Future Truck Committee
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Exploring the Potential for 48-Volt Commercial Vehicle Electrical Systems

Changing the Electrical/Electronic Face of Trucking

Developed by the Technology & Maintenance Council’s (TMC) Future Truck Committee

ABSTRACT

Regulations for the reduction of greenhouse gases — such as carbon dioxide (CO₂) emissions — are becoming more and more stringent, and manufacturers are faced with a difficult mission to meet these goals. The need for an affordable, fuel efficient alternative to existing hybrid vehicles is demanding. In the late 1990s, 42-volt electrical systems were rejected as uneconomical, but today, there is a clear trend towards the introduction of 48-volt systems to achieve the necessary emission targets.

Forty-eight volt electrical systems represent a great potential to save fuel and reduce greenhouse gas emissions. Idle stop-start technology can help save fuel while the vehicle is motionless, and torque assist can also be supplied to the engine for launch and low-speed momentary acceleration. Increased energy storage and recapture of brake energy is also possible through 48-volt electrical/electronic (E/E) technology, further improving on overall efficiency. In addition, there are other possibilities with the use of a 48-volt supply that would not be possible with a 12-volt battery in a commercial motor vehicle (CMV), such as electronically controlled air-conditioning (A/C) compressors and fully electric power steering.

Since 2011, multiple manufacturers in the automotive industry have announced their intention to integrate 48-volt technology, and there has been a determined push by the trucking industry to follow the development and relevant technology suitable for 48-volts. Initially the systems are likely to be applied to and combined with a 12-volt battery to produce efficient hybrid-like CMVs while retaining the standard power supply, but in the near future we can expect trucks to be fitted with just a single power source providing a 48-volt supply.
INTRODUCTION

Brief History of Higher Voltage Systems
The concept of a higher voltage for E/E systems was under discussion as much as 20 years ago, when industry explored the potential for a 42-volt system (so named based on the charging voltage of the system, not the storage voltage), and although the idea was brought to market, the vehicle manufacturing landscape has changed significantly since then. When higher voltages were first being considered, the driving factors were primarily providing additional creature comforts within the vehicle[1]. However, today there is a more pressing need for electric-driven features in vehicles, and a much broader base of powertrain and chassis functions which could also benefit from a 48-volt supply.

Despite the potential benefits, the 42-volt system was ultimately unsuccessful due to the high cost of components, changing vehicle engineering priorities, and the lack of a real driving force for development [2]. In today’s market, the necessary components for implementation have become less expensive, the transformative technology has been upgraded significantly, and the need to reduce greenhouse gas (GHG) emissions has become increasingly important.

Meeting E/E Demands
Before looking at the 48-volt electrical system, it’s good to remember the fundamental reason why the 12-volt system was originally adopted about 60 years ago. The six-volt system could no longer cope with the ever-increasing loads and efficiencies required by the new generation of vehicles. Sixty years later, the industry again faces a similar challenge in upgrading the current net power to meet the demands of current and future developments in E/E systems architecture. With the addition of an assortment of high-power parasitic loads, electronic system controller(s) (ESC), global positioning system (GPS) navigation and media center, engine control module(s) (ECM), etc. Heavy-duty vehicles currently demand about 5-10 kW of electrical power [3], and that’s without using any functions for the powertrain, without propulsion (see Figure 1.)

There is increasing concern over the price of diesel fuel and environmental pollution from its use. The federal government continues to pass increasingly stringent fuel economy and emissions standards for the trucking industry. This will force the development of new technology, which will eventually replace mechanical systems with open-demand electrical systems.

The reason for a 48-volt solution — and not 24, 36, or 60-volt systems — is the need to
anticipate future technology and operational demands and the real concern for human physical harm associated with servicing higher voltage systems. Technology always advances exponentially. If the industry is ready to change the architecture of the entire trucking industry’s electrical system, increasing the allowed voltage to its maximum, safe potential is both practical and in best interest of original equipment manufacturers (OEMs). Such a move on a world-wide scale would uniformly advance automotive electronic technology and achieve for the first time, a global truck design, since both the Western European 24-volt system and the North American 12-volt system would likely be superseded simultaneously.

Challenges to Overcome
The development of 48-volt systems is very much driven by the powertrain, and initial designs must overcome the problem of extra components, particularly when used alongside a standard 12-volt system. To comply with new vehicle standards, a 48-volt system would have to feature: a 48-volt battery, a 48-volt starter-generator, and an additional (direct current) DC/DC converter; and it is important to understand how the 48-volt and 12-volt systems will interact with each other onboard the host tractor and the trailer. It should be recognized, however, that a 48-volt supply could have up to a 56-volt charging state offers both potential benefits and drawbacks for other systems onboard the vehicle, such as the chassis and brake systems.

REASONS FOR ADOPTION

Pollution Control
The steady growth in freight transport by truck presents a challenge to efforts at reducing hazardous air pollution and GHG emissions. Though, most countries have fuel economy standards for passenger vehicles, as of 2011 only Japan and the United States have set efficiency and GHG emission standards for heavy-duty vehicles [4].

Most CMVs are powered by diesel engines that, without pollution controls, can emit high levels of other pollutants that contribute to global warming and local air pollution. For example, uncontrolled diesel vehicles produce high levels of particulate matter, a fraction of which has a warming effect and nitrogen oxides which are an ingredient of ozone (also known as smog), an important greenhouse gas. These pollutants are associated with bronchitis, asthma, and other lung diseases, and are responsible for millions of premature deaths worldwide. In 2013, the World Health Organization classified diesel exhaust as carcinogenic to humans, based on evidence of an increase in lung cancer after long-term exposure [5].

Europe, Japan, the United States and other developed nations have adopted heavy-duty vehicle emission control standards requiring the use of new technologies to reduce these pollutants almost to zero. Currently, Western Europe uses EURO Stage VI emission regulations, equal to the US Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) Phase 1 GHG and fuel efficiency standard that regulates greenhouse gas emissions and fuel consumption for on-road heavy-duty vehicles [6]. Systems that are capable of achieving decreased emissions, for example, include hybrid electric vehicle (HEV) technology (see Figure 2), exhaust gases recovery system (EGERS), and kinetic energy recovery system (KERS). These advanced systems can produce greater CO\textsubscript{2} reductions with a 48-volt supply and there are many other possibilities to meet the increasing demand for new inventions with E/E features in a vehicle. Further reductions are on the horizon and North America is following the movement requiring engine and truck manufacturers to achieve targets of 15-25 percent less gCO\textsubscript{2}/ton-mile by fiscal year 2020 [7].

Parasitic and Hotel Load Losses
Every component that is running when it is
not required represents a parasitic load on the drivetrain and hence an unnecessary consumer of fuel. Currently, DOT-regulated drivers are required to take 10 hours rest for every 14 hours of duty per federally mandated Hours of Service (HOS) regulations — downtime that requires a surprising amount of power for sleeper cab habitability and entertainment. Engine idling, which consumes about half to one gallon diesel per hour, is illegal in California but remains very routine for many drivers because cab habitability trumps regulations during extremes of weather. Diesel-burning auxiliary power units (APUs), driven by small one-cylinder auxiliary engines, are much more efficient, but also are noisy and don’t provide adequate electrical power to prevent advanced technological batteries from being drained by an increasing array of electrical gadgets [8].

At idle during hotel load conditions, Class 8 CMVs on average consume up to 5kW of power from its 12-volt electrical system because of heating and air-conditioning, basic engine electrical features, lighting, computer and communications, and appliances. Most four battery Group 31 packs contain approximately 400 Ampere-hours (Ah) if they are in good condition and at 100 percent state of charge. That’s an estimate of 4.8kW per hour. That means if all hotel loads were able to operate without engine operation, for example, the battery pack supporting those loads would lose its cranking amp potential for starting the engine in less than one hour.

One of the main goals for 48-volt E/E system is providing an opportunity of electrifying engine-driven accessories and adjusting the power consumption of the new E/E components for longer performance. Additional parasitic loads from ESCs, ECMs, GPS, electronic logging de-
Adopting higher voltage E/E systems sooner, rather than later, would help anticipate future regulatory mandates for emissions and fuel efficiency since embracing a more advanced electrical platform would make implementing incremental improvements easier for manufacturers and end users.

Adoption of 48-volt E/E systems may help industry transition into Phase 2 comfortably with OEM-compatible technology improvements to reduce engine-stressed componentry, as with parasitic loads, and energy systems with pollution control. A 48-volt solution would diversify industry efforts to control emissions and improve fuel efficiency beyond conventional efforts that have previously focused on aftertreatment systems, such as the diesel particulate filter (DPF), diesel oxidation catalyst (DOC), and selective catalytic reduction (SCR) systems that use diesel exhaust fluid (DEF). A higher voltage system could yield potential benefits such as reduced DPF “regen” operations, extended DPF cleaning intervals, and reduced DEF use.

48-VOLT ELECTRIC SYSTEM FEATURES AND APPLICATIONS
Engine components that rely on mechanical motion to operate and function have the opportunity to be electrically controlled without placing added stress to the main powerplant. This would include components such as the A/C and air compressor, engine fan, alternator, coolant pump, and the power steering pump. The air braking system could become partially electric or have fully integrated electronic-controlled braking dependability.

<table>
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<tr>
<th>TABLE 1: NHTSA/EPA PHASE 1 FUEL EFFICIENCY STANDARDS</th>
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<tbody>
<tr>
<td>EPA CO2 (gram/ton-mile) Standard Effective Model Year 2014</td>
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<tr>
<td>Light Heavy-Duty Class 2b-5</td>
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<tr>
<td>CO2 Emissions</td>
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<tr>
<td>NHTSA Fuel Consumption (gallon per 1,000 ton-mile) Standard Effective 2014 Model Year</td>
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<tr>
<td>Light Heavy-Duty Class 2b-5</td>
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<tr>
<td>Fuel Consumption</td>
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Forty-eight volt solutions also enable regenerative braking and integrated starter-generator (ISG) technology that make it both possible and practical to lower emissions and increase fuel economy. Along with ISG technology are the availabilities of start-stop vehicles (SSVs) and the relief of parasitic loads during driver on- and off-duty time and sleeper berth time. Electric turbo-generator compounding (i.e., EGERS) and electromechanical valve train (EVT) technology are also available opportunities that are enabled by 48-volt E/E systems. This may permit lighter materials and fewer mechanical moving parts, thus reducing component failure and preventive maintenance procedures.

Each of these new electrical loads requires power in the range of several hundred watts or higher. Conversion of existing functions and features to electrical power offers valuable opportunities for vehicle performance benefits in such important areas as fuel economy, emissions, and driver comfort. Electronics provide a potent means of adding engineered intelligence to vehicle functions so that power is used only when needed, or, on demand as a means of saving energy. An excellent example of this approach is electric power steering. Today’s conventional hydraulic power steering system uses an engine-powered, crank-driven pump to generate the necessary hydraulic pressure. This pump runs continuously, placing a constant power drain on the engine. By converting the steering function from hydraulics to electrics, power is applied only when the steering wheel is rotated, and then only in proportion to the amount of the rotation.

<table>
<thead>
<tr>
<th>Current Technology</th>
<th>Benefits of 48 volt Architecture</th>
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<tbody>
<tr>
<td>Electric power steering</td>
<td>More power, improved fuel economy</td>
</tr>
<tr>
<td>Electric brakes</td>
<td>Redundant power supplies</td>
</tr>
<tr>
<td>Power windows, locks, seats, power rear cargo doors</td>
<td>Reduced size and mass of motors; more efficient operation</td>
</tr>
<tr>
<td>Heated exhaust assembly treatment</td>
<td>Lower emissions; quicker light-off time</td>
</tr>
<tr>
<td>Heating, ventilation, air conditioning blower motors and cooling fans</td>
<td>Greater efficiency; smaller/lighter units; flexible packaging</td>
</tr>
<tr>
<td>Mobile multimedia</td>
<td>More power available for video, mobile phones, navigation systems, audio amplifiers, fax machines</td>
</tr>
<tr>
<td>Electric water pumps</td>
<td>Improved efficiency; longer service life</td>
</tr>
<tr>
<td>Selected engine management system components (e.g. exhaust gas recirculation valves, ignition systems, control actuators)</td>
<td>Reduced size and mass; increased performance</td>
</tr>
<tr>
<td>Fuel pumps</td>
<td>Reduced size and mass</td>
</tr>
<tr>
<td>Heated seats</td>
<td>Faster heating, more efficient operation; increased power</td>
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Electronically Controlled A/C Systems
The A/C compressor and other pressure-related components become very flexible for positioning and mounting throughout the engine and cab as they would operate electronically. A smaller inverter is located inside the main inverter assembly, via ISG. This inverts a portion of the 48-volt battery DC power into alternating current (AC), which operates the A/C compressor [9]. Since the engine is not always running, the A/C compressor must still be able to operate. Through the use of an electric inverter compressor (as opposed to a belt-driven unit), the compressor is driven by an electric motor that’s built into the compressor housing and powered by AC voltage from the vehicle’s power supply system. Except for the portion that is actuated by the electric motor, the basic construction and operation of this type of compressor is the same as a scroll compressor.

The electric thermal expansion valve, as well as other regulating components, is controlled by an A/C ESC via a logic program that takes into consideration multiple factors (e.g., sensors, vent actuators, etc.) in order to control the A/C operation. Also, a new heating, ventilation, air-conditioning (HVAC) unit would replace the two separate units used today on most trucks with sleeper cabs — one in the dashboard and one under the sleeper cab bunk. The HVAC system would combine everything into one assembled, charged, and sealed module that eliminates multiple parts and improves vehicle serviceability, which contributes to lower maintenance costs.

E/E Pneumatics
The air compressor is one of the heaviest crank-driven auxiliary loads that is applied to the internal combustion engine (ICE). Its availability to be operated electronically would reduce friction on the engine load tremendously. This

<table>
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<tr>
<th>Future Technology</th>
<th>Benefits</th>
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<tr>
<td>Electric supercharging</td>
<td>Higher engine efficiency</td>
</tr>
<tr>
<td>Ride control systems</td>
<td>Improve ride, handling and vehicle stability</td>
</tr>
<tr>
<td>Brake by wire</td>
<td>Improved vehicle packaging and vehicle performance</td>
</tr>
<tr>
<td>Steer by wire</td>
<td>Enhanced performance; improved packaging; improved passive and active safety</td>
</tr>
<tr>
<td>Electromagnetic valve control</td>
<td>Lower emissions; optimal power; individual cylinder control; lower cost</td>
</tr>
<tr>
<td>Integrated starter/generator</td>
<td>Faster starts; quicker charging; design flexibility; low noise and vibration; improved fuel economy</td>
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**Figure 4: Electronically Controlled A/C Systems**
could be possible with 48-volt E/E systems through an electronically controlled braking system (ECBS) [10]. With ECBS, actuation of the pneumatic brakes is done through electronic messaging and active computer control (i.e., ESC), but the motive force for stopping and parking remains air pressure. This would eliminate oil and excessive moisture build-up in the air system that is a current issue with failed components and weather related freezing conditions.

The air supply and storage can be customized to OEM chassis including smaller air tanks, fewer pressure regulators, smaller air drier, as well as allow pressure-on-demand per driver response rate. ECBS also allows CAN J1939 (controller area network) to be interconnected with ABS and ISG for optimum performance during extreme braking conditions and deceleration of the vehicle without brake pad wear. With ECBS, brake actuation time is significantly reduced and costly plumbing in the CMV is reduced [11].

**Engine Temperature Control**

The mechanical fan and coolant pump could be generally driven directly by the engine via a pulley arrangement. This means that cooling air flow and coolant fluid flow would be a function of engine RPM only. Presently, there is no control over the way these components operate. This leads to over-cooling of the engine during the warm-up phase and under-cooling of the engine during city driving conditions in which there is no control over the operation of the bypass valve (thermostat). An electronically controlled system varies coolant pump speeds based on engine requirements and operating conditions [12]. An advanced thermal management system (ATMS) has the potential to increase the life of the vehicle’s engine and cooling system components as well as decrease fuel consumption and carbon emissions. Whereas a fully electric cooling system is not viable for a vehicle with a low-voltage electric system, it can be applied to a vehicle equipped with a 48-volt E/E system.

In the last decade, research has shown the benefits of increased electrification and control in the thermal management system [13]. This is because ATMS allows a reduction of thermal transients in the coolant system compared to the on/off switching of thermal components. The high electrical load that an ATMS will place on the vehicle’s electrical system makes it more suited to a mild or micro hybrid vehicle where the system voltage is 48-volts or higher. By removing the mechanical load from the vehicle drive train and replacing it with controllable, high efficiency electric components, the auxiliary load reduction imposed by the cooling system can be significantly reduced. Instead of one large mechanical engine fan, it is anticipated for several smaller fans driven independently by brushless DC motors. The thermostat valve is replaced by an electronically controlled valve and the mechanical coolant pump is replaced by an electric one. Control of all the components is implemented over the standard Society of Automotive Engineers (SAE) J1939 CAN network. The performance of the pump is limited by the current that can be accommodated in

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Figure 5: E/E Pneumatics

Fig. 6: Engine Temperature Control
the machine. To achieve a higher pumping power, a higher voltage is required.

**Exhaust Gases Energy Recovery System**

EGERS (also known as waste heat recovery) is a water-cooled, switched reluctance generator coupled to an exhaust-driven turbine. It is capable of operating in exhaust temperatures greater than 900ºC, at speeds over 80,000 RPM, delivering a high shaft power equal to or greater than the needed 48-volt charging power [14]. It is designed to recover and recycle exhaust gas energy, this technology represents a promising means of achieving significant increases in power and efficiency for 48-volt CMVs.

With electric turbo-compounding, a high-speed motor-generator is added to the turbocharger rotating group. In this way, recovered exhaust energy (heat) not used by the turbine to boost engine compression is converted to electricity, which can be stored in the 48-volt battery supply or ISG. When needed, this power can be used to meet electrical demands or routed to the ISG to increase engine output. Conversely, the ISG can be used to further augment energy efficiency through electro-dynamic braking, also known as KERS [15].

**Electromechanical Valve Train**

In a camless engine, electromechanical actuators — a set of electromagnets placed directly on the valves — replace the camshaft. This technology makes it possible to optimize the circulation of gases in the engine, both for intake and exhaust, and to deploy operating modes that improve fuel consumption, clean exhaust technology and performance [16]. EVT has long been under study and never executed to its full potential within limitations of the power needed to operate.

Over time, the valve train in a conventional diesel engine wears and, if not serviced correctly according to OEM-specified intervals, severe engine wear and damages will occur. EVT provides multiple solutions to countless wearable components resulting in vehicle downtime for major repairs. Electromechanical actuators, commanded by an ECM, control the movement of the valves [17]. There is, therefore, no longer any direct mechanical bond between the valves and the crankshaft, decreasing more stress on the engine and increasing horsepower to focus on engine performance. Computer controlled opening and closing of the valves make it possible to improve the various phases of engine running. During urban driving and on the open road, both adequate opening and timing of the valves make it possible to admit a quantity of air limited to the requirements of the engine mixed with a mass of burned gases purposely retained in the engine. This strategy could replace the exhaust gas recirculation (EGR) circuit and ensure reduction of fuel consumption and polluting exhaust emissions [18].

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*Figure 7: Recovery System*  
*Fig. 8: Electromechanical Valve Train*
CO₂ Reductions by Regenerative Braking

Truck emissions are a contributor to poor air quality, but all-electric CMV drivetrains seem unlikely for a long time. Even so, electric assist could improve performance while reducing fuel consumption. Heavy trucks waste a lot of fuel climbing hills, braking down hills, and in stop and go traffic. Even large diesel engines burn a lot of fuel pulling a load to build momentum from a dead stop, and current engine braking and air brakes waste vast amounts of energy during deceleration, especially down hills. In addition, the need for driver cab and bunk power during down time when the truck is stopped unnecessarily uses fuel either by truck engine idling or by an auxiliary motor.

Through E/E system innovation, 48 volts can provide regenerative braking, E-boost assist, and emission-free “sailing” effects with the extension of engine stop phases by using recovered energy from the E/E power supply system [19]. Braking energy recovery systems have been in use for some time now through hybrid automotive and trucking technology and it will be going forward the standard for achieving zero emissions and better fuel economy.

Regenerative Braking Alternatives

EVs and HEVs typically employ motor-generators that can convert electric current into torque (like a motor) or torque into electric current (like a generator). When the brakes are applied, the motor-generator provides the resistance necessary to slow the vehicle as it supplies current to the battery. In the event that the motor-generator cannot slow the vehicle fast enough, a torque coordinator module will apply traditional friction brakes to the extent necessary. Regenerative braking has certain

Regenerative braking systems recapture some of the vehicle’s kinetic energy when the brakes are applied and store this energy so that it can be used to reduce the engine load when the vehicle accelerates. It is widely used in electric vehicles (EV) and HEVs that already have batteries to store the recaptured energy. Regenerative braking has minimal impact on fuel economy during highway driving, but it can significantly improve the fuel economy of vehicles that are driven primarily in city traffic. In CMVs that make frequent stops (e.g., garbage trucks), regenerative braking systems can improve fuel economy substantially.

![Figure 9: Regenerative Braking](image-url)

Figure 9: Regenerative Braking

1. The motor provides extra energy to the engine, allowing it to have more acceleration. Vehicles using this system can have smaller efficient engines.

2. Energy, converted from fuel, produced from the engine and motor, is stored in the batteries. This energy can be used at a later time under optimal conditions.

3. The batteries are also able to store the energy produced from regenerative braking.

4. A vehicle that is in idle mode or low speeds gets its energy from the batteries. The engine is not used during these times.
limitations. In emergency braking situations, regenerative systems can neither provide the necessary stopping power nor handle the amount of electricity generated from a maximum deceleration stop [20]. Regenerative brakes also lose their stopping power and efficiency at lower speeds.

Some regenerative braking systems store the recaptured energy mechanically, typically by pumping hydraulic fluid into an accumulator where the energy is stored in a compressed gas. When the accelerator pedal is pressed, the direction of fluid flow is reversed, and the pressure is used to aid in acceleration. Another means of mechanically recapturing braking energy is the use of a flywheel, commonly referred to as KERS. The energy is conserved in the form of a rotating mass and is therefore efficient, as there is no electromechanical conversion. Both hydraulic and flywheel systems boast higher efficiency than electric battery storage systems, but are primarily implemented only in commercial vehicles due to their size and noise of operation. These systems still require a significant amount of electronics to regulate the energy transfer and to apply the friction brakes as needed.

A mild form of regenerative braking can be achieved in non-electric vehicles by adding a clutch to the alternator. The clutch engages when the vehicle is coasting or braking causing the alternator to help slow the engine as it charges the battery that powers the starter motor and other electric devices in the vehicle. This type of regenerative braking is relatively inexpensive and easy to implement in existing vehicles [21].

**Integrated Starter-Generator**

The ISG is the micro- and mild-HEV propulsion system that improves fuel economy and emissions with potential coasting (“sailing”) effects it induces to the engine for engine-off driving capabilities. The ISG configuration is attractive
because one electric machine can be used to propel the vehicle, to start the engine, and to function as a generator [22]. The performance, efficiency and peak torque characteristics of the motor-generator is possible through switched reluctance motor-generator technology. It is widely used in HEV design between the transmission and engine and is positioned with an auto-clutch design on the same shaft as the electric motor and the transmission [23]. The auto-clutch is used to connect/disconnect the engine from the powertrain. The vehicle can be propelled by the engine, the electric motor, or both at the same time. The electric motor and the 48-volt battery are sized to meet the maximum power required in the EV mode, if applicable.

Since the AC produced by the ISG can’t be stored in a DC battery, the generator’s second job is to rectify AC to DC, in order to recharge the 48-volt battery. Also inside the ISG is an additional three-phase AC inverter for the electric A/C compressor used for the electronically controlled A/C system. The ISG supplies AC voltage for the A/C compressor during most driving phases and allows the 48-volt battery to do so as well through its inverter during most non-driving phases. The 48-volt battery pack has enough power to supply energy to the A/C compressor to keep the cabin cool (even with the engine is off) and still have enough power to propel the vehicle down the road at low speeds for a limited distance [24].

48-VOLT /12-VOLT (‘HYBRID’) SYSTEM APPROACH
Mild and micro-hybrid vehicle technologies are the two design directions that the trucking industry would likely consider if 48-volt is implemented to solve its emission control issues. Hybridized diesel engines using 48-volt would benefit from lower nitrous oxide (NO$_x$), CO$_2$, and particulate matter (PM) emissions. Not only do these designs overcome technical and organizational challenges, they also create an overall system design as the basics for 48-volt requirements of components. Using one of the two approaches is also an essential way of designing the maximum efficiency of a 48-volt vehicle electrical system, via micro-mild HEV.

Mild HEV
Mild HEV uses the engine for primary power, with a torque-boosting electric motor (i.e., ISG) connected in parallel to a largely conventional powertrain. EV mode is only possible for a very limited period of time, and this is not a standard mode. Compared to full HEV, the amount of electrical power needed is smaller, thus the size of the battery system can be reduced. The electric motor-generator, mounted between the engine and transmission, is essentially a very large starter-motor, which operates not only when the engine needs to be turned over, but also when the driver accelerates and requires extra power. The electric motor may also be used to re-start the ICE, deriving the same benefits from shutting down the main engine at idle, while the enhanced battery system is used to power accessories. The electric motor is a generator during regenerative braking [25].

Micro HEV and SSV
The micro HEV is essentially a vehicle with an oversized starter-motor; allowing the engine to be turned off whenever the car is coasting, braking, or stopped, yet restarted quickly and cleanly. This is also the definition of a start-stop vehicle. During restart, the larger motor is used to spin up the engine to operating RPM
speeds before injecting any fuel. As in other hybrid designs, the motor is used for regenerative braking to recapture energy. But there is no motor-assist and no EV mode at all.

Some provision must be made for accessories such as air conditioning which are normally driven by the engine. Those accessories can continue to run on electrical power while the engine is off. Furthermore, the lubrication systems of ICE’s are inherently least effective immediately after the engine starts; since it is upon startup that the majority of engine wear occurs, the frequent starting and stopping of such systems reduce the lifespan of the engine considerably. Also, start and stop cycles may reduce the engine’s ability to operate at its optimum temperature, thus reducing the engine’s efficiency.

48-Volt Battery
The first component that is thought of in a 48-volt electric vehicle system is the battery. The battery or battery pack can be a single 48-volt battery or four 12-volt batteries con-
nected in series. Four Group 31 commercial 12-volt batteries connected in parallel is the common battery pack in the average Class 7 and 8 heavy-duty vehicle today. Battery types range from valve regulated lead acid (VRLA), absorbed glass mat (AGM) type, and gel-cell type batteries all of which are “sealed” and maintenance free. The 48-volt direction is in lithium-ion (Li-Ion) technology, which has had an impact in many consumer technologies today such as cell phones and electric hand tools [26]. A single CMV 48-volt Li-Ion battery is larger than one Group 31 style battery but smaller and lighter than four AGM type batteries connected together.

The 48-volt battery compartment, otherwise can be known as the power electronic carrier (PEC), would consist of the Li-Ion battery(s) and battery controller(s) and would be located on the inside rail of the frame usually under-neath or close to the cab. The 12-volt battery(s) would stay located on the outside of the frame rail or behind the cab under the deck plate for serviceability. Other battery technologies are in the works to compete with the up and coming electrical driven automotive industry such as lead-carbon, lithium-polymer, and carbon nanotube battery technology. Depending on the 48-volt method used, it could consist of a 48-volt battery source and E/E system, one 48-volt battery source and one 12-volt battery source with two E/E systems, or one 48/12-volt battery source combination and two E/E systems.

**Wiring Renovation**

After batteries come wiring and the changes are even more substantial thereafter. The 48-volt electrical system is being considered for many reasons, but most especially for its power output. The average 12-volt heavy-duty E/E system powers around 5 to 10kW whereas the 48-volt E/E system could power around 20 to 40kW [27]. Current and voltage are proportional to equal high power outputs; therefore, current may be decreased to formulate correct amounts of power needed in the electrical system. Lower current allows the wiring system to be much lighter-duty than the wiring systems today allowing reduced cost on rare earth metals, fewer routing complications, and weight restriction relief.

There are many different types of wiring in a heavy-duty vehicle, ranging from those that transmit signals from switches or sensors and carry almost no current to those that provide power to large electric motors and carry lots of current. The amount of current that a wire can handle depends on its length, composition, size, and how it is bundled. A 12-volt, 12 American Wire Gauge (AWG) wire, typical for head lights, can become as small as 28 gauge size AWG with 48 volts. The wiring, connectors, and fuses decrease in size by more than half,

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**Figure 14: Cable Thickness vs. Maximum Power**
staying in consistency with power and current to all electrical functions.

48-Volt /12-Volt System Design
OEM specifications will dictate the design and E/E architecture for any proposed change. The 48-volt /12-volt system design replicates the already configured automotive plan and existing heavy-duty parallel HEV. It would consist of the micro-mild HEV platform (ISG design) with the Li-Ion 48-volt PEC containing the 48-volt /12-volt DC/DC converter. Like a hybrid, the ISG starts the engine only when the 48-volt battery decreases to a specified charge amount, depleted during driver start-up and amount of accessories used. Then, before increasing to a vehicle speed that the ISG can’t comply with, the auto-clutch turns the engine over for operational speeds [28].

The 48-volt battery is charged by the ISG, regenerative braking and EGERS technology. Forty-eight volts is the voltage power for the A/C system and blower motors, except for the HVAC controls as well as all cab related electrical functions (e.g., power windows and mirrors, interior lighting, media center, etc.) which stay at 12 volts. Additional DC/DC converters would apply where and when necessary for parasitic and hotel load conditions.

The air compressor as well as ECBS is also powered by the 48-volt E/E system but the ABS system will stay 12-volts. Other than trailers, all exterior lighting will be 48 volt as well as all previous mentioned engine auxiliary loads (e.g., coolant pump, power steering, etc.). All 48-volt wiring and componentry will be separated schematically from 12-volt systems and secured safely by element dimension except DC/DC converters. All related ECMs and ESCs will be powered by their appointed electronic function voltage levels and be designed without confusion thereof. Also, the EVT would be powered by the higher voltage system for ample delivery of power to operate the strong electromagnetic actuators variable valve timing [29].

BARRIERS TO ADOPTION
Development of the 48-volt system is very much driven by the powertrain, and initial designs must overcome the problem of extra components, particularly when used alongside a standard 12-volt system. The increased space requirements and isolated system manage-

Figure 15: 48-Volt/12-Volt System Design
ment for the dual system become barriers to adoption. Among the additional components will be a 48-volt battery, a 48-volt starter-generator and additional DC/DC converters just to name a few, and it is important to understand how the 48-volt and 12-volt systems will interact with each other.

**Dual-Voltage System**

The most efficient dual-voltage system architecture being considered for heavy-duty vehicles is the same design that is used in the heavy-duty hybrid parallel powertrain. Modern hybrid CMVs and 48-volt systems are very similar due to the fact that both have 12-volt systems and both are being developed for the same reasons of adoption (emissions, fuel economy, etc.). Therefore, both systems use the same technology. Forty-eight volt technology offers HEV-like features, which is the reason why mild or micro HEV is so named for 48-volt systems. The SSV costs are much less expensive while providing functions on the engine to be removed and made more resourceful reducing loads on the engine which induce stress and takes away horsepower (also kW).

The dual-voltage system requires space and isolation of components that is new for its environment in a mobile habitat. New E/E components and existing technologies are going to need to be mounted and secured in specific locations throughout the chassis for operation while during normal driving conditions and all weather related constraints.

Identification by color code, like high-voltage componentry in HEVs is identified by the color orange, will have to be modeled and mandated by OEMs. Blue was the color that was in conjunction with the 42-volt E/E system when that was in the works 20 years ago. Existing components like the automatic transmission or transmission clutch combination will need to be redesigned to fit such 48-volt mechanisms.

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**Figure 16: Dual-Voltage System**
like an ISG, extra wiring and connections, and hybrid control module(s) (HCM). The service-ability and access to these and other certain parts have to be designed for technician provision also [30].

48-Volt Limitations

The base architecture, depending on the focus of the OEM in CO₂ reduction or performance enhancement, involves the unchanged 12-volt E/E system, which is powered by a DC/DC converter in the power class of 5 kW, and the portion of the 48-volt system in the power range of 20 kW for energy generation, acceleration support and recuperation plus a storage device [31]. Electrical propulsion in HEVs operate on a high voltage level between 150-volts and 650-volts. At this voltage level a high effort for protection against electrical shock is legally required. For this reason, it is planned to supply high power functions on the 48-volt level in heavy-duty vehicles the same. Currently the only official specifying document for 48V is “Chart LV 148,” issued by German OEMs (see Figure 17). Chart LV 148 specifies all the voltage levels of a 48-volt E/E system [32]. The usual operation range is between 36- and 52-volts where a 48-volt system is at nominal operating range. Following are areas with functional restrictions for lower operating range, between 36 and 24 volts, and upper voltage operating range, between 52 and 54 volts. Just as the charging limits of a 12-volt system may reach up to 14-volts, the 48-volt system can charge at a maximum 56-volt range in overvoltage territory. If Chart LV 148 has the same +/- 2-volt fluctuation as standard 12-volt batteries have, 48-volt battery design would have to operate with capped voltage spikes to stay within safe operating range, according to Chart LV 148. Important limits are below 24 volts for under voltage, above 54 volts for over voltage, and 60 volts or above for shock protection voltage. In addition, Chart LV 148 provides some properties where requirements can be derived from, as:

- Electrical shock protection is not required for DC voltage < 60-volts [No high voltage interlock system (HVIL) is required to protect humans against electrical shock] (e.g., heavy-duty connections.)
- A single malfunction must not lead to a short circuit between 48-volt and 12-volt E/E systems. Such a short circuit between the voltage levels without connection to ground might destroy the complete 12-volt system due to permanent overvoltage.
- There is a common ground (chassis) with potential for both 12-volt and 48-volt, which is connected by spatially divided wires and ground terminals. Loss of common ground might lead to reverse voltage on the 12-volt side and thus destruction of 12-volt electronics.
- No component may lead to a transition into the overvoltage level (54-volt) due to load dump or resonance step-up. This is a very important statement, as this requires special measures at inductive loads and limits the effects of arcing.

With these facts from Chart LV 148 and regulations from International Electrotechnical Commission (IEC) 60038 and United Nations Economic Commission for Europe (ECE) R-100 to enforce its content, it can be derived that no electrical shock protection is required or any voltage below 60 volt can be treated...
as 12 volts [33]. But there are some effects at higher voltages such as 48 volts which might require additional system protection measures for technical reasons.

One critical effect is arcing. If arcing occurs, the surrounding materials might be set on fire due to the high temperatures. Wiring smaller than 12 AWG has a greater chance of being pinched, cut, pulled apart, and worn through due to normal driving conditions. Such wear and tear conditions raise the point of arching, creating heat, and produce electromagnetic interference (EMI) with which the industry is not familiar. Wiring not only carries current to some components but also conducts heat away from connections and provides the circuit’s physical integrity. Other serious failures by many constituent problems involve short to ground, loss of common ground, voltage short circuit, and broken wiring.

**Truck Transient Conditions**
Under normal vehicle operation, voltage at the supply lines range between 9 and 16 volts (12-volt system), or between 36 and 60 volts (48-volt system). However, a substantially wider range of voltages of both positive and negative polarity may appear along the supply lines as a result of conducted electrical transients. Electrical disturbances generated by disconnecting inductive loads, sudden power cutoff in the main circuit, or switch bouncing are commonly referred to as inductive switching. Disconnecting an inductive element causes a high inverted overvoltage on its terminals.

Positive high voltage transients may occur at the supply lines after the ignition key cuts the battery-supply circuit. In this case, the ignition circuit continues to release disturbances until the engine stops rotating.

Fast input transients can present a serious problem for 48-volt devices due to low dynamic impedance of the components themselves. The driver circuitry must provide very fast input supply rejection to protect the devices from high peak currents that could be potentially destructive. Both the power topology and the control scheme of the 48-volt drivers must be carefully selected in order to ensure reliable operation of the devices. In addition, dual voltage devices are expected to survive continuous application of +24 V/-12 V (12-volt systems) or +96 V/-48 V (48-volt systems) during a jumper start. Garages and emergency road services have been known to utilize 24-volt sources for emergency starts, and there are even reports of 36-volts being used for this purpose. Higher voltages such as this are applied for up to five minutes and sometimes with reverse polarity. Thus, CMV 48-volt driver devices are required to:

- operate from a wide input-supply voltage range.
- provide immunity to input voltage transients.
- include protection from input overvoltage and undervoltage conditions.
- include input reverse polarity protection.

Figure 18: Damage Caused by Arcing
Recent advances in higher voltage systems open new horizons in trucking applications. However, optimal solutions for driving 48-volts in the trucking environment are needed. Immunity to conducted transient emissions is one of the key requirements that must be addressed by OEMs. The right choice of a power topology and a control scheme for the 48-volt driver circuit becomes critical for meeting these requirements. [34]

**Corrosion Control**

Corrosion prevention has always been a problem in the electrical system for the trucking industry. Commercial vehicles drive to some of the most exotic areas on earth and back, and anti-icing and deicing chemicals build up under the chassis and on every component possible. There has been little work done on the effects of a 48-volt system in a truck and what potential corrosive damages can prompt new failure modes. Particular geographic areas of concern include the northern hemisphere and Pacific and Atlantic coastlines. All of these are exposed to saltwater and chemical environments during the year which tend to promote corrosion. On a rainy day, there are few places where the wiring system will not get wet. Water has the potential to cause shorting between adjacent conductors or initiate corrosion processes due to the presence of very small amounts of salt, wash agents or other dissolved materials. Forty-eight volt systems more than quadruple the rate of corrosion activity in a worn or open connection, as well as the potential for arcing damage.

Corroded connections will frequently occur at regenerative braking components and depending where DC/DC converters, motor-generators, and ECMs are placed, will unconditionally corrode because of moisture and road chemicals. The entire higher voltage system will have to have a solid connectivity eminence to it and an extra casing or wrapping of each component for additional corrosive resistant support. Insulated surroundings would have to be implemented throughout the system for anti-arching and fire prevention (i.e., HVIL). No longer could electrical tape or easy butt-connectors be used to repair wiring in a 48-volt system. Wiring harnesses may have to be replaced entirely and connections from part-to-part would have manufacturer specifications on how to properly maintain contacts. These type of barriers will have a heavy impact on service providers and either will burden the trucking industry or encourage new countermeasures to come about.

**48-Volt Precautions**

To work successfully with the new higher voltage, fuses and circuit breakers must be redesigned to avoid harness fires. Alternators will need enclosed interior and exterior connections to avoid corrosion induced failures. Connectors will have to be redesigned to make unfailingly tight connections, as those that are loose will

Figure 19: Potential Damage Caused by Corrosion
quickly burn open. This requires a complete redesign of the electrical system and will provide solutions to the heavy-duty electrical system that have not been available for the problems in 12-volt E/E systems. Trailers, on the other hand, are an entirely different matter when discussing dual and higher voltage constraints. Lighting and brake systems would be easiest to stay at 12-volts, omitting the combination vehicle issue and keeping higher voltage where it is needed — at the engine. This will allow the Society of Automotive Engineers (SAE) J560 seven-pin electrical connector to stay the same or be improved only by new higher voltage contingencies.

Direct 12-volt system or DC/DC converter from a 48-volt system will supply the trailer with lighting, ABS, and possible liftgate operations. If 48 volts were to be connected to the trailer, the seven-pin connector will no longer tolerate wear and spray incursion. It would have to be tight and secure by new means of connect/disconnect or it will either weld itself shut or burn up if connected and disconnected improperly. Also, all lights will have to be long-lasting light-emitting diodes (LEDs) which isn’t an issue since that’s the movement towards exterior lighting as it is. LEDs eliminate shock impact and water intrusion damage as well as emit a more intense lighting effect for clearance, marker, turn signal, and head light proportions. OEMs are attracted by the potential reduction in energy consumption as well as the space savings realized by smaller lighting fixtures. High-brightness LEDs offer substantial benefits in truck lighting applications, but they require power conversion that can function over a wide range of input and output voltage and provide immunity to electrical transients.

**12- TO 48-VOLT GAPS**

Standardization is an essential part of developing componentry for a higher voltage system. The battery industry is well organized through IEC and SAE, which should enable future battery designs specific to 48-volt systems that regulate its terms of use. When developing standards for EV programs, the automotive industry discovered that safety considerations were necessary for the manufacturer, the occupant, the rescue crews, and technicians in the field. It is essential that special training programs be developed for each of these stakeholders, particularly those that are the least expecting. The 48-volt system provides enough voltage in some cases that will involve shock hazard; even though research indicates that risk is low, it still remains.

**Dual Voltage Dare**

Before 48-volt systems can be adopted widely, many engineering problems must be addressed, including the engine/electrical system architecture and a migration strategy (dual 12/48-volt systems vs. straight 48-volt systems). Short-term challenges associated with dual voltage systems include more wiring, extra weight, and added complexity. Regardless of migration path, suppliers need time to develop new components and a part identification system that distinguishes between 12-volt and 48-volt parts.

**Evaluation of Electrical and Electronic Components**

While 48 volts is not far from 12 volts in physical terms, real world issues are a cause for concern. Current 12-volt designs won’t automatically work at 48-volts; even simple fuses will not migrate, let alone dimmers and active load controllers. Some fuse panel and harness makers have found that common 12-volt mini- and maxi-fuses do not behave properly
at 48 volts. They can fail to interrupt excessive currents properly, causing serious overload conditions. Also, interconnection technologies have evolved for optimal cost and performance in a 12-volt environment. The present design of connectors, circuit breakers, and relay contacts may not be optimal at 48 volts. Therefore, manufacturers must re-evaluate component suitability for the higher voltage. Tests can range from simple continuity tests to full electrical characterization of a component’s functional performance at 48 volts.

Reliability and Safety Issues
At 48 volts and higher power levels, many components, such as wires and relays, experience electrical stress that is four times higher than before. With higher stress, components tend to break down more often. Therefore, component and module manufacturers have to perform more reliability testing, such as burn-in and accelerated stress tests, to ensure adequate service life.

Safe distribution of 48-volt power throughout a heavily optioned CMV also is a challenge. In the first place, the 48-volt standard was established because higher voltages (with the right current) create human safety issues. For example, 50-volts can stop a human heart, and anything higher than 60-volts requires more heavily insulated wires and connectors, which add weight. To prevent fires, electrical distribution designs must allow for jump-starting at the higher voltage, and provide protection if battery connections are reversed [35].

Component and Conductor Arcing
Relay, switch, and conductor arcing is another problem that must be addressed. Its potential for serious damage is greatly increased in 48-volt systems. Recent research shows that 48-volt arc energy is 75 to over 100 times higher than in a 12-volt system [36]. Such arcing can generate temperatures up to 1800°F, ignite fuel vapors, start a fire in plastic insulation, and even melt metal. Simply redesigning relays, switches, and fuses for higher voltage and using flame-retardant materials is not a total solution; these component designs should suppress arcs. The same is true for other connections, particularly those that could be opened during replacement of fuses, batteries, and other components. Mechanical design features must ensure that electrical terminals are correctly seated and locked; therefore, increased use of clips, clamps, and shields may be required.

Industry Constraints
Multiple voltage systems increase the possibilities of cross voltage system wiring mistakes, which can lead to component damage and potentially fires. For the dual voltage design, where do the 12-volt systems end and the 48-volt system begin? Each OEM differs from one another and they will continue to build equipment accordingly. There is a long list of electrical loads on a truck and if OEMs do not comply with one another, the technician and service provider that are not in the dealership concept will make costly mistakes. The Massachusetts Right to Repair Act (and similar legislation) will be critically burdened and the cost of information will be as advanced as 48-volt technology [37].

Manufacturers will once again recreate a battery and voltage system structure that would innovate the future of trucking industry as automotive did 60 years ago. Just as the HEV research and development ignited throughout the automotive industry into the trucking industry, 48-volt E/E systems would have the same effect through dual voltage systems. The problem with implementing this type of higher voltage now, rather than 20 years ago, is because there are more electronics onboard CMVs than there ever has been.

The number of parts and part suppliers in the trucking industry is considerable and to decommission any amount of it — say half of 12-volt systems — stresses the industry in such a
way that it may not be up for the challenge nor the expense. The future 48-volt infrastructure would have to be built from the ground up to meet proper testing, material handling, cost logic, and OEM specifications. Also, there are a number of aftermarket companies and independent shops that would suffer through this transition. After all, 80 percent of fleets and independent shops use aftermarket service and parts for their availability, quality, and price to factor in an additional level of provision.

**Extensive Test Requirements and New Manufacturing**

Implementation of 48-volt systems will affect the design, manufacturing, assembly, and testing of most electrical and electronic components. Electromechanical components such as alternators, motors, and starters may require more time on field coil winding machines to get the same number of ampere turns (given that the current and wire gauge will be one-quarter of what it was for 12-volt devices). Other components will be redesigned or replaced. In many cases, suppliers will be asked to make them lighter, more efficient, and less expensive. This probably means that semiconductors will replace electromechanical designs in some switch and relay applications. This will call for higher power devices, such as metal-oxide semiconductor field-effect transistors (MOS-FETs) in higher voltage packages.

While basic designs of existing assembly and test equipment should be adequate for 48-volt components, the higher voltage will require some modifications. For instance, additional production testing may be required to verify arc suppression and EMI compatibility compliance. To design the new 48-volt components properly, CMV manufacturers and their suppliers must understand critical engineering and performance issues. As a result, there will be increased research and development activity involving the electrical characterization of devices and their designs. Typically, this entails electrical measurements under various load conditions, insulation resistance and high-potential testing, and very low resistance measurement of relay contacts and connector terminals.

**GOALS**

Return on investment (ROI) is the absolute main goal for any type of technology improvement, even if it involves competing with government regulations. Anyone who purchases anything extra from its original investment wants the value of that extra cost to be returned in a minimum amount of time and repeatedly thereafter in financial savings. The 48-volt E/E system is meant in the near possible future to become the standard in everything mobile that requires electrical power. If the 48-volt revolution comes to pass, there will no longer need to be an ROI for the sake of complete trucking manufacturer change. It will become the adopted source of natural ROI because its purpose is to save fuel and leave less of a carbon footprint.

**Price and Benefit**

The cost of new higher voltage platforms will be of greater expense than the modern commercial vehicles today because with advanced technology arises an advanced price tag. HEVs market the same way, although for mild or micro HEVs the value will almost be the same and the cost will be mild as compared to a full HEV. In the trucking industry, fuel efficiency gains and acquisition costs always increase together and for whichever HEV is decided by OEM specification preference will meet or surpass the emission standards. Compared to 12-volt conventional Class 8 heavy-duty vehicles, micro HEVs with 48-volt E/E systems are expected to return fuel savings of up to 15 percent in city driving and 15 percent less emissions; mild HEVs are expected to return fuel savings of up to 25 percent in city driving and 25 percent less emissions. Full HEVs that have been experimented with reportedly return fuel savings of up to 40 percent. The fuel economy trend could almost equal the
increased price difference from a conventional CMV. The problem is fleets expect payback in 24 to 36 months since the average turnaround of a truck is 3 to 5 years before warranty and residual value is depleted.

Although mild and micro HEVs have great potential in the stop-start areas of operation, it isn’t of great importance to long distance freight carriers that rarely operate in heavy traffic conditions. Therefore, the rest of the 48-volt potential is of significance when considering the amounts of horsepower and fuel mileage that is gained from engine mechanical mounted components changed to electrical powered loads. When an engine’s main goal is to run at maximum efficiency, any available HEV technology used onboard is decreased driving over 60 mph. Fleets are all different and each fleet has different goals. Therefore, fleets will select different technology pathways depending on their application, emission requirements and fuel efficiency needs.

**Outlook**
There is potential long-term merit in exploring 48-volt E/E systems for more than just fuel economy improvements. It is likely that the ultimate value of higher voltage systems will lie with its potential empowerment for advanced technologies that constantly suggest a superior way of CMV improvements. For example, new engine technology, such as multi-fuel turbines, is in development that will completely redesign the CMV engine by removing piston and valves and implementing a turbine rotor that operates by flex-fuel. Benefits in current areas of consideration go beyond regenerative braking as by significantly increasing foundation brake life. This has always been an inhibitor for fleets and will ultimately reduce maintenance costs. Significant driveability enhancement can aid in driver retention and improve safety by possible increase in driver workload.

Fleets, OEMs, and suppliers are eager to participate in the “green revolution,” but there are significant challenges that will take time to overcome. Development of economical, reliable energy storage (batteries) is foremost in this lineup. As with other initiatives, such as electronic engine controls and electronic stability controls, this journey will likely take 10 to 15 years. With E/E technology always at an exponential rate of improvement, there will almost never be a solid base architecture for the constant ever changing trucking industry improvements. Model results are promising, but the case has yet to be made in real world operations. This is not a market to jump into lightly, but for those companies in it for the long haul, it’s a journey worth making.
REFERENCES


