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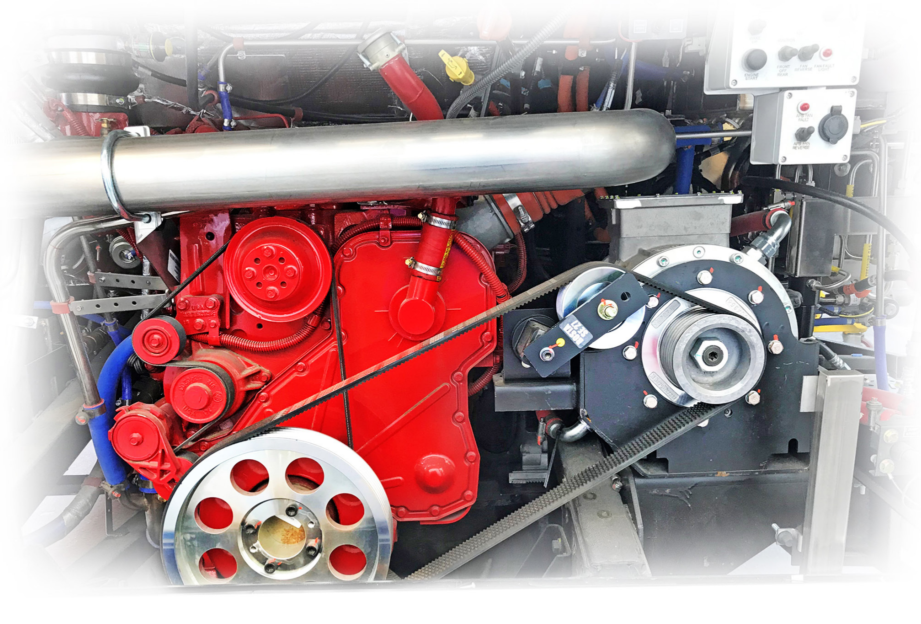
Reduced Engine Idle Load (REIL) System for Conventional Propulsion Diesel & CNG Buses: Development, Validation & Market Study Program

FEBRUARY 2020

FTA Report No. 0157
Federal Transit Administration

PREPARED BY

Jason Hanlin, Blake Whitson, and Joe Empert
Center for Transportation and the Environment



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Center for Transportation and the Environment
730 Peachtree Street, Suite 450
Atlanta, GA 30308

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Federal Transit Administration
Office of Research, Demonstration and Innovation
U.S. Department of Transportation
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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liter	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY	2. REPORT DATE February 2020	3. REPORT TYPE AND DATES COVERED Final

4. TITLE AND SUBTITLE Reduced Engine Idle Load (REIL) System for Conventional Propulsion Diesel & CNG Buses: Development, Validation & Market Study Program	5. FUNDING NUMBERS GA-2016-004-00

6. AUTHOR(S)
Jason Hanlin, Blake Whitson, Joe Empert

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSE(ES) Center for Transportation and the Environment 730 Peachtree Street, Suite 450 Atlanta, GA 30308	8. PERFORMING ORGANIZATION REPORT NUMBER FTA Report No. 0157
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Transit Administration Office of Research, Demonstration and Innovation East Building 1200 New Jersey Avenue, SE Washington, DC 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER FTA Report No. 0157

11. SUPPLEMENTARY NOTES [https://www.transit.dot.gov/about/research-innovation]

12A. DISTRIBUTION/AVAILABILITY STATEMENT Available from: National Technical Information Service (NTIS), Springfield, VA 22161. Phone 703.605.6000, Fax 703.605.6900, email [orders@ntis.gov]	12B. DISTRIBUTION CODE TRI-30

13. ABSTRACT
The Center for Transportation and the Environment partnered with New Flyer, BAE Systems, and MARTA to design, build, test, and evaluate the technology and market readiness of a Reduced Engine Idle Load (REIL) system for diesel and CNG (compressed natural gas) transit buses. A REIL system replaces traditional mechanically-driven accessories with electric accessories to increase fuel efficiency, reduce emissions, and simplify maintenance on conventional propulsion transit bus fleets. The project team was responsible for the system design, laboratory and performance testing, collection of real-world duty cycle route data, development of operational route simulation, and a market evaluation to determine the performance benefits and cost/benefit of such a system. This project received funding under FTA's Bus Efficiency Enhancements Research and Demonstration (BEERD) Program.

14. SUBJECT TERMS Fuel efficiency, bus maintenance, CO_2 emissions, electric accessories, engine idle, parasitic loads, ROI, market readiness, technology readiness	15. NUMBER OF PAGES 49

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

This research, development, and demonstration project could not have been successful without key partners across the industry that contributed key activities and expertise. In particular, we would like to thank the following people who were members of or otherwise supported the project team: Bart Mancini, Yesh Premkumar and Barry Rosenkrans of BAE Systems; Yvonne DeBellotte, Tony Morrow, and Tami Murphy-Taylor of MARTA; Thomas Small and Brydon Owen of New Flyer; Michael Lewis of the University of Texas at Austin, Center for Electromechanics (independent evaluator); and Samuel Yimer of the U.S. Department of Transportation, Federal Transit Administration. FTA's Office of Research, Demonstration and Innovation was the sponsor of this project and provided guidance throughout its execution. Finally, thanks to the associates and interns at CTE who assisted the authors in compiling notes throughout this project and in formatting this final report.

ABSTRACT

The Center for Transportation and the Environment partnered with New Flyer, BAE Systems, and MARTA to design, build, test, and evaluate the technology and market readiness of a Reduced Engine Idle Load (REIL) system for diesel and CNG (compressed natural gas) transit buses. A REIL system replaces traditional mechanically-driven accessories with electric accessories to increase fuel efficiency, reduce emissions, and simplify maintenance on conventional propulsion transit bus fleets. The project team was responsible for the system design, laboratory and performance testing, collection of real-world duty cycle route data, development of operational route simulation, and a market evaluation to determine the performance benefits and cost/benefit of such a system. This project received funding under FTA's Bus Efficiency Enhancements Research and Demonstration (BEERD) Program.

EXECUTIVE SUMMARY

A Reduced Engine Idle Load (REIL) system replaces traditional unmanaged, mechanically-driven accessories on transit buses with managed, electrically-driven accessories to improve efficiency and allow for accessories to run without the engine idling. The primary purpose of the project was to develop a REIL system and evaluate technology readiness, expected fuel efficiency improvements, and market readiness as if used in revenue diesel and CNG (compressed natural gas) transit bus service. FTA awarded funding to the Center for Transportation and the Environment and project partners BAE Systems, New Flyer, and MARTA to complete this study with University of Texas at Austin–Center for Electromechanics as a third-party evaluator.

The team determined that technology readiness was proven and efficiency gains were realized. REIL system hardware was tested at BAE Systems in both a dynamometer test stand and a full engine test pod using a Cummins ISL engine to imitate a real-world transit bus duty cycle. In addition, the team performed computer simulations of the system on multiple MARTA duty cycles/routes to evaluate fuel efficiency. Results showed that the system met all operational load, response, transition, and safety requirements and demonstrated an expected fuel efficiency improvement of 10–15% for systems that include an Energy Storage System (ESS) and 2–4% for systems without an ESS, relative to traditional systems without REIL. Emissions reductions of up to 15 metric tons CO_2e per bus are expected to be realized annually using this system.

The scope of this project also included a determination of market readiness and financial benefits of the REIL system. First, accessory system maintenance cost reductions of approximately 34% (approximately $1,450 per bus) can be achieved due to the simplification and reduction in moving parts associated with electrifying the various accessory systems including HVAC, power steering, air compressor, and alternator. Second, the improvement in fuel efficiency results in annual fuel cost savings ranging from $429–$3,396, with the most savings realized when outfitting a diesel bus with a REIL system that includes an ESS. Finally, REIL would be offered as an add-on option when purchasing a bus at an estimated incremental cost of $30,000–$62,500. Without any subsidy, the payback period is more than 10 years (up to 24 years worst case), but with typical Federal subsidies that period is significantly reduced to 2–5 years—an attractive return on investment (ROI) for a transit agency/operator.

Due to its superior gains in fuel efficiency and the addition of engine-off operation during vehicle start/stop conditions, the REIL system with an ESS provides the most benefits per investment dollar. However, both electrified accessory systems show tangible benefits in reducing emissions and operational cost in an otherwise conventionally-powered bus fleet, be it diesel or CNG. The team plans to pursue future additional opportunities to test this system on actual vehicles in revenue service and to support the development of next generation systems.

SECTION 1

Introduction

This report describes the results of a project to develop a Reduced Engine Idle Load (REIL) system and evaluate the associated efficiency improvements and market readiness as if used in revenue diesel and CNG (compressed natural gas) transit bus service.

The project was funded as part of the Federal Transit Administration (FTA) Bus Efficiency Enhancements Research and Demonstrations (BEERD) Program.

The BEERD Program was developed "to promote the development and demonstration of targeted energy efficiency-enhancing technologies–specifically enhanced Electrification of Accessories and improvements in Thermal Management of Bus Bodies–for buses utilized in public transportation" [1]. The program also aims to produce overall favorable impacts on the transit-riding public and participants in the industry as well as advancing the US Department of Transportation's (USDOT) research goals. Finally, "this program invests in promising technologies that could help save energy, reduce emissions, and bring cost-savings to transit providers across the country" [1].

Background

Conventional transit buses sold and operated in the United States use a diesel or CNG engine to power both the drivetrain and accessory systems. The accessories are powered by the engine's crankshaft via mechanical linkages (e.g., belts and pulleys). Because of this arrangement, the engine must be operating for the accessories to function, and the control strategy for the accessory loads is limited. Replacing the traditional mechanically-driven accessories with electric accessories can potentially reduce fuel consumption and emissions, improve reliability, and decrease life cycle costs; however, there was no comprehensive "more electric" and/or anti-idle system available for these buses at the time of this project's inception. Some companies offer stand-alone electric accessory sub-systems, such as engine cooling or air-conditioning or DC/DC converters, but not in a coordinated and integrated fashion and not including anti-idle or waste energy recovery capability. Series and parallel hybrid propulsion systems are available for these types of transit buses, but their cost and complexity relegate hybrid propulsion technology to a somewhat niche market.

Conventional propulsion buses account for nearly 80% of the 3,000–4,000 new transit bus and nearly 100% of the 2,000–3,000 new OTR (over-the-road) coach purchases in North America annually, with the European market being 3–5 times larger. Yet these huge numbers of diesel- and CNG-fueled transit buses cannot take full advantage of the benefits enjoyed by the electric systems on hybrid-electric buses. A lower cost, lower complexity, "more-electric" system for conventional propulsion diesel and CNG passenger bus markets is needed.

FTA awarded funding to the Center for Transportation and the Environment and project partners BAE Systems, New Flyer, and MARTA to study, develop, and demonstrate a REIL system. The REIL system is expected to improve fuel efficiency and maintainability by replacing the multiple mechanical linkages between engine crankshaft and accessory systems with a single belt-driven electric generator feeding an accessory power system (APS). The APS manages the power to various electrified accessory systems, including an HVAC (heating, ventilation and air conditioning) system, power steering pump, air compressor, 28V supply, and various cooling fans. An optional energy storage system (ESS) enables additional use cases involving the removal of parasitic loads from the engine during vehicle stops, which further improves efficiency and emissions reductions.

This project provided the team with the unique opportunity to build and test a REIL system, assess technology readiness, and estimate achievable benefits. The scope of this project also included an assessment of market readiness and ROI of such a system.

Partners

Five organizations contributed to the project—the Center for Transportation and the Environment (CTE), BAE Systems, New Flyer of America, Metropolitan Atlanta Rapid Transit Authority (MARTA), and the University of Texas at Austin–Center for Electromechanics (UT-CEM).

Center for Transportation and the Environment

The Center for Transportation and the Environment (CTE) is a non-profit, 501(c)(3), member-based organization that facilitates the development of technologies to improve the sustainability of transportation systems. CTE relies on the experience and resources of members and project partners to successfully develop, demonstrate, and deploy advanced transportation technologies across an array of markets. Recognizing the value of working collaboratively in a team environment, CTE manages large, technical, multi-partner grants, contracts, and cooperative agreements. CTE's centralized, structured management of its work program enables team members to concentrate on exceeding project goals and ensure production of deliverables in a clear and well-coordinated manner. CTE also provides technical support to project teams such as technical oversight, risk analysis, and mitigation strategies.

Since 1993, CTE has managed a portfolio of more than $400 million in Federal, State, and local cost-shared research, development, and demonstration projects involving more than 100 organizations in the advanced transportation technology field. CTE has facilitated and leveraged funding for its projects and initiatives from Federal, State, and local entities including the U.S. Departments of Defense, Energy, Interior, and Transportation as well as from the U.S. Army and NASA, the California Air Resources Board, and the California Energy Commission, among others. CTE maintains offices in Atlanta, GA; Berkeley, CA; Los Angeles, CA; and St. Paul, MN.

CTE managed this REIL project.

BAE Systems

BAE Systems is a designer, manufacturer, and integrator of hybrid electric propulsion and power subsystems for heavy-duty commercial transit bus and truck applications and military ground vehicles. Focusing on commercial transit buses, BAE Systems has delivered more than 5,000 series hybrid electric propulsion systems, logging more than 940,000,000 miles of revenue service operation. It has direct experience with the conditions required to successfully transition to the production of new propulsion technologies for the commercial transit bus market.

The HybriDrive® Systems Business Unit (HDS) is headquartered in Endicott, New York, and is part of the Electronic Systems division of BAE Systems. HybriDrive Systems is responsible for the design and development of hybrid-electric propulsion systems. Although Endicott is the home of the innovative research, technical expertise, and manufacturing that has allowed it to become a world leader in hybrid electric propulsion technology solutions for the transit bus industry, BAE Systems also has operations in Southern California where the buses are built.

BAE Systems' expertise in power management and machine controls is a key competency in this project in developing an impactful stand-alone electric accessories power plant for the transit bus market. The REIL's innovative design leverages system controls based on millions of miles of revenue service with the HybriDrive Propulsion system. BAE Systems has significant experience performing and delivering on government-funded advanced technology programs and is a hybrid electric propulsion supplier for leading bus manufacturers serving the US transit market. In this project, BAE Systems led tasks associated with the design, validation, simulation, and supply of the REIL system.

New Flyer

New Flyer of America, the U.S. subsidiary of NFI Group, is a leader in the North America heavy-duty transit bus industry and offers an advanced product line under the Xcelsior® brand. New Flyer currently offers diesel, CNG, hybrid, battery electric, and hydrogen fuel cell Xcelsior® buses.

New Flyer actively supports more than 44,000 heavy-duty transit buses currently in service and serves 24 of the 25 largest transit agencies in North America, in addition to 400 others across the continent. In 2018, New Flyer celebrated the delivery of its 10,000th Xcelsior transit bus in North America. It is the only manufacturer to offer three zero-emission bus propulsion systems (battery-electric, fuel cell-electric, and trolley-electric) in addition to low-emission propulsions (CNG and diesel-electric hybrids) in 35-ft, 40-ft, and 60-ft models.

A leader in safe and efficient manufacturing, New Flyer is the first and only North American original equipment manufacturer (OEM) to achieve all three ISO certifications: ISO 9001 (quality), ISO 14001 (environmental), and OSHAS 18001 (safety).

New Flyer provided input on the feasibility of integrating the REIL system on a modern transit bus.

MARTA

Metropolitan Atlanta Rapid Transit Authority (MARTA), the 8th largest transit system in the US, has provided fixed-route buses, heavy rail, and complementary paratransit service for Atlanta since 1972. The MARTA service area includes the jurisdictions of Clayton, DeKalb, and Fulton counties and the city of Atlanta, with a total estimated population of 2,000,000 and nearly 1,000 square miles. The estimated population for the entire metropolitan Atlanta area is 5.6 million, which is also served by the MARTA transit system.

Fiscal Year (FY) 2017 weekday boardings averaged 0.424 million, and annual passenger trips 126.4 million. Paratransit annual ridership for FY2017 was 0.687 million. Operating statistics for FY2017 are 29.8 million bus miles and 23.2 million rail miles. MARTA currently has 554 transit buses (391 CNG buses and 163 diesel buses), 211 paratransit vehicles, and 316 railcars providing transit service. It operates four bus maintenance facilities and one paratransit vehicle maintenance facility. More than 97% of its 91 bus routes connect at one of 38 rail transit stations; these connections are a critical element of the transit system, providing connectivity within the system and, therefore, access to employment, education, training, and other activities within the region.

MARTA provided real-world duty cycle and maintenance data crucial to the team's evaluation, validation, and market evaluation tasks.

University of Texas at Austin–Center for Electromechanics (UT-CEM)

UT-CEM is a research center world-renowned for development and demonstration of advanced energy storage and power generation systems; it teams with companies to get the technology to market, and its annual budget addresses both development programs and active technology transfer programs.

UT-CEM conducts research and public outreach programs, educates students, and transfers research results to industry for commercialization. Research projects in the transportation sector include fuel efficient hybrid electric vehicles and trains, zero-emission fuel cell vehicles including hydrogen generation technologies, active suspension for improved ride control, and advanced vehicle energy storage for improved fuel economy and reduced emissions. Research projects in the Electric Power, Defense, and Space sectors include advanced generators with large-scale energy storage, electric grid control, electric aircraft launch for the next-generation all-electric ship, advanced wheeled and tracked military vehicles, and space power with integrated attitude control.

UT-CEM has completed multiple programs funded by US DOT and DOD to advance hydrogen-powered, hybrid electric vehicles, including state-of-the-art energy storage (chemical batteries, ultracapacitors, and flywheels) for improved vehicle performance. It has also recently led the systems design and simulation for the demonstration tasks in an FTA program to develop a Bus Exportable Power Supply (BEPS) system for emergency response. UT-CEM's 140,000 square foot laboratory features extensive prototype testing and assembly facilities.

UT-CEM assessed the overall effectiveness of this research and demonstration project act as a third-party evaluator. Its assessment is included as Appendix B of this report and referenced herein.

Purpose

The purpose of the project was to develop a REIL system and estimate fuel efficiency improvements as if used in revenue diesel and CNG transit bus service. Efficiency improvements were estimated by demonstrating the REIL system hardware in a BAE Systems engine test pod that was configured to imitate a real-world MARTA bus duty cycle and would use a Cummins ISL engine. In addition, the team performed computer simulations on multiple MARTA duty cycles/routes of the REIL system in configurations with and without the ESS.

Another purpose of this project was to assess the overall commercial readiness of this system and its ability to reduce operations and maintenance costs for the operator. The project team assessed the potential operating cost savings that would come from fuel savings by incorporating electrified accessories, which also have fewer moving parts and a presumed lower maintenance burden as compared to mechanical components. Cost savings were assessed against the incremental cost to implement to determine the overall financial benefits.

Approach

The overall elements of this project were as noted below (see Appendix A for specific task details).

System Design, Build, and Test

This task included 1) developing design specifications and a final system design, 2) specifying all components and Bill of Material, 3) procuring and building all system hardware and associated wiring, 4) validating and testing the system, and 5) addressing packaging and installation requirements for hypothetical integration on a transit bus.

Market Evaluation

This task included 1) characterizing the MARTA duty cycle using real-world drive cycle data from MARTA routes, 2) simulating revenue service operation and accessory loads in the BAE test pod using the REIL hardware developed in this project and record results on fuel economy, emissions, and overall performance, and 3) using the above results, developing a market analysis to assess the financial attractiveness of the REIL system.

Independent Evaluation

This task included an evaluation by a university faculty member/researcher to 1) assess the team's ability to produce project deliverables within the project schedule and budget, 2) assess the technology readiness level of the REIL system, 3) verify the efficiency improvements and resulting ROI of the REIL system, and 4) assess the overall effectiveness of the project.

Project Management

This activity entailed overall management of the project from beginning to end and included the following specific deliverables: 1) kickoff and regular team meetings, 2) quarterly reporting to FTA, meeting the requirements of FTA Circular 6100.1E at a minimum, with elements such as status updates, cost and cost share tracking, and schedule tracking, and 3) final reporting (this document), meeting the requirements of FTA Circular 6100.1E with elements such as technical and evaluation results, assessment of the project against objectives and goals, final cost summary, and recommended next steps.

SECTION

2

Technical Description

A REIL system provides power to vehicle accessories while reducing the impact to the engine during idle conditions. The basic system uses a generator driven by a single belt from the engine and an accessory power system (APS) to convert and manage that power to support the required loads for electrified accessories. Adding an energy storage system (ESS) offers expanded operational modes and efficiency improvements by taking load off the engine during both intermittent and long-duration vehicle stops and enabling the implementation of regenerative braking.

Design Goals and Expected System Benefits

The REIL system has several potential benefits associated with electrifying vehicle accessories and in accordance with its design, including the following:

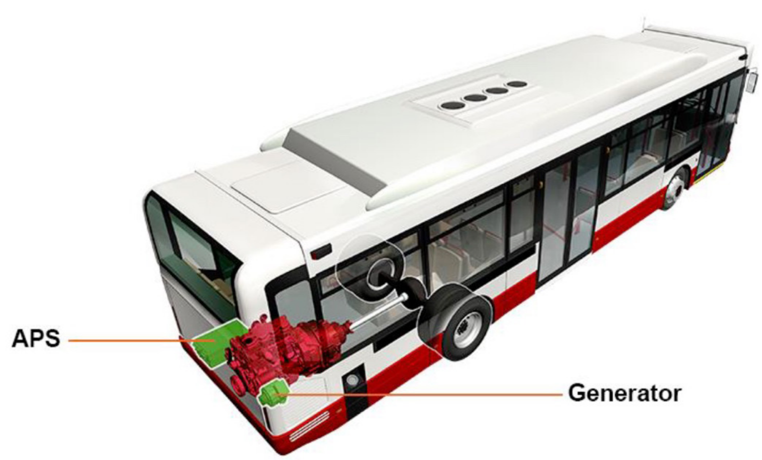
- Efficiency (mpg) improvements, most notably with systems that include an ESS, and associated emissions reductions dependent on duty cycle
- Reducing or eliminating the need to idle/load the engine to run the accessories while the bus is not in motion
- Reduced operating and maintenance costs for accessory systems
- Reduced internal and external noise and vibration
- Relatively small footprint within the structure of current diesel- and CNG-powered buses, including just one accessory belt drive

System Design

Figures 2-1 and 2-2 show the location of the system on a typical bus and a schematic of the system architecture, respectively.

Figure 2-1

Transit bus with REIL system (APS and generator)



BAE presented two options for the REIL system architecture—with and without a battery energy storage system (ESS).

Figure 2-2 depicts REIL with an ESS. As shown, all accessories are driven electrically in the REIL system with power coming from a belt-driven generator and distributed and managed through the APS.

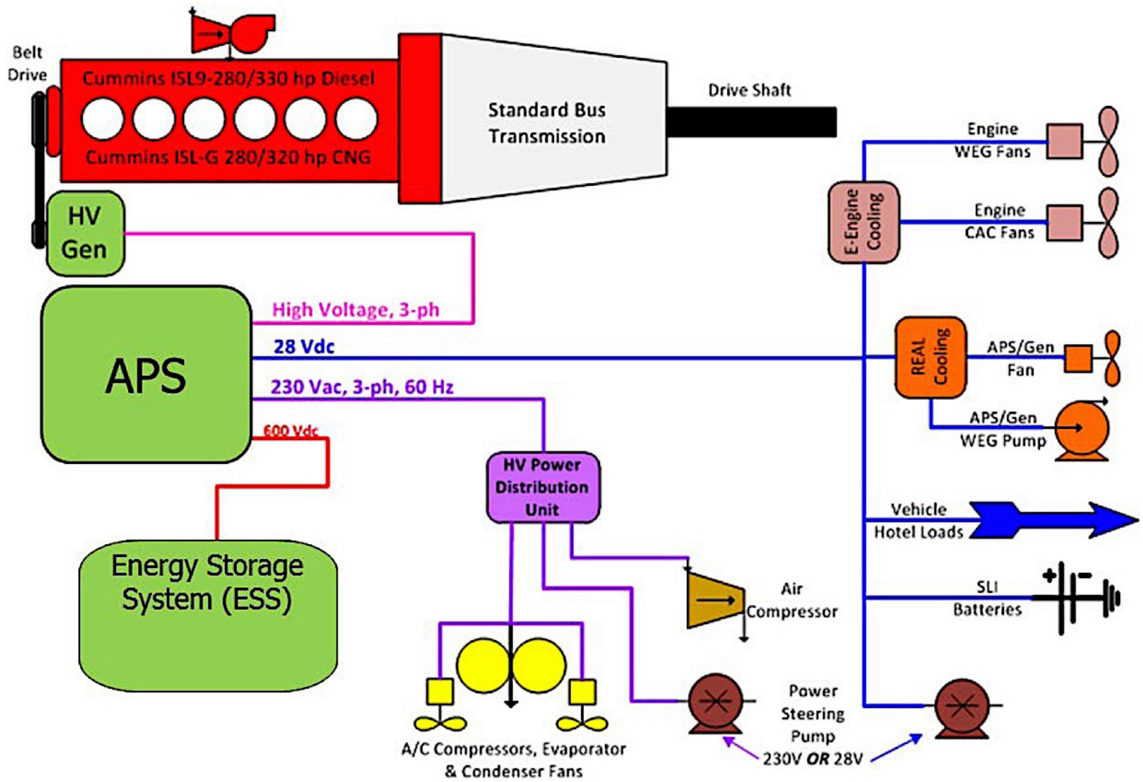


Figure 2-2

REIL system architecture (with ESS)

The APS brings in three-phase power from the generator and provides output to both 28 Vdc and 230 Vac systems. In addition, the APS may be connected to an ESS, which in this system operates at 600 Vdc.

Modes of Operation

Fundamentally, the REIL system has four modes of operation in response to the vehicle engine operating condition:

1. During accelerating or constant velocity cruising:
   a. Accelerator is depressed, engine speed is greater than 600–800 rpm, bus speed greater than zero.
   b. Engine is providing propulsion power.

   c. REIL system generator is generating power sufficient to power accessory systems and maintain ESS state of charge (SOC) regulation, as needed.

2. When coasting or braking:
   a. Accelerator pedal is lifted or brake pedal is depressed, engine dissipating kinetic energy from drive train, bus speed greater than zero.
   b. ngine being "back-driven" by drive train.
   c. REIL system generator goes to maximum generation capability, acting as an "electric retarder" powering accessories as needed and providing excess regenerative power to ESS. Regenerative energy stored by ESS during this mode is used to support accessory system power demand in Modes 1, 3, and 4.
3. During intermittent vehicle stops when on-route (e.g., bus stops, traffic lights, heavy traffic), typically less than 1–2 minutes in duration:
   a. Vehicle velocity is at or near zero, and engine is at idle speed
   b. REIL system ESS provides necessary power for accessory systems, generator does not generate power, thus unloading engine of all parasitic accessory load burden, reducing/minimizing inefficient idle fuel burn and emissions.
   c. Engine continues to idle unloaded, reducing fuel burn and powering the transmission oil pump to maintain necessary transmission functionality.
4. During long vehicle stops (e.g., end of route layovers, transfer stations, restroom/lunch breaks etc.) typically 5–30 minutes in duration:
   a. Bus at zero speed, parking brake set, driver or GPS (preferable) indicates bus is in predesignated long-term stop location.
   b. Engine is shut down, either automated though GPS (preferable) or by operator via a special designated "anti-idle" switch ("key-off" will disable the entire system as normal).
   c. REIL system ESS provides necessary power for continued accessory system operations (about 20 min @ 15 kW accessory draw or 45 min @ 7½ kW accessory draw).

There are several important points to understand relative to the REIL system as it relates to engine and transmission operation:

- There is no mode of operation in which the REIL system "assists" in propulsion. The REIL system is not a "propulsion hybrid," as it does not provide energy to the drive train or otherwise modify the propulsion related power/energy requirements of the engine and/or vehicle. The REIL system is an energy sink or energy absorption system only for the purpose of operating the electric accessory systems.

- Conventional drive train vehicles use standard automatic transmissions, which require engine rotational speed to drive the transmission's internal hydraulic pump necessary to maintain basic transmission functionality. Consequently, for short duration stops as noted in Mode 3 above, the engine cannot be shut down, as the bus is active in traffic and the transmission must maintain its functionality and be ready to instantly respond to operator commands.
- For dedicated longer-term anti-idle engine shut-down conditions (Mode 4), there are limitations on the frequency of these events imposed by the engine OEM design criteria.
- It is assumed that the automatic transmission will be a modern design incorporating "auto-neutral" functionality or equal, thereby minimizing torque converter slip/shear losses on the engine when the bus is stopped and in-gear.

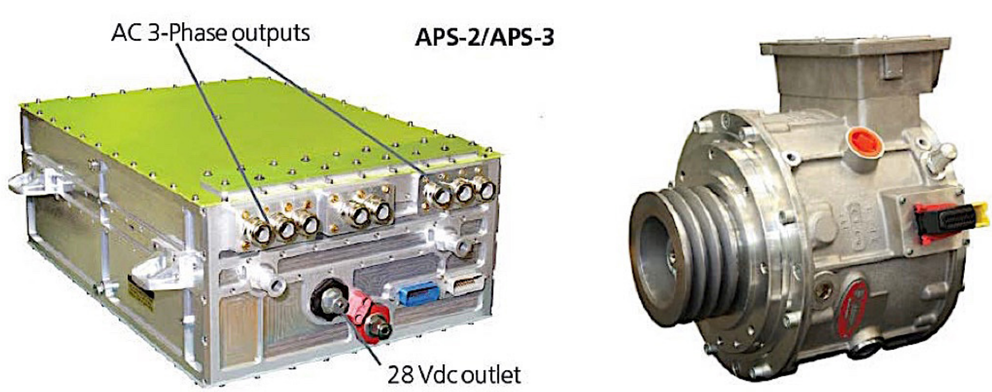
Bill of Materials

The primary components of the REIL system include the following:

- BAE Systems supplies (see Figure 2-3):
  - APS-3 Accessory Power Supply 115E4662G4
  - Generator 364A7807 (with drive pulley specified by bus OEM)
- Bus OEM supplies:
  - HVH250 mounting, belt drive system and application (w/ approval from engine OEM)
  - APS-3 mounting and application (w/approval from BAE Systems)
  - APS-3 and generator cooling system
  - HV-PDU (Power Distribution Unit)
  - High-Voltage cables (3-phase generator to APS-3 and 3-phase APS-3 to HV-PDU)
  - Low voltage cables (2-pole, APS-3 to 28V power distribution)
  - Electrified accessory systems
  - Power cables from HV-PDU to accessories

Figure 2-3

APS (left) and generator (right) for REIL system



SECTION

3

Testing Program Summary

Test Design

The testing performed by BAE Systems was designed to test both the basic operational modes of the REIL system and its operation under an actual duty cycle loading using a complete engine test stand. There are two stages in the test: 1) system characterization using a motor dynamometer test stand, and 2) system operational duty cycle performance using complete engine test stand with simulated traction loads.

Stage 1: System Characterization Test

System characterization tests consisted of the following:

- *Generator speed control* – characterize and calibrate the APS firmware to ensure safe and accurate control of the generator within 10% of nominal, across the operational speed range.
- *Verify operational mode transitions* – verify that the APS OS and AS are stable during changes in operating mode (between startup, operate, shutdown)
- *Load management (system response to load steps)* – verify that load management control engages when power generation is not sufficient to maintain the DC link voltage
- *Generator line start test* – verify that the REIL system output remained stable during an electric motor line start event

Figure 3-1 shows four views of the dynamometer test setup for the system characterization tests, and Figure 3-2 is a schematic of the system.

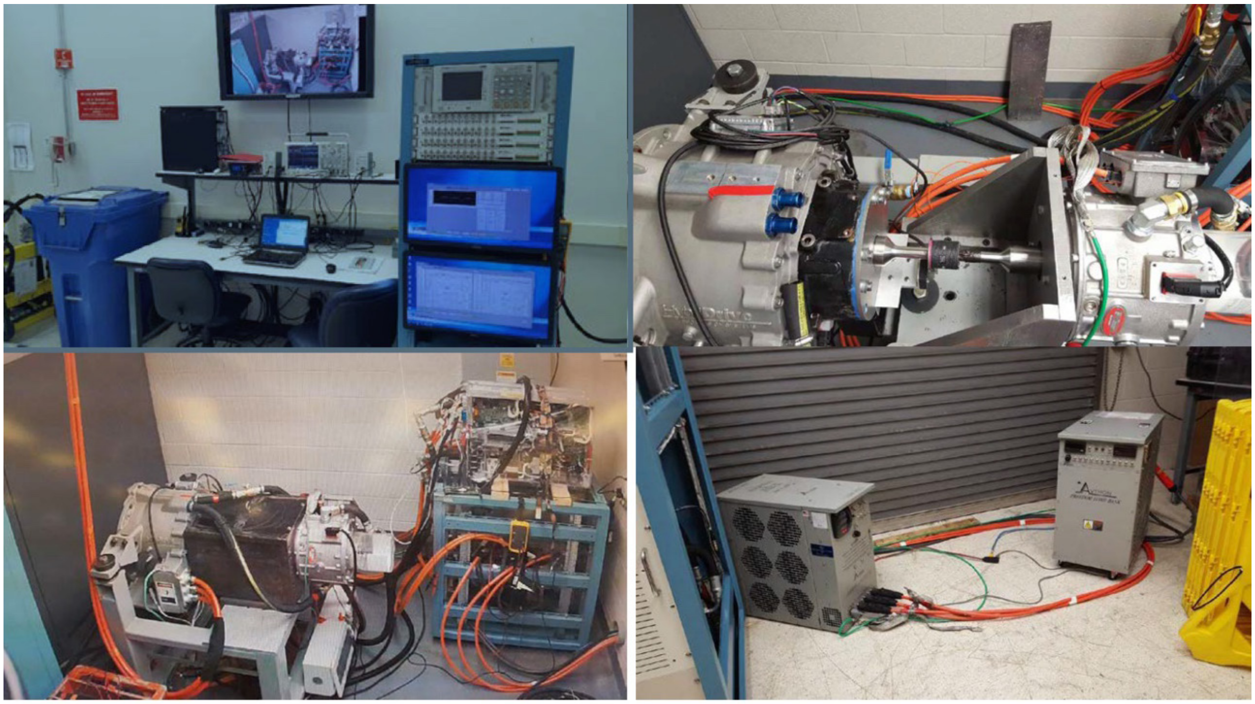


Figure 3-1

Dyno Stand control interface (top left), Dyno motor, generator, and torque cell (top right), Dyno and APS (lower left), and AC and DC load banks (lower right)

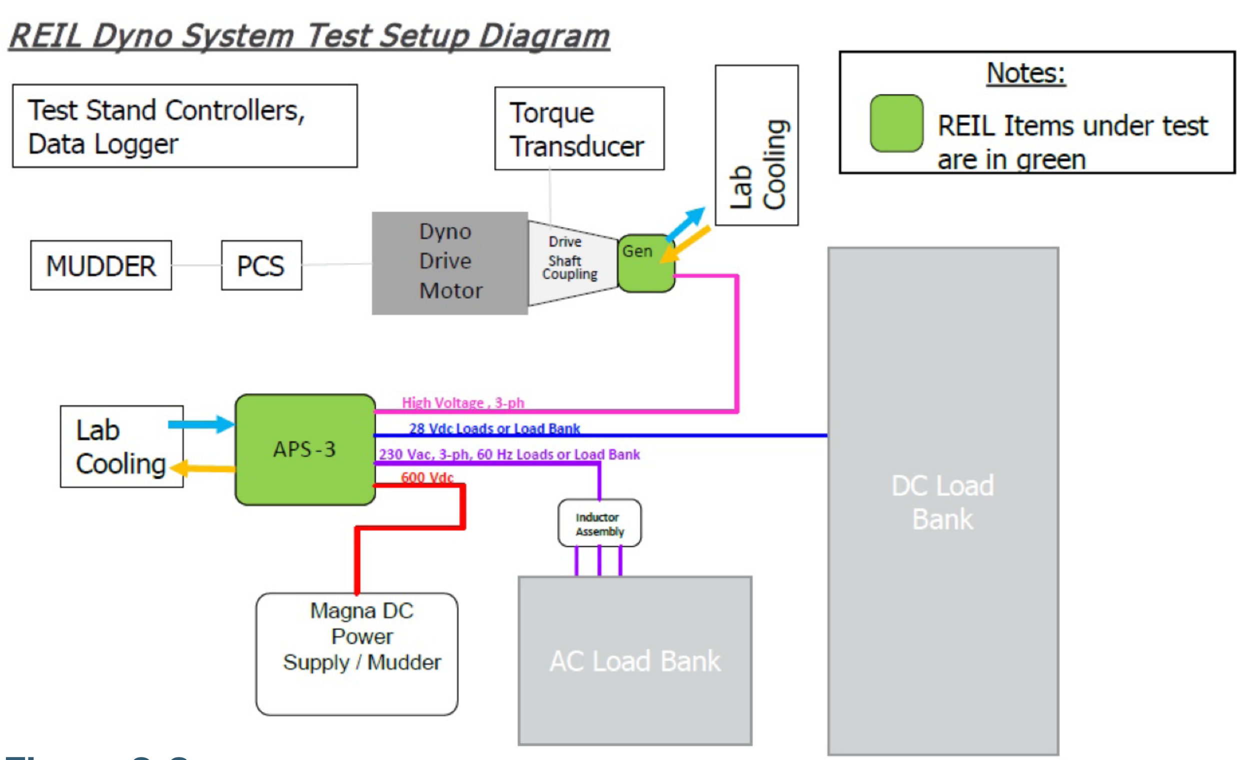


Figure 3-2

Block diagram of REIL dynamometer setup

Stage 2: Duty Cycle Test

The system operational duty cycle performance tests used a complete Cummins ISL engine test stand with simulated traction loads. The tests consisted of the following:

- *REIL System control stability verification during engine start up and shutdown* – investigate the impact to system stability during startup and shutdown with an analog load applied to the DC and AC outputs of the system.
- *System load transitions* – examine the system response at different speeds to different load step conditions. These tests were considered a "Pass" if the system remained stable when subject to the load transitions.
- *Duty cycle test* – verify the dynamic response of the REIL System firmware and software controls when engine speed and the generator load change during an actual duty cycle

For the duty cycle test, BAE Systems gathered several weeks of vehicle performance data on a MARTA transit bus operating in normal routes. These data were used to develop a speed and load duty cycle that BAE Systems used to test the dynamic response of the REIL System. Figure 3-3 is a representation of engine speed and generator load for the MARTA duty cycle data used in this test; Table 3-1 shows the cases studied. Figures 3-4 and 3-5 are photos of the full engine test stand setup, with corresponding block diagram in Figure 3-6.

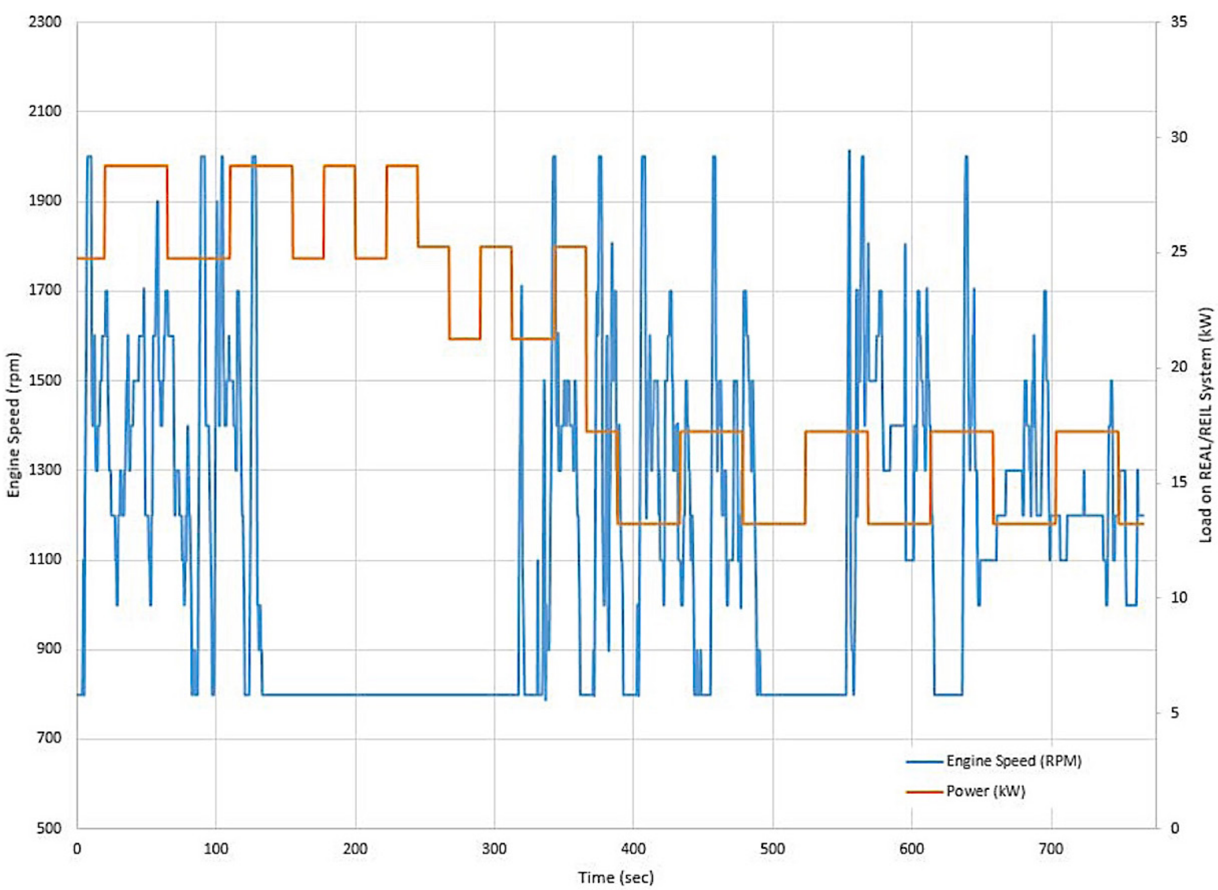


Figure 3-3

Composite duty cycle

Table 3-1

Duty Cycle Data Cases Gathered for Analysis

Duty Cycle Data Set	Distance	Duration	Average Speed	High Ambient
MARTA Case A	300 mi	19 hrs	16 mph	71°F
MARTA Case B	165 mi	18 hrs	9 mph	87°F
MARTA Case C	190 mi	16 hrs	12 mph	80°F

Figure 3-4

Engine test stand and ISG used to simulate vehicle transmission loading

Figure 3-5

Generator belt and pulley drive subsystem on engine test stand

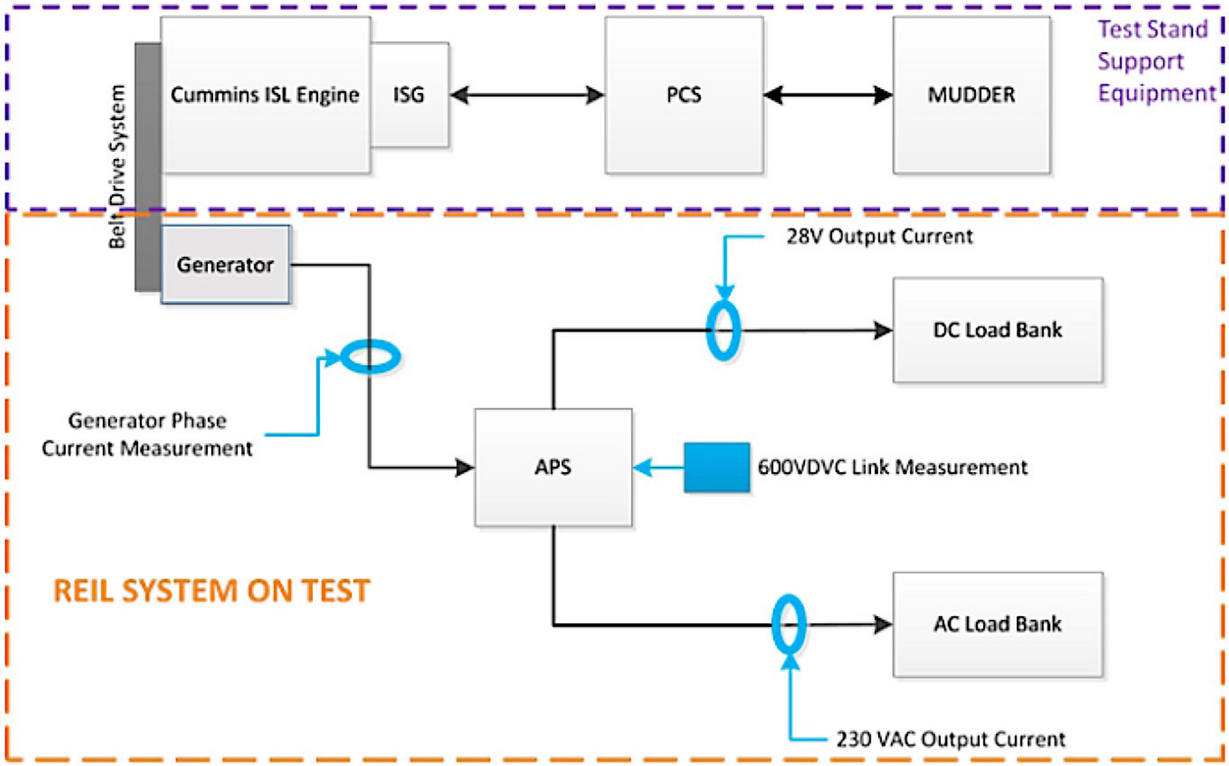


Figure 3-6

Block diagram of engine test stand

Test Results

All tests were completed successfully and yielded the results shown in Table 3-2.

Table 3-2

System Characterization and Duty Cycle Test Results

	Test Description	Result Demonstrated
Stage 1: System Characterization (Dynamometer)	Generator speed control calibrations	Safe control over operational speed range
	Verification of operational mode transitions	Proper transitions between startup-to-operate and operate-to-shutdown
	Load management (system response to load steps)	Proper load management control across multiple load steps
	Generator line start test	1) Commanded and measured generator torque match 2) APS HV DC link stable with APS pre-existing electrical loads
Stage 2: Duty Cycle (Full Engine Stand)	System control stability during engine start-up and shutdown	Startup and shutdown occurred smoothly and without APS faults
	System load transitions	Stability achieved at 18 combinations of engine speed and load transitions
	Duty cycle test	System provided stable power output at expected levels across demand loads of MARTA duty cycle

The tests demonstrated that the system was able to meet operational mode transitions and changes in loads and to respond to system commands and safety protocols. Three specific key results are as follows:

- Belt slip at the generator was within design thresholds, which is important since slip leads to inefficiencies and reduced belt life
- REIL system preformed stably during the stop/start cycle
- Step changes in load were handled in a stable manner

Refer to the independent evaluation in Appendix B for additional observations

SECTION

4

Market Potential and Readiness

Efficiency Simulation and Evaluation

One of the primary objectives of this study was to estimate real-world efficiency gains expected from the REIL system, the results of which are used in the overall economic assessment and market readiness evaluation. This also included a determination of any associated emissions reductions. After the system characterization and duty cycle tests confirmed stable and reliable operation, the team developed computer simulations to estimate the anticipated fuel efficiency improvements. BAE Systems simulations focused on the REIL system with an ESS since the bulk of the efficiency improvements were expected to occur as a result of energy recovery and storage. However, BAE Systems also estimated that a small efficiency improvement could be expected for systems without an ESS due to more efficient accessory operation than in a baseline case without REIL (see further discussion on this topic below). Furthermore, as part of the third-party evaluation process (see Section 5 of this report), UT-CEM performed independent simulations that included both ESS and non-ESS configurations. See Appendix B for more detailed information regarding the third-party simulations. Full BAE Systems test and simulation results were documented via a memorandum distributed to the project team [2].

The team performed computer simulations on cases consisting of actual duty cycle data collected from MARTA buses during the project and were representative of the routes the REIL system would be required to operate under (see Table 3-1). The cases consisted of different speed profiles and ambient temperatures used to assess the effectiveness of the REIL system in various realistic operational scenarios. The specific duty cycle dataset includes the following variables vs. time, collected at a 2 Hz sample rate over each of the three routes—engine speed, vehicle speed, auxiliary engine load %, fuel usage, and throttle percentage.

The simulation findings presented by BAE Systems also included the following conclusions. First, there was a strong correlation between baseline mechanical accessory loads and ambient temperature due to the HVAC and engine cooling loads. This is in line with CTE's vehicle and route modeling experience, which has consistently shown clear trends of the effects of ambient temperature (and associated HVAC usage) on bus efficiency. Second, BAE Systems concluded that the savings of the REIL system associated with regenerative braking and start/stop operations were higher for routes with lower average speeds, and the savings decreased as the average speed of the cycle increases. This was expected, as lower speed routes are typically associated with more stop/start and braking opportunities. Third, savings associated with regenerative braking and start/stop operations decreased as the overall accessory load demand increased. As noted previously, high HVAC usage is a primary driver of accessory loads and would apply across a route, somewhat offsetting efficiency gains achieved during start/stop operations.

Finally, the results from simulation showed that the vehicle efficiency (in terms of miles per gallon) across the duty cycles studied was **improved by 10–15% in a REIL system with ESS**. This is because the REIL system recovers braking energy during deceleration and uses this "free" waste energy to power accessory systems. Although there is no such energy recovery for the REIL system without ESS, BAE Systems estimated that a minor efficiency improvement (<5%) could be realized due to more efficient accessory operation and control. UT-CEM confirmed this improvement via independent simulations performed on the same datasets as part of their assessment (Appendix B), whereby a **2–4% improvement was realized in a REIL system without an ESS**.

Economic Assessment

Cost of the System

The REIL system would be offered as an option on the purchase of new diesel and CNG buses. The total upcharge is estimated to be $30,000–$45,000 for a system without the ESS and $47,500–$62,500 for a system that includes the ESS. If potential Federal cost share programs are accounted for (80%/20% for diesel buses and 88%/12% for CNG buses), then the resulting costs would be as shown in Table 4-1.

Table 4-1

REIL System Cost Impacts

	REIL without ESS	REIL with ESS
For CNG Buses		
Base bus price (est.)	$500,000	$500,000
Total REIL upcharge	$30,000–$45,000	$47,500–$62,500
Total bus price	$530,000–$545,000	$547,500–$562,500
REIL System agency share (18% w/federal subsidy)	$5,400–$8,100	$8,550–$11,250
Diesel Buses		
Base bus price (est.)	$450,000	$450,000
Total REIL upcharge	$30,000–$45,000	$47,500–$62,500
Total bus price	$480,000–$495,000	$497,500–$512,500
REIL System agency share (20% w/federal subsidy)	$6,000–$9,000	$9,500–$12,500

Maintenance Cost Comparisons

As described earlier, the electrified components comprising a REIL system are expected to achieve higher reliability and associated lower maintenance task burden. The major systems improved by the implementation of a REIL system are as follows:

- *HVAC* – replacement of belt-drive, clutched, soft-line, non-hermitic reciprocating A/C compressor with factory-charged self-contained hermetic A/C systems with electric hermetic scroll compressor(s)
- *Power Steering* – replacement/relocation of engine-driven hydraulic power steering pump from engine compartment to 28V electric-hydraulic unit located in front of vehicle near steer axle
- *Air Compressor* – replacement of engine-driven, oil-lubricated reciprocating air-compressor with electric oil-less scroll compressor
- *Alternator* – replacement of the belt-drive 28V alternator with solid-state DC/DC converter
- *Belts/Pulleys* –reduction in the number and type of belts and pulleys due to electrification of the above systems

To analyze the impact of these system improvements, CTE and MARTA worked together to obtain detailed records of approximately 7,000 individual maintenance tasks representing 35,000 labor hours performed on the five key traditional accessory systems listed above for the 568 vehicles in the MARTA fleet during the full year period July 2016–June 2017. CTE initially assessed this maintenance activity at a very granular level to properly categorize each task into two maintenance types (preventive vs. repair) and two cost types (labor and parts) for each system. This resulted in the cost structure for each accessory system shown in Figure 4-1.

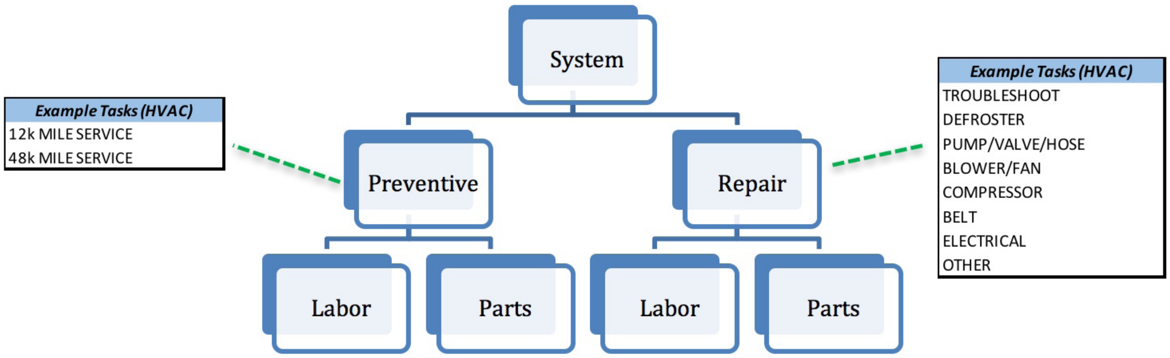


Figure 4-1

Maintenance cost analysis structure

BAE Systems then evaluated the underlying detailed replacement and inspection tasks (see example task categories above) to determine the estimated percentage reduction in maintenance cost expected for each task type if the old system were replaced with an electrified REIL system. Once applied to the actual dollar costs for each task and rolled up to the system and maintenance type level, the resulting distribution of savings and impact is shown in Table 4-2. As an example, the cost to maintain the HVAC system represents 48% of the total for all five systems combined, and with a REIL system installed, a 27% reduction in those costs (25% reduction in preventive maintenance cost and 28% reduction in repair costs) would be expected relative to a traditional accessory system.

Table 4-2

REIL System Maintenance Cost Savings and Distribution

	Distribution of Maintenance Costs	REIL % Cost Reduction from Traditional		
	Percent of Overall Cost	*Preventive*	*Repair*	*Total*
HVAC	48%	25%	28%	27%
Power steering	24%	0%	24%	24%
Air compressor	5%	50%	50%	50%
Alternator	11%	100%	73%	80%
Belt/pulley	13%	44%	25%	31%
Overall	100%	39%	32%	34%

Based on the maintenance data collected, the combined 34% cost reduction in the maintenance of these five systems relative to conventional systems results in an overall estimated annual savings per bus of $1,450.

Fuel Cost Savings

The fuel efficiency improvements denoted above (2–4% for a REIL system without an ESS and 10–15% for a system with an ESS) result in direct fuel cost savings that are included in evaluating the market potential and ROI of such a system. This fuel cost savings is generalized across the US market by applying these improvements to baseline fuel efficiencies and mileage extracted from Argonne National Laboratory's GREET data as part of its Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool [3]. The baseline fuel efficiencies and mileage used in this analysis are as follows:

- 4.1 mpg for diesel
- 3.5 mpg (diesel equivalent) for CNG
- Baseline mileage–35,000 for a transit bus

Assumed fuel pricing for this analysis is shown below, extracted from the US Department of Energy's Clean Cities Alternative Fuel Price Report [4]. The following prices are based on average retail price for private refueling stations, with CNG numbers converted to dollars per diesel gallon equivalent (DGE):

- $3.05 per gallon for diesel
- $2.19 per DGE for CNG

The resulting fuel efficiencies and expected annual fuel savings are shown in Table 4-3.

Table 4-3

REIL System Maintenance Cost Savings

	REIL without ESS	REIL with ESS
CNG Buses		
Baseline efficiency (mpg)	3.5	3.5
Efficiency w/REIL (mpg)	3.57–3.64	3.85–4.03
Annual gallons saved (DGE) per bus	196–385	909–1,304
Annual fuel cost savings per bus	$429–$842	$1,991–$2,857
Diesel Buses (per bus)		
Baseline efficiency (mpg)	4.1	4.1
Efficiency w/REIL (mpg)	4.18 -4.26	4.51–4.72
Annual diesel gallons saved per bus	167–328	776–1,113
Annual fuel cost savings per bus	$511–$1,001	$2,367–$3,396

ROI Analysis

Taking all of the information in the previous sections into account, a simple payback analysis reveals that with adequate additional funding assistance (e.g., US Code Title 49/5339 Bus & Bus Facilities grant or equivalent), the REIL system can be an attractive investment for a transit operator evaluating this upgrade option when purchasing new buses, with payback periods of 2–4.6 years, depending on whether a system with or without an ESS is chosen. However, without funding assistance, payback period would be 10–24 years, which is beyond what would be considered attractive considering the typical useful life of a bus.

From a long-term financial standpoint, REIL systems with ESS included provide the best investment due to the substantially higher efficiency gains (and therefore fuel cost savings) they provide versus systems without an ESS. This helps offset the incremental upfront costs to purchase and install the system.

Table 4-4 is a high-level summary of the payback analysis.

Table 4-4

REIL System Payback Analysis

	REIL without ESS	REIL with ESS
CNG Buses		
Upfront cost of system	$30,000–$45,000	$47,500–$62,500
Est. cost net Federal subsidy (5339(c))	$5,400–$8,100	$8,550–$11,250
Maintenance savings per bus	$1,450	$1,450
Fuel savings per bus	$429–$842	$1,991–$2,857
Total O&M annual savings per bus	$1,879–$2,292	$3,441–$4,307
Payback period (years, no subsidy)	13–24	11–18
Payback period (years, with subsidy)	2.4–4.3	2.0–3.3
Diesel Buses		
Upfront cost of system	$30,000–$45,000	$47,500–$62,500
Est. cost net Federal subsidy (5339(c))	$6,000–$9,000	$9,500–$12,500
Maintenance savings per bus	$1,450	1,450
Fuel savings per bus	$511–$1,001	$2,367–$3,396
Total O&M annual savings per bus	$1,961–$2,451	$3,817–$4,846
Payback period (years, no subsidy)	12–23	10–16
Payback period (years, with subsidy)	2.4–4.6	2.0–3.3

Emissions Reduction

In addition to providing direct cost benefits, the fuel savings realized from increased efficiency also translate into emissions reductions due to the fewer (diesel or diesel equivalent) gallons consumed. To estimate CO_2 emissions benefits, the team used data compiled by CARB regarding energy density and carbon intensity to determine the reduction in CO_2 emissions resulting from the improved fuel economy [5].

Emissions reductions are essentially the same for REIL systems in CNG buses compared to diesel buses largely because although carbon intensity (gCO_2e/unit of energy) is lower for CNG, resulting in lower emissions per DGE, the baseline fuel efficiency (miles/DGE) of CNG buses is also lower. These two relative effects, combined with slightly higher energy density (energy per DGE) for CNG, rendered no significant difference in the overall reduction in CO_2 emissions between REIL systems installed in a diesel bus and a CNG bus.

For REIL systems without an ESS, operators can expect an emissions reduction of 66–129 grams of CO_2e per mile of travel. For a bus that averages 35,000 miles per year, this equates to 2.3–4.5 metric tons of reduced emissions annually per bus. For REIL systems with an ESS, the savings is expectedly more substantial, with an emissions reduction of 304-437 grams CO_2e per mile or an estimated 11– 15 metric tons of greenhouse gas (GHG) reduction annually per bus. Based on these results, operating one bus outfitted with a REIL system including an ESS for one year is the equivalent of taking 2–3 cars off the road for the same period [6]. Therefore, operators can substantially reduce their carbon emissions by increasing the efficiency and simplicity of the accessory systems installed on their non-electric fleet by using a REIL system. Clearly, the total impact is even more substantial for operators with a large number of conventionally-fueled vehicles that are coming due for replacement. Table 4-5 provides a summary of unit emissions reductions expected from the REIL system.

Table 4-5

5 Expected Emissions Reductions

Reductions for Each Bus	REIL without ESS	REIL with ESS
Grams CO_2e per mi	66–129	304–437
Annual metric tons CO_2e (@35k mi/yr)	2.3–4.5	11–15
# passenger cars emissions equivalent	0.5–1.0	2–3

SECTION

5

Independent Evaluation Findings

As part of this project, a third-party evaluation was performed by Michael Lewis, Senior Engineering Scientist at The University of Texas at Austin–Center for Electromechanics (UT-CEM). The purpose of this evaluation was to determine the overall effectiveness of this research and demonstration project and the validity of its results. Mr. Lewis was an active participant in monitoring this project and was present for the final test results readout by BAE systems in March 2018 as well as follow-up discussions in the months afterward to discuss results and future steps. (Refer to Appendix B for the full report.) A summary of the primary findings is as follows.

First, UT-CEM agreed with the overall approach for the system characterization and duty cycle tests performed in the BAE Systems lab. It made a point that simulating the battery energy storage by using a power supply/load was a small shortcoming. However, it also acknowledged that the laboratory demonstration served to advance the technology readiness level of the system substantially, citing successful belt slip tests and stable performance during start/stop and load step tests.

Second, UT-CEM deemed as valid the various results of the system simulation and resulting efficiency improvement estimates. It also performed its own independent simulations using historical duty cycles, the results of which were in good agreement and further validated the BAE Systems' simulation results as well as their efficiency savings estimate for the non-ESS system.

Third, UT-CEM evaluated the findings of the team regarding REIL system market potential and ROI and agreed with the overall conclusions, including that relative to the unsubsidized total cost of the REIL system, the ROI provided by maintenance savings alone was not apparent from the data available, especially for the system without an ESS. However, fuel savings combined with maintenance savings can help make the system more financially attractive, and the best value for transit agencies is with a REIL system with an ESS. The potential for Federal subsidies makes the payback for both system configurations substantially more competitive.

UT-CEM's overall assessment of the execution of the project and results of the work was positive, noting that the project results demonstrated great promise for a REIL system to reduce fuel consumption in traditional buses. UT-CEM also noted that all the work leading up to and including this project have led to a large procurement of buses outfitted with the REIL system.

SECTION

6

Conclusions and Future Steps

This project was a successful first step in evaluating the technical feasibility and realization of benefits for a REIL system in an effort to increase the efficiency and maintainability of accessory systems for buses with traditional diesel- and CNG-fueled propulsion systems. Through the specification and build-out of an actual system, testing to validate technical robustness and readiness, simulation to estimate benefits using actual route data, and a market and financial assessment, the team established that a REIL system is both a feasible and beneficial technology to further develop and optimize for the marketplace.

The design, build, and test phase proved that a REIL system can be built and operate as expected, including demonstrating stability during various transitions and loads that would be expected in service. Furthermore, simulation and analysis of test data verified that the system does provide efficiency gains, especially the variant that includes an ESS. The ESS version provides the additional operational benefit of engine-off operation during stop/start conditions. The fuel efficiency gains also result in associated emissions reductions. Finally, there is a place in the market for such a system. Based on current technology and anticipated pricing, REIL provides the best ROI when including an ESS, especially when coupled with applicable and available subsidies. Table 6-1 is a summary of the maximum estimated benefits expected from a REIL system based on the analysis, data, and assumptions used in this study.

Table 6-1

Maximum Estimated Benefits from REIL System with ESS

Benefits Realized per Bus	REIL with ESS
Annual maintenance savings	$1,450
Annual fuel savings	$3,396 (1,113 DGE)
Annual emissions reductions	15 MT CO_2e (~3 cars equivalent)

From the initial planning stages of this project, the team considered potential future activities that are now considered prudent and valid based on the above results. First, the team will pursue additional opportunities to install and test the latest system (with and without an ESS) in revenue service on one or more New Flyer buses in the MARTA fleet. Second, the team will continue to use the results of this study to improve the overall system design and overall packaging and installation plan. BAE Systems is also developing its next-generation auxiliary power supply and distribution system, called the iAPS. The data from this study can be used, along with laboratory tests of the new iAPS, to evaluate the efficiency benefits of including the iAPS in future REIL architectures. Finally, the team plans to pursue real-world tests of an iAPS- enabled REIL system on an actual New Flyer diesel or CNG bus in revenue service to further the operational understanding and advancement of this technology.

APPENDIX

A

Project Work Plan

Task 1 – System Design, Validation, and Supply

1.1 Develop Detailed Design Specifications – BAE, with input from the project team, will develop detailed specifications to guide the design of the REIL system.

1.2 Complete Final System Design (including Generator, APS, High Voltage Distribution, ESS) – BAE Systems will complete the final mechanical and electrical design of the REIL system, including all hardware specifications and control logic, but not including packaging of the system into the vehicle.

1.3 Specify Components and LV Wiring – BAE systems will produce a system bill of materials (BOM) and specify details for the low voltage wiring sub-system.

1.4 Procure/Build High Voltage CAN Bus, Wiring Harness, and Wiring – BAE will produce (by procurement or build) the high voltage CAN bus, wiring harness, and wiring for the REIL system.

1.5 Procure/Build REIL System Hardware – BAE will complete building the REIL system, including all hardware, connections, and control logic.

1.6 Validate and Test System – BAE will install the REIL system connected to a Cummins ISL engine and all appropriate auxiliary loads in a BAE engine test pod. Tests will be performed to validate the REIL system functionality and performance, and to establish fuel economy and emissions improvements in the lab environment.

1.7 Complete Preliminary Install Plan – BAE, with support from New Flyer, will complete a preliminary installation plan that will identify packaging requirements and any potential installation issues for the REIL system when installed in diesel and CNG transit buses.

Task 2 – REIL Market Evaluation and Trade Study

2.1 Characterize the MARTA Duty Cycle and Operating Environment – CTE, with support from MARTA, will use real-world drive cycle data from transit buses on MARTA routes to characterize the MARTA duty cycle and operating environment. Drive cycle data includes speed and roadway grade profiles, including layovers and dwell periods, for given routes.

2.2 Perform Hardware Simulation using MARTA Duty Cycle and Report Results – BAE will use the real-world drive cycle data (developed in Subtask 2.2) to simulate revenue service operation in its engine test pod. Appropriate accessory loads will be integrated within the test pod to emulate real-world transit bus accessory loads, such as the HVAC system, power steering, cooling fans, and air compressor. Simulation results, including fuel economy, emissions, and general system performance will be recorded.

2.3 Perform Market Analysis and Relevant Trade Studies – The project team will use the simulation results and performance metrics to gauge the commercial potential of the REIL system. CTE will lead development of the market analysis using information produced from the simulation and current market assumptions. The project team will accomplish trade studies to determine if and how market potential and emissions benefits can be improved. New Flyer will provide feedback as the vehicle OEM on the effectiveness and potential of REIL to serve as a standard product offering. MARTA will provide feedback as a potential end-user and will evaluate whether the system can provide value to its service operations.

Task 3 – Independent Evaluation

3.1 Independent Test and Evaluation – A University of Texas faculty member will receive a written summary of project activity and task deliverables. The evaluator will perform an independent evaluation of the overall effectiveness of the research and demonstration. At minimum, the evaluator will report the following:

- Team's ability to produce project deliverables within the project schedule.
- Team's ability to produce project deliverables within project budget.
- Technology Readiness Level (TRL) of the REIL system.
- Verification of the perceived efficiency improvements and resulting ROI of the REIL system.
- Overall effectiveness of the research and demonstration.

3.2 Independent Evaluation Reporting – The independent evaluator will submit a final report summarizing the evaluation results. This report will be included in the final version of CTE's final project report.

Task 4 – Project Management

4.1 Kickoff Meeting – CTE will lead a project kickoff meeting with the project team and all relevant stakeholders, including FTA. Objectives of the meeting will be to provide introductions and roles, review the Scope of Work, schedule, project requirements, and next steps, and answer any questions so that all parties are well informed at the outset of the project.

4.2 Quarterly Reporting – CTE, with support from the project team, will develop and provide a quarterly report to FTA that meets the requirements of FTA Circular 6100.1D, at a minimum. In particular, the report will provide status updates, cost and cost-share tracking against the project budget, and schedule tracking against the project plan.

4.3 In-Service Data Collection and Reporting – CTE, with support from BAE and MARTA, will categorize and report Subtask 2.2 simulation results.

4.4 Final Reporting – CTE, with support from the project team, will develop and provide a final report to FTA that meets the requirements of FTA Circular 6100.1D, at a minimum. In particular, the report will provide technical results of the project, evaluation criteria results, if the project met objectives and goals, final cost summary, and recommended next steps.

APPENDIX

B

Evaluation of Reduced Engine Idle Load (REIL) System for Conventional Propulsion Diesel and CNG Buses Development, Validation, and Market Study Program – Third-Party Evaluation Report

Date: May 4, 2018

Submitted by: The University of Texas at Austin–Center for Electromechanics (UT-CEM)
Mr. Michael Lewis, Senior Engineering Scientist
(512) 232–5715, mclewis@cem.utexas.edu

Submitted to: Center for Transportation and the Environment
Mr. Blake Whitson, Technical Project Manager
(404) 386–3400, blake@cte.tv

Project Description and Approach

Under the FTA Bus Efficiency Enhancement Research and Demonstration (BEERD) Program, the Center for Transportation and the Environment and project partners BAE Systems, New Flyer, and MARTA studied, developed, and demonstrated a Reduced Engine Idle Load (REIL) system. The REIL system is expected to improve the fuel efficiency of a vehicle by replacing the traditional mechanical linkages between the engine crankshaft and non-propulsion parasitic loads with a belt-driven electric generator, energy storage system (ESS), accessory power system (APS), and electric accessories. The REIL system replaces the unmanaged mechanical loads of vehicle accessories, such as the HVAC system, power steering pump, air compressor, 28V supply and cooling fans, on a conventional diesel or CNG engine with managed, electrically-driven loads. The system architecture also allows periods of engine-off accessory operation, which is especially beneficial on routes with long layovers and dwell periods. The team considers the project to be a first-of-its-kind effort to bring a multimode electric accessory "power system" to the conventional-propulsion bus market, taking advantage of both the efficiency and environmental benefits of hybridization.

During the project, efficiency improvements were estimated by demonstrating the REIL system hardware in a BAE Systems engine test pod that was configured to imitate a real-world MARTA bus duty cycle and used a Cummins ISL engine. In addition, BAE performed computer simulations on multiple MARTA duty cycles/routes of the REIL system in configurations with the ESS.

The University of Texas at Austin–Center for Electromechanics (UT-CEM) participated in a final review meeting at BAE Systems in Endicott, NY, on March 27, 2018. The meeting included technical review presentations outlining the system architecture with simulation and demonstration test results. In addition, UT-CEM witnessed a demonstration of the REIL system in a BAE test pod. This report serves as a third-party evaluation by UT-CEM of the outcomes of the REIL project under the FTA BEERD Program.

REIL System Efficiency Improvement

BAE presented two options for the REIL system architecture, with and without a battery ESS. Figure B-1 depicts REIL with an ESS. As shown, all accessories are driven electrically in the REIL system with power coming from a belt-driven generator and distributed and managed through the APS (accessory power system). The APS brings in three-phase power from the generator and provides output to both 28 Vdc and 230 Vac systems. In addition, the APS may be connected to an ESS, which in this system operates at 600 Vdc.

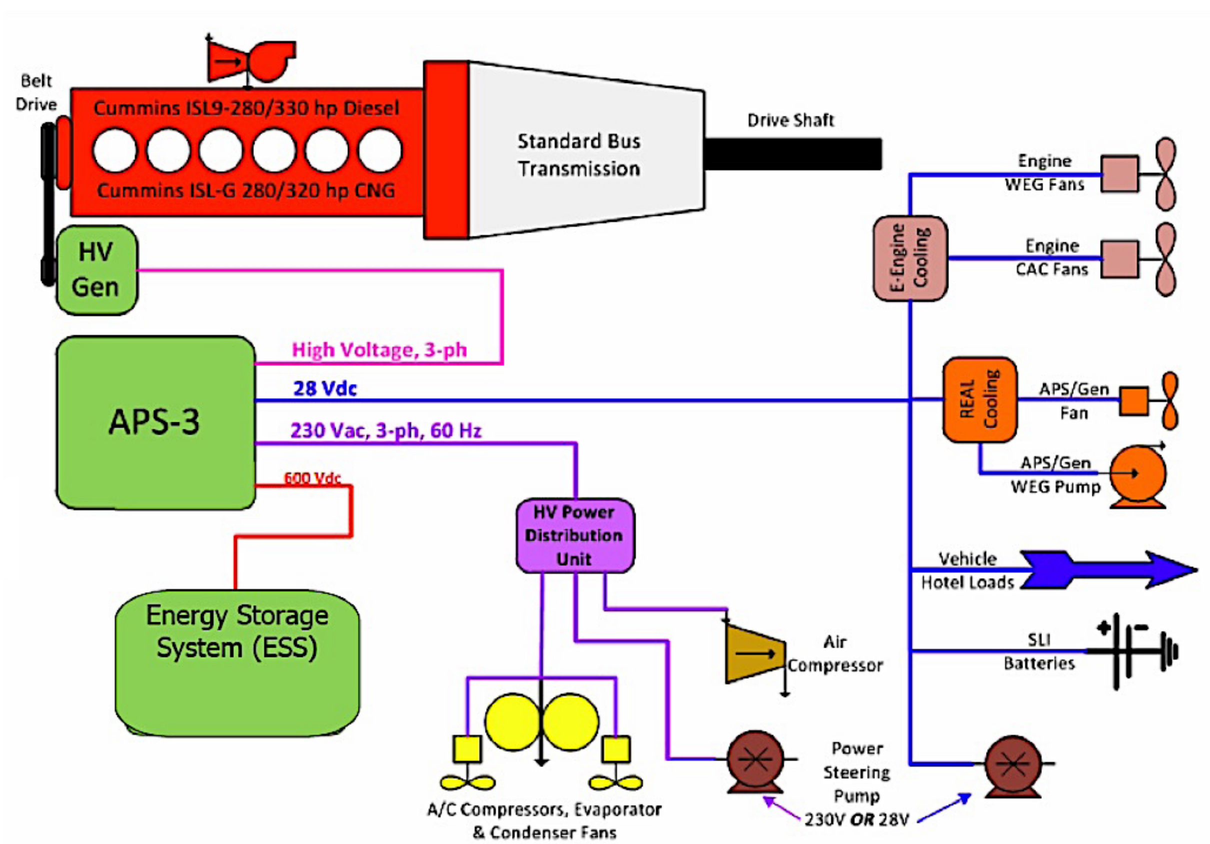


Figure B-1

BAE REIL system architecture

BAE presented simulation results to quantify the expected fuel efficiency enhancement potential of the REIL with an ESS. These simulations relied on duty cycle date collected from MARTA buses during the project. The duty cycle data included engine speed, bus speed, and auxiliary loads versus times. An example of the data collected is shown in Figure B-2.

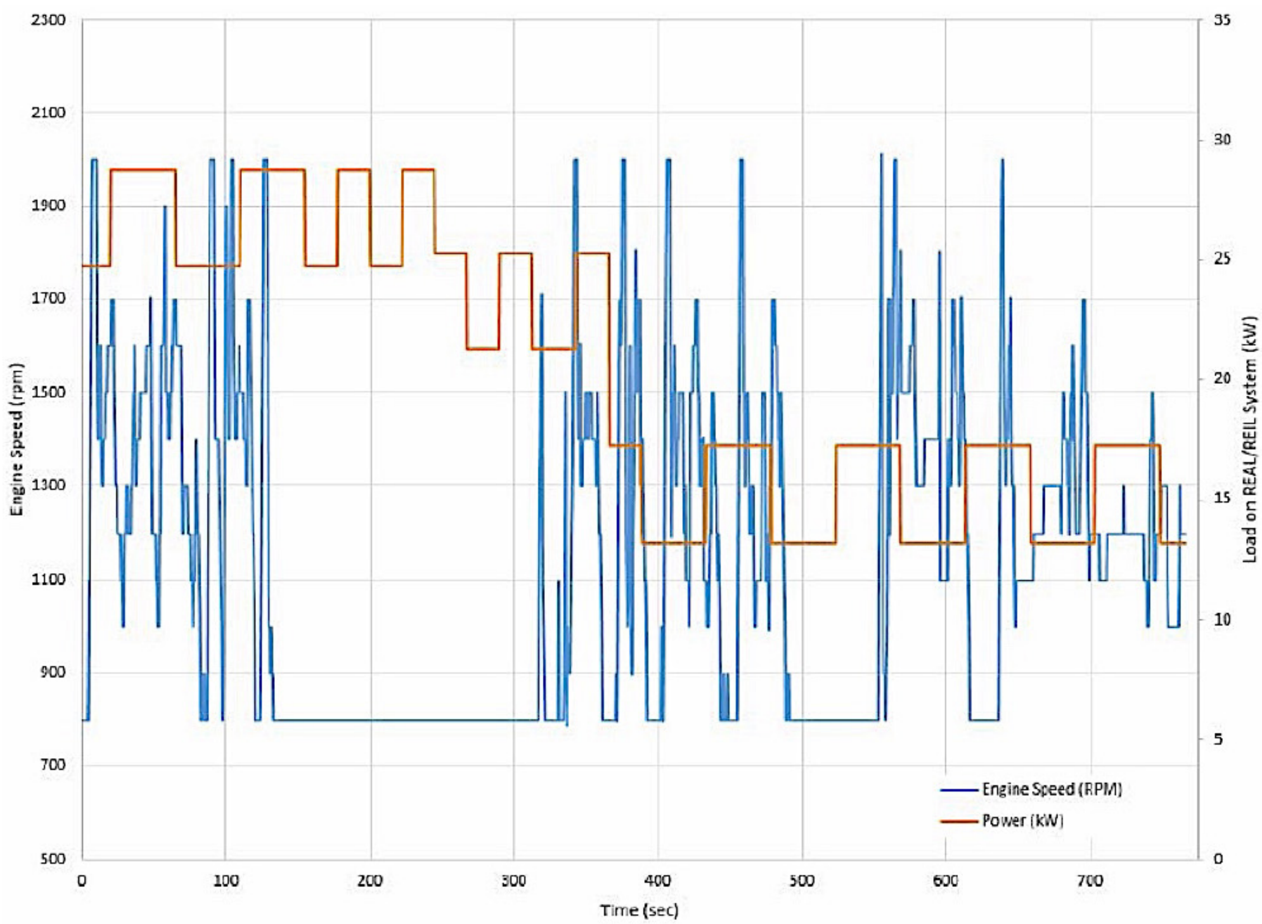


Figure B-2

Duty cycle data collected during project

The simulations were performed on various data sets with different average speeds and ambient temperatures to study the effectiveness of the REIL system in various operational scenarios. Three cases were presented, which are summarized in Table B-1.

Table B-1

Duty Cycle Cases Simulated by BAE

Duty Cycle Data Set	Distance	Average Speed	High Ambient
MARTA Case A	300 mi	16 mph	71°F
MARTA Case B	165 mi	9 mph	87°F
MARTA Case C	190 mi	12 mph	80°F

The findings, as presented by BAE, showed that the efficiency of the bus had a strong correlation to the ambient temperature, i.e., the HVAC load. This is to be expected, as UT-CEM's prior experience in bus modeling and evaluation has seen similar trends. It was also noted by BAE that the stop/start savings of the REIL system increased with lower average speeds and decreased with higher accessory loads. Once again, this is a natural conclusion, as a lower average speed typically implies more stops, thus taking advantage of the stop/start attributes of REIL. In addition, since the HVAC loads do not stop during these stop/start cycles, it would be expected that the benefits of stop/start are less effective in duty cycles with higher accessory loads.

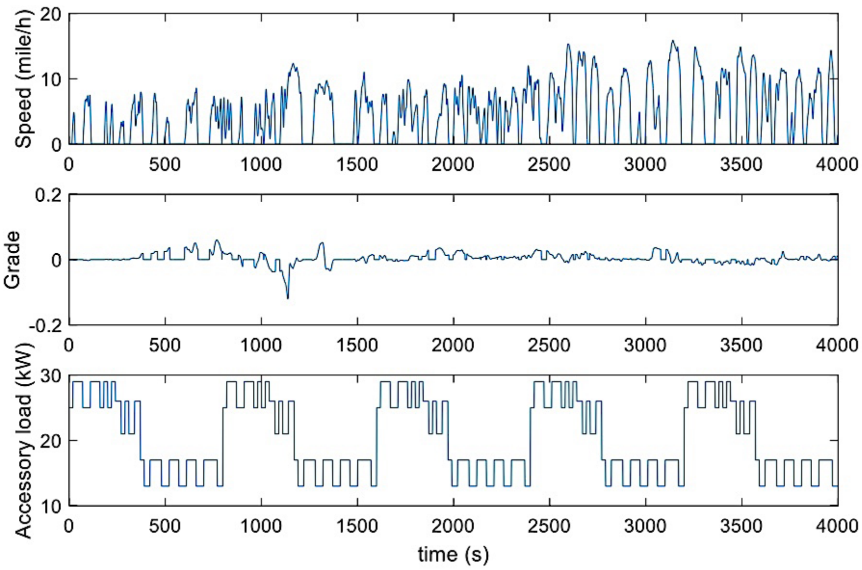
The results from the BAE simulation showed that the bus efficiency across the duty cycles studied was improved by 10–15% in a REIL system with ESS. BAE submitted no results for the REIL system without ESS; however, BAE said during the meeting that there could be some minor improvement (less than 5%) resulting from more efficient accessory operation, noting that the primary value for transit agencies for REIL without ESS would result from maintenance savings.

BAE also presented results from the REIL system demonstration in its laboratory environment. The setup included a Cummins engine with the belt-drive generator and an APS unit. Battery energy storage was simulated with a power supply/load, which is a small shortcoming of the demonstration approach. This testing did not focus on estimating efficiency improvements or a comparison to a non-REIL system; instead, it focused on the operation and hardware to prove technical feasibility. Dyno tests were presented showing the system was able to meet operational mode transitions, changes in loads, and respond to system commands and safety protocols. Three key results were as follows: (1) Belt slip at the generator was within design thresholds, which is important since slip leads to inefficiencies and reduced belt life; (2) The REIL system performed stably during stop/start cycle; and (3) Step changes in load were also handle stably.

To verify the efficiency enhancement results presented by BAE, UT-CEM performed an independent study of the REIL system using historical duty cycles of its own and building up a notional transit bus powertrain with a REIL system. For accessory loads in the UT-CEM models, the load sample provided by BAE in its review was repeated. Figure B-3 shows the UT-CEM duty cycle and accessory loads used in simulation.

Figure B-3

UT-CEM duty cycle and accessory loads used in simulation to verify REIL efficiency



The UT-CEM analysis ran three scenarios for the efficiency enhancement comparison. The first was a traditional diesel engine bus with typical mechanical load accessories and only low-voltage electrical accessories. The second was the REIL system without an ESS. In this scenario, there was no benefit of regen or stop/start with the REIL system since there was no ESS to supply power to the all-electrical accessory load without the engine running. The third was a bus outfitted with the REIL system and an ESS. In this case, regen was allowed and a simple control law was implemented to manage bus stop/start. Figures B-4 through B-6 show the simulations results graphically for each scenario, and Table B-2 summarizes the results.

Figure B-4

Simulation results for traditional diesel engine bus showing vehicle speed and fuel consumption

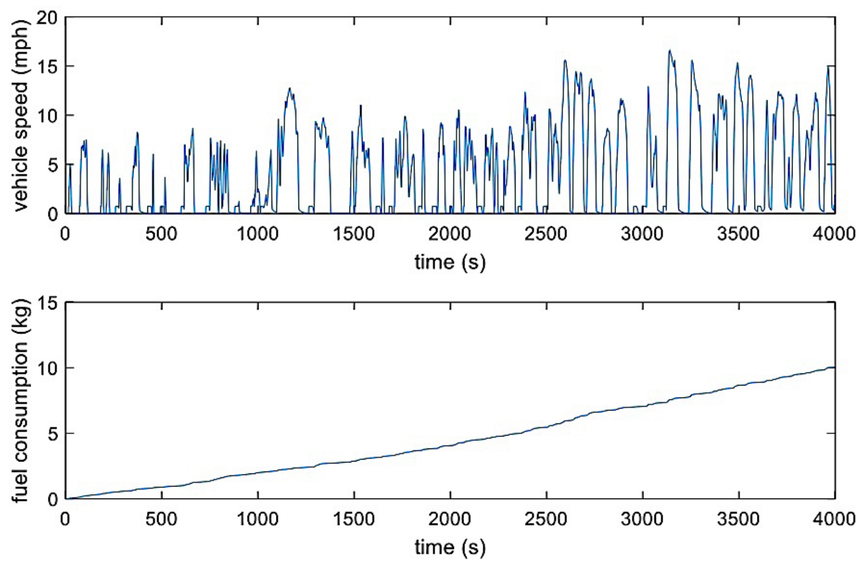


Figure B-5

Simulation results for bus with REIL without ESS showing vehicle speed and fuel consumption

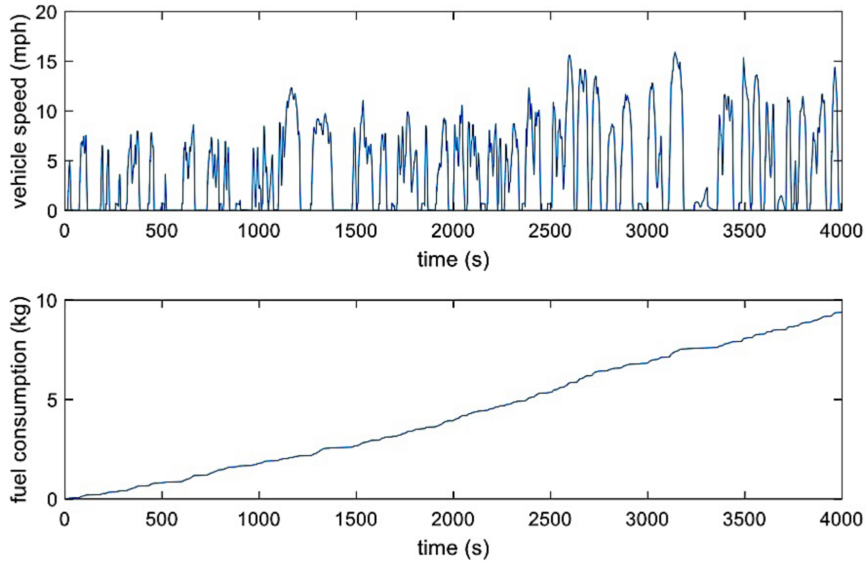


Figure B-6

Simulation results for bus with REIL plus ESS showing vehicle speed and fuel consumption

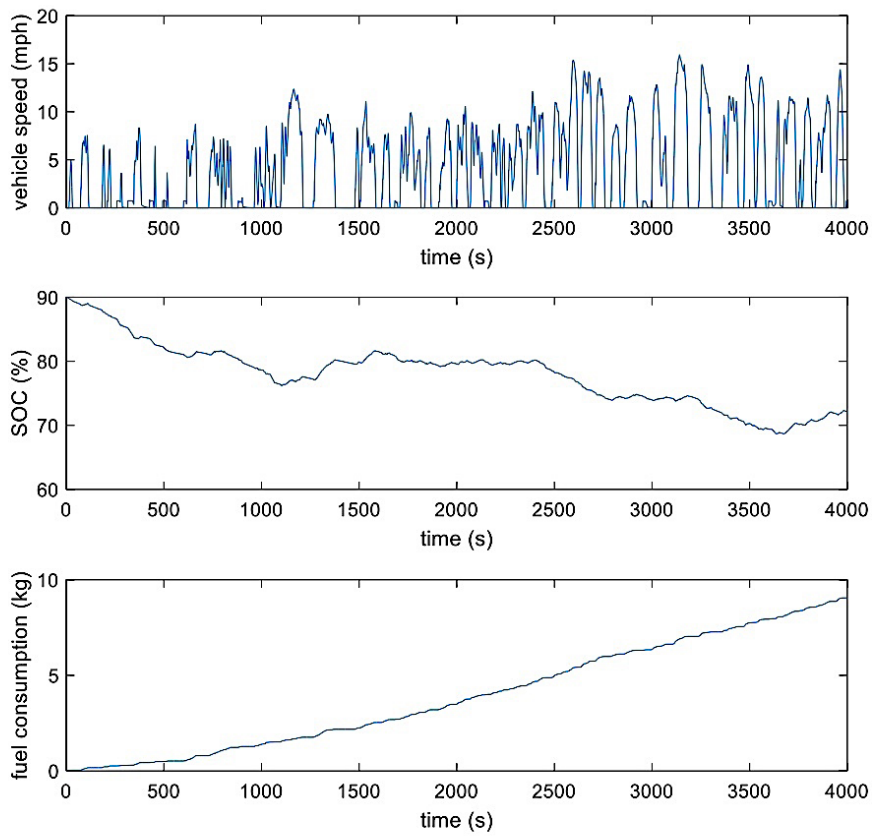


Table B-2

UT-CEM Simulation Results for REIL System Efficiency Verification

	Case 1 – Traditional	Case 2 – REIL no ESS	Case 3 – REIL w/ESS
Fuel efficiency	2.93 mpg	3.07 mpg	3.42 mpg
Regen	Not allowed	Not allowed	Allowed
Engine idle	Not allowed	Not allowed	Allowed
Accessory load	Electrical + mechanical	All electric	All electric
Improvement	Baseline	+4.78%	+16.72%

The simulation results showed a slight improvement when implementing REIL without ESS, about a 4% efficiency gain. When an ESS was added to the REIL system, the efficiency enhancement was nearly 0.5 MPG, or about 16%. These results agree well with the BAE simulations, providing confidence in its results and the anticipated efficiency improvements to the REIL system. Furthermore, the UT-CEM simulations help to quantify the efficiency improvements of REIL without ESS, which was not investigated by the project team. These results show some potential fuel savings with the REIL system even if an ESS is not part of the system.

REIL System Technology Readiness Level

Through this laboratory demonstration, the technology readiness level of the REIL system has been advanced significantly. The more interesting questions are the potential market for this system and the degree to which the ESS is needed for REIL.

BAE currently has a large order of approximately 300 buses with the REIL system that does not include the ESS. It is BAE's belief that the value of this system, even though it is an added $30–45K to the full bus price paid by the transit agency, is in reduced maintenance. An analysis was presented by CTE regarding baseline maintenance costs at MARTA for the traditional systems that would be replaced by a REIL electrified accessory implementation. Detailed results were based on an analysis of granular preventive maintenance, inspection, and repair tasks for each accessory system. BAE Systems then assessed these detailed data for areas/aspects that would be directly improved the implementation of the REIL electrified accessory approach (see final project report for summarized findings). Admittedly, these data were one subset of maintenance activity, and more data are needed for a more comprehensive and fair assessment of the potential value of REIL with respect to maintenance alone. Acknowledging this limitation, the current assessment found approximately $1,450/year per bus in maintenance savings. Consequently, relative to the total cost of the REIL system, the value was not readily seen by the UT-CEM evaluators. It appeared that potential maintenance savings alone would not provide an effective ROI for transit agencies.

However, if potential capital procurement subsidies at 80%/20% or 82%/18% Federal/local share are taken into consideration, the payback period for a REIL system without ESS based on maintenance savings alone is approximately 4–6 years.

Noting the potential for some increased fuel savings, on the order of 4% based on the UT-CEM simulation results, it is likely that the ROI for a REIL system without ESS could become attractive with both maintenance and fuel cost savings considered, with a payback period of roughly 2.5–4.5 years (including Federal subsidy). Again, without some form of subsidy, the ROI to transit agencies is not apparent from the data presented in terms of pure payback period analysis. Of course, all benefits, including potentially substantial emissions reductions over the life of a fleet, should be considered when deciding on whether to incorporate a REIL system.

Although REIL without ESS may provide value with some additional fuel savings on top of maintenance, the added efficiency enhancement and engine-off features of REIL with ESS likely provide the best value for transit agencies when adopting this technology.

Overall Project Effectiveness

The project team, its execution of tasks, and its ability to complete the project timely and on budget appeared to be very effective. The results from this work show great promise in reducing fuel consumption for traditional engine-driven buses. The most notable aspect and value from this FTA-funded project, beyond technical success and demonstration of the technology, was that it has led to a large bus procurement with the REIL system.

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