Bernoulli principle (using differential pressures to determine flow velocity). For the prototype hybrid switcher, two flow meters manufactured by Sensors, Inc. would be used on the two gensets in the locomotive. These are the standard exhaust flow meters sold for use with the SEMTECH-DS. For the conventional switcher, a primary standard, “S” type Pitot tube would be used following the requirements in EPA Method 2.

Locomotive power output was to be determined by recording voltage and current from the power generators and applying a generator efficiency factor to back-calculate the power required from the engine to produce that measured from the generator(s). The conventional switcher produced its power using a large DC generator coupled to the prime mover. Voltage and current would be recorded using a Dranetz PowerVisa 440 datalogger and a LEM PR4010 2000/4000A Busbar AC/DC Current Probe.

Test Duty Cycle

The duty cycle under which the locomotives would be tested was to be as similar as possible to actual revenue service. The instrumented locomotives were to be used on similar days during the same shift. Emissions would be measured during as much of the shift as possible, but especially when the switchers were working in Eastman’s “E” yard where strings of hopper cars (full of the same materials daily) are switched, resulting in predictable and consistent locomotive loads from day to day.
Data Analysis Methods

The emissions data would be reduced according to methods found in 40 CFR 1065. Further, the data would be subdivided into load categories relative to the maximum loads observed. This involves converting raw data into “engineering units,” time-aligning and combining the data recorded by the various data collection systems, applying corrections related to ambient conditions, etc. For example: idle, low load, medium load, and high load emission factors would be developed for the two locomotives. These would then be combined into a “cycle average” emission factor, based upon a common cycle as observed during testing or based upon the cycle weighting factors used in 40 CFR 1033 for switch locomotives.

From the Grant Activities (Scope of Work):

2.4.1.4. The PERFORMING PARTY will install the emissions measurement systems on both the conventional road switcher locomotive and the prototype hybrid genset road switcher locomotive.

The emissions measurement contractor infoWedge hired support personnel and equipment from the University of Houston’s Diesel Testing and Research Center to help perform the gaseous emissions testing. Before testing began on each locomotive, the team installed the required emissions measurement and supporting equipment. This effort is described below, where we also describe the testing process.

Testing Process

From the Grant Activities (Scope of Work):

2.4.2. Emission and fuel consumption testing of the conventional and prototype switchers

The testing team consisted of the main emissions measurement contractor, infoWedge, and personnel from the University of Houston’s Diesel Testing and Research Center (UHDTRC). Both infoWedge and UHDTRC transported equipment to enable the in-use tests. AMPS and Railserve personnel were also on-site and could provide support when their knowledge was required and they were available. Also, a local ducting contractor helped install the exhaust duct manifold onto the conventional switcher.

Since testing occurred during actual revenue service, the test equipment and all modifications had to be installed in a way that could withstand the significant impacts and accelerations that often occur during rail yard switching. Also, the strict safety and security requirements of the Eastman facility had to be observed. A particularly unfortunate security requirement of the facility was that no photography was allowed. So the only photos of testing were taken off the property where some installation occurred on the conventional switcher.

The ducting manifold for measuring exhaust velocity on the conventional switcher was fabricated by a Longview company. The photograph in the figure below shows the manifold installed on the SW1200 test switcher.
As shown in the figure above, the ducting joined two, 12-inch ducts into a single, 16-inch duct so that the total cross-sectional area of the single duct approximately equaled the total cross-sectional area of the two single ducts. The long straight section of the single duct allowed gas flows to straighten so that an accurate velocity measurement could be taken at the indicated port. An S-type Pitot tube and differential pressure transmitter were installed in the indicated location on the duct. The exhaust sample and temperature were also taken at the same location. Notice also that the PEMS had been installed at the time of the photograph.

The PEMS was installed on the back deck of the conventional switcher, directly behind the switcher operator. Power supplies for the instrumentation were also mounted on the back deck. The Siris PM monitor was mounted on the roof of the switcher so that it was within a few inches of where the exhaust sample exited the duct. The heated sample line of the PEMS was connected directly to the exit of the Siris, enabling the sample pumps of the PEMS to also serve for the Siris.

Inside the cab of the SW1200 is where instruments and recorders were mounted to monitor voltage and current from the locomotive’s generator. The remote control laptop for the PEMS was also operated from inside the cab and time lapse video with a frame rate of 1 Hz was taken of the operator’s control panel as a back-up source of information on generator current and notch position (i.e., relative engine load).

Installations of instruments on the prototype locomotive were similar to those for the conventional switcher. The primary differences were that two complete PEMS systems were installed, no independent measurement of generator power outputs was required, and the exhaust flow measurements were taken as is normally done for in-use testing with PEMS. Unfortunately, no photographs of the instrumented prototype were possible since it never left the facility during installation or testing.

From the Grant Activities (Scope of Work):

2.4.2.1. The PERFORMING PARTY will collect the emissions and fuel consumption data from the installed PEMS systems on both the conventional and prototype hybrid genset switcher locomotives under normal use conditions during a two-week period.
Once the instrumentation had been installed and powered up, the instruments were warmed up and calibrated. In the case of the prototype switcher, two complete PEMS installations were simultaneously prepared in this way. When the instruments were all prepared, the test team waited until the switcher operating team arrived. Then the switcher was simply operated as is normal at the facility as the emissions test team rode on-board and monitored the operation of the systems.

During testing, instrument outputs were monitored for reasonableness. There were a few instances of dropped signals and disconnected pressure tubing. But the vast majority of testing went very smoothly and the field quality assurance indicated that ample quantities of high quality data had been collected. After the shift came to an end, the switcher was parked at about the same location where installation had occurred and the emissions test team archived the data and removed the instrumentation.

From the Grant Activities (Scope of Work):

2.4.2.2. The PERFORMING PARTY will analyze the emissions and fuel consumption data collected from the PEMS systems as well as fuel consumption data from operator logs and compile a comprehensive report comparing the emissions and fuel consumption of the conventional and prototype hybrid genset switcher locomotives.

After data collection was completed, the data were quality assured, reduced and analyzed. This process is described in an report delivered to AMPS by infoWedge. The final results are summarized in the tables below. Note that for the conventional locomotive PM emissions were at times too high to measure without dilution.

### Table 1. Conventional SW1200 switch locomotive emissions.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emissions in grams per brake horsepower-hour (g/bHp-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>1440.8</td>
</tr>
<tr>
<td>CO</td>
<td>12.07465</td>
</tr>
<tr>
<td>NOₓ</td>
<td>27.026</td>
</tr>
<tr>
<td>THC</td>
<td>4.186</td>
</tr>
<tr>
<td>PM</td>
<td>&gt; 1</td>
</tr>
</tbody>
</table>

### Table 2. Prototype hybrid switch locomotive emissions.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emissions in grams per brake horsepower-hour (g/bHp-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>272.9</td>
</tr>
<tr>
<td>CO</td>
<td>0.011941</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.692</td>
</tr>
<tr>
<td>THC</td>
<td>0.417</td>
</tr>
<tr>
<td>PM</td>
<td>0.000355</td>
</tr>
</tbody>
</table>

Before discussing the above results we first discuss differences in how they were calculated for each locomotive. Then we discuss the modal analysis that was necessary to bring the measured, second-by-
second results to a common basis (i.e., test duty-cycle) so the relative emissions levels could be compared on an “apples-to-apples” basis.

In overview, these final results were calculated for both locomotives using the results from exhaust constituent (pollutant) measurements, exhaust gas flow measurements, and power output measurements. For both locomotives, the gaseous and particulate exhaust constituents were measured in exactly the same way – using conventional and well documented processes for the SEMTECH-DS. On the other hand, measurements of power output and exhaust flow were significantly different for the two locomotives. We describe the analysis of the significantly different techniques below.

**Exhaust Flow Analysis**

Exhaust flow for the conventional locomotive was measured using an S-type Pitot tube in a single, flow-straightening section, retrofitted onto the existing exhaust ducts. The Pitot tube directly measures the difference between gas velocity pressure (also called impact pressure) and static pressure. This difference is then used, along with corrections for gas temperature and pressure, to calculate gas velocity on a second-by-second basis using the Bernoulli principal. The gas velocity is then combined with the cross-sectional area of the duct to calculate a volumetric flow rate, corrected to standard conditions (e.g., standard cubic feet per minute). Although the Pitot tube is recognized as a primary standard method, the flow results were checked at idle against a “known” exhaust flow rate. The “known” idle flow rate was calculated from the known fuel flow rate at idle and the measured air/fuel ratio of the exhaust at idle conditions. The values agreed within 2%.

Exhaust flows for the two gen-sets on the prototype hybrid locomotive were measured as is normal for in-use testing using the SEMTECH-DS system. The flow meters sold with the SEMTECH-DS use the same principals as described for the conventional locomotive, but these are standardized flow meters that have been pre-calibrated in a lab and have years of testing and correlation data behind them.

**Power Output Analysis**

Power output from the conventional locomotive was directly logged as the product of voltage and current outputs of the generator. Using a generator efficiency assumption, the brake-power output of the engine was back calculated from the measured generator output.

The same principal was also used for the prototype hybrid locomotive, but the necessary inputs for the net power output calculation were collected from the values broadcasted on the CAN network used to control the prototype, instead of being independently measured. This was necessary since power can come from either of the gen-sets and/or the battery pack, depending upon constantly changing operational requirements. So the net power output of the hybrid system was calculated using the convention that power flowing to the batteries (charging) is negative power flow and all other power flows from the gen-sets or batteries are positive. In other words, the net power output of the hybrid at any instant is the sum of power outputs from the batteries and gen-sets, minus the battery recharging power. Induction generator efficiencies and battery efficiencies were also accounted for in the hybrid power calculation. As a matter of system control strategy, the battery pack state of charge is only allowed to vary between about 50% and 60%. So during the average work day, the state of charge can be assumed to be constant. This assumption was confirmed by the “state of charge” parameter from the hybrid’s CAN network.
Duty Cycle Analysis

Since the two locomotives did not do exactly the same work as they were being tested, it was necessary to categorize emissions into work “modes,” calculate average emission rates for those modes, then use a “weighted average” to calculate an overall emissions level during a hypothetical work shift for the locomotives.

The work modes defined for this comparison were: idle, low power, and high power. Idle for the conventional locomotive was simply anytime the engine sat at idle speed for 5 seconds or longer. Idle for the hybrid is not as straightforward because when the engine control is set to the “idle” notch, the engines may be at a high work load for charging the batteries and running auxiliary equipment that maintains battery conditions, air conditions the cab, etc. Also, the engines may not be running at all during idle since often the battery state of charge is high enough that power for hotel/auxiliary loads can be provided by the batteries alone. So for the prototype hybrid, idle mode was defined as when the engine control was set to the idle notch. Low power and high power modes were defined for both the conventional and the hybrid locomotive by looking at the distribution of non-idle power outputs for the two locomotives. Both of the distributions were tri-modal, with the two lower groups being combined into the low-power mode and the highest group being defined as the high-power mode. The concept is illustrated in the figure below from the hybrid locomotive data.

![Graph showing distribution of non-idle net power events for prototype hybrid, categorized into power modes.](image)

**Figure 3.** Distribution of non-idle, net power events for prototype hybrid, categorized into power modes

The net power event distribution for both the locomotives gave a clear indication of when high loads were demanded by the operator, such as when a string of cars was being accelerated or being pushed up a grade. During testing it was noted that the highest notch setting used for the conventional locomotive was 5 and for the hybrid was 6, so neither locomotive used notches 7 or 8. The lower loads for both locomotives represented power during coasting, stopping and accelerating the locomotive-only (i.e.,...
without other cars attached). Unique to the hybrid locomotive in the lower load groupings was battery charging and air conditioning the cab.

Using the overall proportion of events in each work mode (idle, low-power, and high-power) for the two locomotives, we arrived at a hypothetical work day (shift) to use for comparing their overall, in-use emissions. We determined that a reasonable fraction of time for each mode was fairly constant, no matter the shift, but that the low-power and high-power modes could represent a fairly wide range of fractions. The final ranges we observed to be reasonable are shown in the following table.

### Table 3. Range of power mode fractions by shift type

<table>
<thead>
<tr>
<th>Hypothetical Work Day Type</th>
<th>% Idle Mode</th>
<th>% Low-Power Mode</th>
<th>% High-Power Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy shift</td>
<td>45</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Light shift</td>
<td>42</td>
<td>49</td>
<td>9</td>
</tr>
</tbody>
</table>

#### Cycle-Average Fuel Consumption and Emissions

Once a work mode had been assigned to each second of emissions, power, and flow measurements, and a range of mode fractions had been established from observed data, it was possible to calculate mode-average emission and fuel use rates. These were then used to calculate cycle-average emissions and fuel use for intercomparison of the two locomotives.

Mode-average fuel consumption rates were calculated using the measured combustion products in the exhaust and the exhaust flow rates. The cycle-average rates for a heavy-shift and for a light-shift were then compared to determine the effect of shift type on the relative consumption rates. As shown in the table below, time-specific fuel consumption rate for the conventional locomotive is highly dependent upon the shift type with a heavy-shift consuming a significantly larger amount of fuel per hour. This is not the case for the prototype hybrid, which was fairly insensitive to shift power intensity. This is likely due to the fact that the engines of the hybrid function in about the same way for short-term light and heavy loads because the battery pack supplies the surge power needed for accelerations and short inclines.

### Table 4. Cycle-average fuel rates of conventional and prototype hybrid

<table>
<thead>
<tr>
<th>Locomotive</th>
<th>Heavy Shift Fuel Use (kg/hr)</th>
<th>Light Shift Fuel Use (kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>61.9</td>
<td>46.0</td>
</tr>
<tr>
<td>Hybrid</td>
<td>20.6</td>
<td>20.0</td>
</tr>
<tr>
<td>% Reduction</td>
<td>66.7%</td>
<td>56.5%</td>
</tr>
</tbody>
</table>

According to Railserve records, a typical diesel consumption rate for the conventional locomotive is about 44 kg/hr, so it is possible that the shifts we observed were biased toward being more heavy than normal. With that in mind, a fuel consumption benefit that could be conservatively claimed for using the hybrid instead of the conventional locomotive would be at least 50%. This savings will likely increase with the intensity of the shift work. This also assumes that they both do about the same amount of work during a shift, which probably biases this estimate in favor of the conventional locomotive since it likely would work a bit slower than the hybrid due to lack of traction controls.
In the same way cycle-average fuel consumption was calculated, so were pollutant emissions rates. The pollutant emissions rates were found to be fairly insensitive to cycle type, so they are presented in the table below for a heavy-shift duty-cycle. Since the emissions differences between the conventional and hybrid locomotives are so vast, the choice of duty cycle is not important anyway. Note that for the conventional locomotive PM emissions were at times too high to measure without dilution.

Table 5. Cycle-average emissions: Conventional vs hybrid switch locomotive

<table>
<thead>
<tr>
<th>Locomotive</th>
<th>CO (g/bHP-hr)</th>
<th>NOx (g/bHP-hr)</th>
<th>THC (g/bHP-hr)</th>
<th>PM (g/bHP-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>12.07</td>
<td>27.03</td>
<td>4.186</td>
<td>&gt;1*</td>
</tr>
<tr>
<td>Hybrid</td>
<td>0.01194</td>
<td>0.6920</td>
<td>0.4170</td>
<td>0.0003550</td>
</tr>
</tbody>
</table>

The real-world reductions in the above table may be somewhat understated due to the fact that they are on a gram per horsepower-hour basis. Since, for a given amount of switching work, the hybrid will likely expend less horsepower at the flywheel (i.e., brake horsepower) than the conventional locomotive, the relative pollutant emissions from the hybrid would be further reduced from the amounts shown in the above table. Since this probable reduction in the amount of the horsepower per unit of switcher work for the hybrid has not yet been estimated, we will not speculate on the magnitude of that difference beyond saying that it should be roughly similar in magnitude to the fuel consumption difference between the two locomotives.

Schedule and Deliverables

From the Grant Activities (Scope of Work):

2.4.3. Schedule: The PERFORMING PARTY shall complete this task within 23 months of the signed Notice to Proceed Date as issued by TCEQ.

Testing was concluded on June 7, 2013.

From the Grant Activities (Scope of Work):

2.4.4. Deliverables: The PERFORMING PARTY shall submit a report to the TCEQ upon completion of this task comparing the emissions and fuel consumption of the conventional and prototype hybrid genset switcher locomotives.

This report was finished on June 26, 2013.

Task 5: Evaluate Operator Acceptance of Prototype Locomotive

From the Grant Activities (Scope of Work):

2.5. Task Statement: The PERFORMING PARTY will evaluate operator acceptance of the hybrid genset system in use.

2.5.1. The PERFORMING PARTY will develop a questionnaire for operators of the prototype genset hybrid switcher locomotive to track their impressions of its operation and performance. The PERFORMING PARTY will train operators of the prototype hybrid genset switcher in the use of this questionnaire. The PERFORMING PARTY will ensure that operators of the prototype
hybrid genset switcher locomotive complete the questionnaire near the end of the one month break-in period in Task 4.

2.5.2. If necessary, the PERFORMING PARTY will conduct follow up interviews with operators of the prototype genset hybrid switcher locomotive during the emissions testing in Longview, Texas, to clarify information provided by the operators on the questionnaire.

2.5.3. Schedule: The PERFORMING PARTY shall complete this task within 24 months of the signed Notice to Proceed Date as issued by TCEQ.

2.5.4. Deliverables: The PERFORMING PARTY shall submit a report to the TCEQ upon completion of this task including a summary and evaluation of the operators’ feedback.

AMPS developed a survey for the operators employed at the Railserve yard to compare the performance of the prototype locomotive with a conventional switcher locomotive and a Railserve LEAF locomotive (a single genset switcher). The categories on which the locomotives were rated are as follows: Power; Throttle Response; Braking, Noise; Layout of Controls; In-Cab Visibility; and Heating and Cooling. Three out of the four possible operators employed at the yard were able to fill out the survey (the fourth being on vacation). Copies of the responses are attached at Appendix A.

Operator response was generally positive with 22 responses over all the categories rating the prototype as better than the conventional or Leaf locomotives, 18 responses rating the prototype as the same and 2 as worse.

In addition to developing and administering the questionnaire, Brian Couchene, one of AMPS principal investigators, has ridden with the operators since the prototype locomotive has been at the Railserve yard and has had on ongoing dialogue with them about the locomotive’s performance.

**Task 6: Final Report**

From the Grant Activities (Scope of Work):

Task 6: Reporting

2.6. Task statement: The PERFORMING PARTY will prepare and submit monthly detailed project reports and a comprehensive final report while ensuring compliance with all TCEQ program requirements

2.6.1. The PERFORMING PARTY will coordinate all project resources to ensure compliance with NTRD program requirements while providing deliverables on-schedule and on-budget.

2.6.2. The PERFORMING PARTY will generate monthly progress reports and a final report summarizing all aspects of the project based on data from the task completion reports.

2.6.3. Schedule: The PERFORMING PARTY shall submit monthly reports to the TCEQ by no later than 10 days after the end of each month. The PERFORMING PARTY shall submit the final report to complete this task within 25 months of the signed Notice to Proceed Date as issued by TCEQ.
2.6.4. Deliverables: The PERFORMING PARTY shall submit monthly progress reports with associated billing statements and a final project summary report to the TCEQ upon completion of this task.

This report serves as the final report for this project.
Discussion/Observations

Objectives vs. Results

The data collected during the emissions testing of the prototype locomotive clearly demonstrate that repowering an in-use conventionally powered road switcher locomotive with a multiple genset/hybrid genset package reduces NOx emissions by an average of 96.3%, CO by an average of 99.3% and PM by an average of 99.8% (with EV correction).

Compared to repowering a conventional locomotive with a non-hybrid genset package, AMPS has demonstrated that the prototype locomotive is able to achieve an additional 25% NOx reduction and 20% fuel saving compared to the results achieved through repowering with conventional genset technology. As discussed further below, AMPS is confident that the project results validate the commercial viability and cost effectiveness of the modular approach to the design and installation of the multiple genset/hybrid genset package.

The increased emissions reductions are achieved, in part, by completely eliminating “idle emissions” through use of the on-board battery pack. For railcar movement indoors or in sensitive areas, the Hybrid Genset locomotive is able to function for short periods of time with zero emissions due to the ability to operate without running the internal combustion engine. This, together with the smokeless start, is of particular importance for railcar movement indoors or in sensitive areas. In addition, AMPS Sweet Spot Control Technology (SSC) optimizes both the efficiency and performance of individual systems and as a result affords dramatic improvements in longevity of the locomotive power and control system as well as traction motors.

The choice of the battery packs for the prototype locomotive was particularly important given the poor quality of batteries used in some earlier hybrid attempts. AMPS selected 16 Corvus Energy industrial use lithium-ion AT6500-48V batteries because they have an excellent charge/discharge rate, a high performance rate even in cold weather, they are air-cooled rather than water-cooled, and the battery management system has safety and protection built into a streamlined case that cannot be readily accessed.

The prototype design has exceeded expectations for efficiency to the extent that AMPS believes that a locomotive equipped with only the 250hp/150 kw GenSet along with the small Corvus Energy 104kw Lithium Battery Pack as described above is capable of performing at least 90% of the switching functions at the Texas Eastman yard without the necessity of using the larger 600 hp/400 kw genset.

While completion of the project is behind the originally envisaged schedule due to project changes, delays at the Railserve Longview shop, and AMPS involvement in a military contract which went on longer than anticipated, some of the delay time allowed AMPS to make improvements to the prototype “modularity” as well as to the overall design. Modularity allows AMPS to assemble genset modules in one location, populated cab / short hood modules in another, truck assemblies in another, etc, then bring all the modules together either at the final assembly location or, if the client purchases a “module kit”, at the client’s own site for self-assembly.

AMPS plans to continue to acquire data, monitor locomotive performance and operator feedback, and make any required programming adjustments. AMPS also plans to install Thermal Plates to manage battery pack temperature (the aim is to maintain this as closely as possible to 10 degrees C/50 degrees F).
Until the company is able to obtain the thermal plates which will be the permanent solution, an 8,000 BTU industrial climate control unit has been installed to provide proper performance of the battery pack in high temperatures. In July, a maximum pulling capacity test will be performed against a Dual GenSet Railserve LEAF which will test overall locomotive design integrity, AMPS Axle Generator dependability, and our overall power management and control scheme.

**Critical issues**

There are no critical issues with this locomotive. The AMPS locomotive now operating in Longview, Texas, is actually better than AMPS initially envisioned when the Grant Application was submitted. Although the locomotive is a “prototype” it will not need to be treated as one. Railserve will be able to use the locomotive with no conditions and AMPS expects it to operate at least as reliably as a conventional locomotive but with much less maintenance.

**Technical and commercial viability**

As discussed above, the project objectives have been achieved and the locomotive is technically viable. Currently, locomotives with 2 gensets but without the hybrid genset module are selling for approximately $1,200,000 to $1,400,000. AMPS currently estimates that the Multiple Genset/Hybrid Genset Dominant package, when fully installed, will cost the locomotive owner approximately $1,034,000 (this includes the cost of installation of the modules, rebuilding locomotive truck assemblies, and repair and repainting of the owner’s original locomotive - a savings of between $200,000 to $400,000 for a locomotive which, compared to a conventional genset locomotive, emits less pollutants, is more fuel efficient, and is repowered to meet the specific needs of the owner/operator. If AMPS provides the whole locomotive not just the modules for an owner’s existing locomotive, it is likely that the cost to the buyer of the complete multiple Genset/Hybrid Genset locomotive will be around $1,400,000 which is competitive with a Dual GenSet (non-hybrid) Locomotive from competitors. A locomotive capable of performing switching functions without the necessity of using the larger 600 hp/400 kw genset will cost approximately $95,000 less than the Multiple Genset/hybrid Genset Dominant package.

AMPS has developed a strong reputation in the market place which will enhance the commercialization of this technology and has already received expressions of interest in the prototype locomotive from two locomotive manufacturers, and two Class I Railroads as well as a manufacturer of components for locomotives and railcars. AMPS has Non-Disclosure Agreements (NDA) in place with two of these entities and an NDA in progress with another. Two of these organizations are tentatively scheduled to visit the locomotive and a preliminary face to face meeting with another organization located in Texas is in the process of being set up. AMPS will also work in conjunction with Railserve to market the hybrid genset package and within two years of completion of this project AMPS aims to achieve, at a minimum, sales of 23 repower packages in the Texas nonattainment areas. The locomotive will be used at Texas Eastman in Longview and be operated by Railserve for the foreseeable future.

In preparation of scaling up to meet market demand, AMPS is in discussion with the Norfolk Southern Thoroughbred Shop in Altoona, PA about building the locomotive if the end user does not have
locomotive rebuild facilities. For the southern United States, Railserve will be the builder/assembler for those end users without rebuild facilities.

**Scope for future work**

AMPS foresees a range of further spin-off technology possibilities resulting from this project such as natural gas or propane powered GenSets and a road coupled hybrid locomotive module (either as a “tender” or as “distributed power). The road coupled hybrid would have batteries and no engine. The batteries are charged when the locomotive uses its traction motors to assist in braking the train. Instead of wasting that energy, some of it is recovered by charging the batteries. With an “intelligent” control system, this energy can then be used for propulsion in anticipation of the next braking event, etc. With distributed power railroads can optimize the distribution of power and braking control over the entire length of a train. In addition, AMPS is exploring the option of using an EMD* 8-710 2,000hp engine in the design for Short Line applications. This option has at least two benefits: the engine would allow for operation at speeds of up to 65 mph and railroads are very familiar with this engine.

**Intellectual Properties/Publications/Presentations**

AMPS does not foresee any intellectual property issues in relation to implementation of the commercialization plan. Certification or verification of the gensets used in this package is not required as the total diesel engine power of the gensets in the package is less than 750 kw (1006 hp) and the engines used are certified non-road engines allowable under 40 CFR section 1033.150 Interim Provisions. In addition, there is no certification or verification protocol currently available from EPA or CARB for the hybrid element of the package. If such a protocol is developed then AMPS will consider pursuing certification or verification testing to enable credit for emission reductions beyond those attributed to the gensets alone.

**Summary/Conclusions**

The tests conducted on the prototype locomotive during the grant period demonstrate that AMPS new Multiple GenSet/Hybrid Genset package is an ideal cost effective product to address emission reduction needs while filling the heavy duty application requirements of road switcher/short line locomotives which operate below 35 mph. Although the project took longer than originally planned the prototype locomotive developed in this project will be the first genset package with a hybrid genset module in the road switcher/short line locomotives marketplace.
Acknowledgements

AMPS would like to acknowledge the following partners for their significant contributions to the project:

- Railserve, Inc.: Donor Locomotive; Truck Assembly and Air System Rebuild; Fabrication; Final Assembly; Paint.
- Superior Diesel: Engines; Radiator; Fabrication and design of GenSet Module.
- Benroth-Nolty Company: Generators for GenSet Module.
- Corvus Energy: Batteries; Battery Management.
- American Traction Systems: Propulsion and Generator Drive Modules.
- Allied Fabricating & Welding Co.: Modifications of Cab / Short Hood Module; Installation of Propulsion Module; Installation of populated Operator Control Stand.

Contact Information

For further information about this project please contact:

Dan Frederick
Alternative Motive Power Systems
740-924-9479
dan@ampsonboard.com
Appendices
Appendix A: Operator Surveys
### GSHX 3380 Operator Survey

**Instructions:** Please rate this locomotive as “Better Than” “The Same As” or “Worse Than” a Conventional Locomotive and a Railserve LEAF® Locomotive by placing an “X” in the appropriate box.

<table>
<thead>
<tr>
<th>Category</th>
<th>Conventional Locomotive</th>
<th>Railserve LEAF®</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Better</td>
<td>Same</td>
</tr>
<tr>
<td>Power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Throttle Response</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Braking</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Noise</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Layout of Controls</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>In Cab Visibility</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Heating &amp; Cooling</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Overall Rating (0-10)</td>
<td></td>
<td>S</td>
</tr>
</tbody>
</table>

**Additional Comments:** Advantages of AMPS Engine: Less maintenance, no P/N codes to lessen on-tested. No oil to add...

**Features you like?** Air Conditioning / Quiet when running

**Improvements?** Electrical knobs light up and good location on panel - Control panel placement and area leaves room for feet placement

**Date:** 6/27/13  **Initials:** SD

---

8550 Jug Street • Alexandria, Ohio 43001  
614.568.7838
# GSHX 3380 Operator Survey

**Instructions:** Please rate this locomotive as “Better Than” “The Same As” or “Worse Than” a Conventional Locomotive and a Railserve LEAF® Locomotive by placing an “X” in the appropriate box.

<table>
<thead>
<tr>
<th>Category</th>
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<td>Power</td>
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</tr>
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</tr>
<tr>
<td>Braking</td>
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<td></td>
</tr>
<tr>
<td>Noise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layout of Controls</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>In-Cab Visibility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating &amp; Cooling</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Overall Rating (0-10)</td>
<td></td>
<td>7</td>
</tr>
</tbody>
</table>

**Additional Comments:**

Only ran “light engine” first time and handled empty railcars second time. Unable to truly rate power.

**Features you like?**

Feels smooth, and much more quiet than Conventional Locomotive.

**Improvements?**

Reliability.

---

**Date:** 6/27/2013  
**Initials:** MJD

8550 Jug Street • Alexandria, Ohio 43001  
614.568.7838
GSHX 3380 Operator Survey

Instructions: Please rate this locomotive as "Better Than" "The Same As" or "Worse Than" a Conventional Locomotive and a Railserve LEAF® Locomotive by placing an "X" in the appropriate box.

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<thead>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>Overall Rating (0-10)</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

Additional Comments:
needs clock.

Features you like?

Air Conditioning
Locomotive Lighting, ground, step, etc.
Load Horn

Improvements?
Add clock for filling out paperwork.
Add cup holders for coffee or Gatoraid.
Need clipboard holders

Date 6-27-2013  Initials BC

8550 Jug Street • Alexandria, Ohio 43001
614.568.7838
Appendix B: Photographs

Figure 4. Stripped locomotive ready for rebuild.
Figure 5. View of locomotive deck prior to rebuild.
Figure 6. Stripped cab/short hood module prepared to receive propulsion module, populated operator control stand, control cabinet, etc.
Figure 7. Locomotive deck prepared to receive sub-systems.
Figure 8. Populated cab/short hood module being installed on prepared locomotive deck.
Figure 9. Populated operator control stand.
Figure 10. Control cabinet.
Figure 11. Propulsion system installed in cab/short hood module.
Figure 12. Genset module #1 (400kw).
Figure 13. Genset module #2 (150 kw).
Figure 14. Genset modules installed on locomotive deck.
Figure 15. Battery module (104 kwh) installed on locomotive deck.
Figure 16. Modular framework for long hood.
Figure 17. AMPS dual signal axle generator.
Figure 18. Locomotive headed to paint shop.
Figure 19. Locomotive in paint shop.
Figure 20. Locomotive out of paint shop.
Figure 21. Locomotive at test site.
Figure 22. Locomotive pulling cars at test site #1.
Figure 23. Locomotive pulling cars at test site #2.
Figure 24. Solidworks CAD drawing of locomotive.

Figure 25. Solidworks “exploded” view showing “modularity of long hood.”
Figure 26. AMPS data acquisition system #1.
Figure 27. AMPS data acquisition system #2.
Figure 28. AMPS data acquisition system #3.
Figure 29. AMPS data acquisition system #4.