California Environmental Protection Agency

AIR RESOURCES BOARD

DRAFT

TECHNOLOGY ASSESSMENT:

MEDIUM- AND HEAVY- DUTY BATTERY ELECTRIC TRUCKS AND BUSES

October 2015

State of California

AIR RESOURCES BOARD

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ACRONYMS AND ABBREVIATIONS

AC	Alternating Current
ARB	California Air Resources Board
AQIP	Air Quality Improvement Program
BEV	Battery Electric Vehicle
BMS	Battery Management System
CEC	California Energy Commission
CHP	California Highway Patrol
CO_2	Carbon Dioxide
DC	Direct Current
DEVC	Dynamic Electric Vehicle Charging
DOE	Department of Energy
EPA	United States Environmental Protection Agency
EV	Electric Vehicle
FTA	Federal Transit Administration
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Inventive Project
g/bhp-hr	Gram per brake horsepower hour
GHG	Greenhouse Gas
GVWR	Gross Vehicle Weight Rating
kW	Kilowatt
kWh/mile	Kilowatt-hours per mile
$LiFePO_4$	Lithium Iron Phosphate; a type of battery
Li NCA	Lithium Nickel Cobalt Aluminum; a type of battery
LMO	Lithium Manganese Oxide; a type of battery
LTO	Lithium Titanate; a type of battery
lbs.	pounds
MMT	Million metric ton
NiMH	Nickel Metal Hydride; a type of battery
NMC	Lithium Nickel Manganese Cobalt Oxide; a type of battery
NOx	Oxides of Nitrogen
O&M	Operation and Maintenance
PEG	Piezo Electric Generator
PbA	Lead Acid, a type of battery
PM	Particulate Matter
RPM	Revolutions per minute
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District
SOC	State of Charge
V2G	Vehicle to Grid
SIP	State Implementation Plan

U.S.	United States
W	Watt
Wh/kg	Watt-hour per kilogram of battery weight; specific energy, or gravimetric energy density
Wh/l	Watt-hour per liter of battery volume; volumetric energy density
W/kg	Watt per kilogram; specific power
ZEV	Zero Emission Vehicle

EXECUTIVE SUMMARY

The Air Resources Board (ARB)'s long-term objective is to transform the on- and off-road mobile source fleet into one utilizing zero and near-zero emission technologies to meet established air quality and climate change goals. The purpose of the Battery Electric Vehicle (BEV) technology assessment is to take a comprehensive look at the current status of and the five to ten year outlook for BEV technology in the medium-duty (8,501 to 14,000 pounds (lbs.) Gross Vehicle Weight Rating (GVWR)) and heavy-duty (14,001 lbs. and above GVWR) truck and bus market.

BEVs, with electricity sourced from the electrical grid to recharge on-board batteries, have the capability to completely eliminate tailpipe emissions of criteria and toxic pollutants and reduce overall greenhouse gas (GHG) emissions compared to a conventional fossil fueled truck or bus. In this assessment, ARB staff examines a number of battery technologies, including lead acid, nickel-metal hydride, lithium-ion, molten salt, and flow batteries, and discusses the current status of BEVs using these battery chemistries.

Overall, the assessment finds that BEVs are beginning to penetrate the medium- and heavy-duty vehicle markets. Battery electric transit buses are increasingly available from a variety of manufacturers. Some school buses are commercially available. Battery electric shuttle buses are also increasingly available, as are other medium-duty BEVs, primarily delivery vehicles. Currently, BEVS in the marketplace typically use lithium-ion battery chemistries. Class 8 heavy-duty trucks remain a significant challenge.

Presented below is an overview of the BEV Technology Assessment that describes the potential for emission reductions, market penetration of BEVs in medium-duty and heavy duty trucks and buses and what the next steps are for BEVs in the on-road arena. For simplicity, the discussion below is in a question-and-answer format and is only an overview of the topics that are evaluated in more detail in the body of the document.

1. What are medium- and heavy-duty BEVs?

A BEV is a vehicle that utilizes batteries as the sole source of power for vehicle movement, vehicle auxiliaries such as heat and air conditioning, and equipment used on board the vehicle such as lift gates or wheel chair lifts. Medium- and heavy-duty BEVs are those BEVs that have a GVWR of at least 8,501 lbs. BEVs are similar in outward appearance to traditional vehicles, but use an electric motor instead of an engine and a battery pack instead of a fuel tank. BEVs can be powered by a variety of types of batteries. At least in the near term, however, most use lithium-ion battery chemistries. There are other components such as inverters and rectifiers used by BEVs, and they may or may not include a transmission.

2. How are BEVs fueled?

BEVs are powered by rechargeable batteries that must be recharged, usually from the grid. Some medium- and heavy-duty BEVs must be charged during a shift via opportunity charging while others can operate for a full shift and then be charged overnight. There is currently no standard charging system or strategy, and each manufacturer may utilize a unique system.

As medium- and heavy-duty BEVs become more widely used, their charging infrastructure needs and impacts on the grid must be considered and addressed.

3. For what medium- and heavy-duty on-road applications are BEVs currently in use?

Current California-based medium- and heavy-duty on-road BEVs are predominantly trucks and buses that operate on urban or suburban routes that have a high frequency of stops and starts, high idle times, lower average speeds and daily ranges of generally 100 miles or less.

Battery electric buses are making inroads into transit fleets, and represent the largest number of medium- and heavy-duty BEVs currently in operation, with over 2,500 electric buses globally. Transit buses from three manufacturers are currently available commercially in the United States, employing different battery charging strategies, quick in-route charging and slow overnight charging, to compete in the transit market.

Most medium- and heavy-duty BEV truck deployments have been in the urban vocational work truck category, focusing on urban transit buses and intracity delivery. A summary of BEV deployments and technology readiness level for several of the vehicle categories that have seen deployment of BEVs is in Table ES-1.

4. What incentive programs are available to offset the current incremental cost for BEVs?

ARB’s Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP), which is funded by Low Carbon Transportation investments and the Air Quality Improvement Program (AQIP), helps offset the incremental cost of eligible hybrid and battery-electric trucks and buses through a purchase voucher on a first-come, first-served basis. HVIP is intended to help encourage California fleet acceptance of the nation’s first commercially-available hybrid and zero-emission trucks and buses, and helps drive production economies of scale and lower technology costs. So far, HVIP vouchers have been issued for over 320 electric vehicles (EV), with about 60 percent of all BEV HVIP vouchers issued, over 200 vouchers, for delivery vehicles. Over $10.7M of HVIP funds have been disbursed, averaging more than $33,000 per vehicle. In addition, the California State Transportation Agency/Caltrans funds transit expansion and capital improvement projects with Greenhouse Gas Reduction Fund monies, some of which have gone to battery electric transit buses. Transit buses also can offset a substantial portion of their incremental costs using Federal Transit Administration (FTA) grants.

Proposition 1B Goods Movement Emission Reduction Program funds may also be used to help existing truck owners who wish to upgrade to BEVs. Additionally, for BEVs not yet commercially available, funds may be available from a wide range of sources for demonstrations by agencies such as ARB and the California Energy Commission (CEC), local air control districts such as the South Coast Air Quality Management District (SCAQMD) and the San Joaquin Valley Air Pollution Control District, and the ports of Los Angeles and Long Beach.

Table ES- 1: Summary of BEV Deployments and Technology Readiness Levels

Vehicle Type	Technology Readiness	Number in Service	Notes
Transit Bus	Commercially Available	~40 in California > 2,500 worldwide	3 models are commercially available in US
School Bus	Limited Commercial Availability	4 in California	3 new buses ordered in SCAQMD 6 repowers underway with V2G
Medium-Duty (8,501 to 14,000 lbs. GVWR)	Limited Commercial Availability	300+	Focused on delivery service
Heavy-Duty (> 14,000 lbs. GVWR)	Demonstration Phase	2 Drayage 1 Refuse	13 Class-8 Trucks under construction

(See Chapter IV for a discussion of deployment levels)

ARB is launching new pilot projects using AQIP and low carbon transportation funds to support larger-scale commercial deployments of zero-emission trucks and buses.

These pilot projects are designed to help increase vehicle production levels to the point where significant economies of scale can be realized. On October 1, 2015, ARB released a solicitation to fund larger-scale deployments of zero-emission trucks, buses, and school buses (including hybrid vehicles capable of operating in zero-emission mode within disadvantaged communities) and associated charging/fueling stations. Close to $24 million is available for these projects from fiscal year 2014-15 funds, with an additional $60 million from fiscal year 2015-16 pending approval by the California Legislature.

5. What additional applications are promising for BEVs in the next 5 to 10 years?

BEV technologies will find additional vocations in the medium-duty (8,501 to 14,000 lbs. GVWR) market with continued penetration for delivery vehicles and shuttle buses. Battery electric transit buses will continue to increase their market share. Heavy-duty (>14,000 lbs. GVWR) BEVs are currently being demonstrated in several vocations, such as drayage trucking service and refuse collection trucks. It is anticipated that the number of electric drayage trucks will increase due to several on-going demonstrations of this technology with funding from the CEC, SCAQMD, and the U.S. Department of Energy (DOE). Looking forward, ARB's $25 million allocation to zero-emission drayage truck demonstrations as part of the AQIP and low carbon transportation Fiscal Year 2014-15 Funding Plan approved by ARB in June 2014 will greatly expand the number of zero-emission BEV drayage trucks. Further, heavy-duty short- and regional-haul trucks may see electrification building off the current BEV drayage truck demonstrations as may other delivery vehicle classes.

6. What constraints limit the applicability of BEVs to medium-duty and heavy-duty on-road applications?

Existing barriers limit the expanded applicability of BEVs in medium-duty and heavy-duty on-road applications. The primary issues are battery cost and power density, highlighting a major issue restricting the applicability of BEVs in many vocations: limitations on vehicle range.

Battery cost is a major component in the overall cost of BEVs, with costs currently in the $500 to $700 per kilowatt-hour (kWh) range. This is substantially more than the cost for a conventional diesel powerplant. In their 2013 I-710 commercialization study, CALSTART estimated the cost of a 350 kWh battery system at over $200,000 in 2012, with costs coming down to $111,000 by 2020 and $70,000 by 2030 (CALSTART, 2013). Reducing the cost of battery packs and increasing the amount of power that can be supplied by those batteries would bring overall BEV cost down considerably, and provide greater vehicle range, while expanding the number of vocations that could operate BEVs economically.

Standardization of vehicle charging connectors, charging protocols and more widespread deployment of vehicle charging stations suitable for medium-duty and heavy-duty trucks and buses would allow BEVs to universally charge while away from their home base, increasing daily range and potentially allowing for smaller battery packs, reducing overall BEV costs and reducing the return on investment timeframe.

7. How do current BEV costs differ from costs of conventional vehicles?

Medium-duty and heavy-duty BEVs currently cost significantly more than conventionally fueled trucks and buses. Table ES-2 illustrates the estimated incremental cost for several BEV vehicle types.

Currently, electrification can double the purchase cost of a BEV truck or bus, when compared to a conventional vehicle. However, it is important to note that BEVs are expected to cost less to maintain than conventional trucks with less frequent brake changes due to regenerative braking and the elimination of most fluid changes typical of conventional truck operations. Data collected as part of the 2013 CEC-funded CalHEAT study looking at BEV parcel delivery trucks determined that maintenance savings are estimated to be between three and 10 cents per mile when comparing electric delivery trucks with conventional trucks in similar classes and vocations. Conventional trucks currently require 12 to 15 cents per mile to maintain (CalHEAT, 2013b); overall, maintenance costs are estimated to be 25 to 80 percent lower than conventional trucks in similar classes and vocations. In addition, the costs for electricity are substantially below that of diesel fuel, providing additional operating cost savings. These savings in operation and maintenance costs will offset most if not all of the increased incremental cost for many BEVs, and over time, the increased incremental cost is expected to be paid back.

The cost for a BEV charger must also be considered. These can range from around $1,000 for a basic charger to $350,000 for a specialized Proterra fast charger that will accommodate up to eight Proterra transit buses. These costs, much like those for any fueling station, will become part of the charging infrastructure for years to come.

Table ES- 2: Estimation of Current Typical BEV Incremental Costs

Vehicle Type	Current BEV Incremental Cost	Baseline Vehicle Costs	Current Incremental Cost (Percent of Baseline Costs)
Heavy–Duty (> 14,000 lbs. GVWR)	$100,000 to $200,000	$100,000	100-200%
Medium-Duty (8,501 - 14,000 lbs. GVWR)	$50,000 to $90,000	$80,000	60-110%
Transit Buses	$315,000	$485,000-$525,000	60%
School Buses	$60,000 to $160,000	$140,000	40-110%

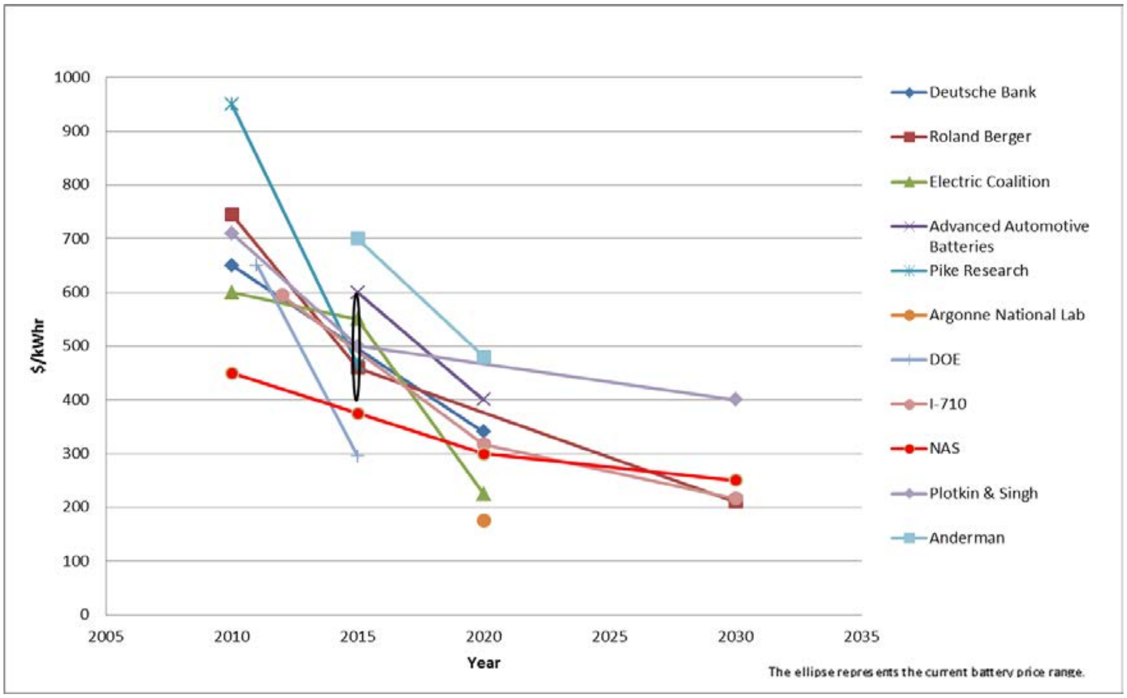
(See Chapters IV and V for an incremental cost discussion)

8. How are BEV costs anticipated to change over time?

Costs for BEVs are expected to decrease over time; the incremental cost between BEV drayage trucks and their conventional counterparts have been estimated to close from $200,000 in 2012, to $100,000 in 2020 and $60,000 in 2030 (CALSTART, 2013). This expected decrease in incremental costs is due to projected advancements along the learning curve, standardization of power electronics across many medium- and heavy-duty truck platforms and further penetration of BEVs in the medium- and heavy-duty market. Battery costs are the single largest driver for overall BEV incremental costs. Figure ES-1 shows the anticipated decline in battery costs per kilowatt-hour. Battery costs are falling even more rapidly for the light-duty fleet, with battery pack costs expected to approach $200/kWh by 2018 (Ayre, 2015; Anderman, 2014).

Table ES-3 indicates how these reduced battery costs are projected to drive down future projected incremental costs for a BEV drayage truck. Other components of the energy storage system such as inverters, converters, motor controllers and the motors

Figure ES- 1: Forecasts for Battery Costs[1,2]



The ellipse represents the current battery price range.

(CALSTART,2013; DOE, 2012; EEI, 2014; NAS, 2013; Sakti, 2015)

themselves can add an additional $20,000 or more to BEV costs (CALSTART, 2013). These costs are offset by savings on the engine and emission control systems.

9. What are the benefits of BEVs, including criteria pollutant and GHG emission benefits?

Not only does the use of BEVs provide significant reductions in petroleum consumption and increase fuel flexibility, electric powertrains are also much more efficient than internal combustion powertrains. This means that less energy is required to move people or goods using electricity than using other fuels.

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[1] Battery cost estimates may be based on the cells only, on the battery stack, or on the entire pack. This, along with production volume assumptions and the year the projection was made, doubtless contributes to some of the range of battery costs and battery cost projections shown in this figure for a given year.

[2] Battery costs for the light-duty fleet are approaching the $200/kWh range. Costs for medium- and heavy-duty vehicle battery packs tend to be higher due to issues such as different chemistries for different duty cycles, ruggedization needs, and expected useful life.

Table ES- 3: CALSTART Estimations of BEV Drayage Truck Costs Over Time

Components	BEV (Year 2012)	BEV (Year 2020)	BEV (Year 2030)
Glider	$79,000	$79,000	$79,000
350 kW motor	$9,000	$8,000	$7,000
Power Electronics	$12,000	$10,000	$8,000
350 kWh Battery System	$210,000	$111,000	$74,000
Total Vehicle Cost	$308,000	$208,000	$169,000
Baseline Diesel Truck Cost	$104,000	$108,000	$111,000
Incremental Cost	$204,000	$100,000	$58,000

(CALSTART, 2013)

BEVs by definition have no tailpipe emission and therefore completely eliminate the emission of criteria pollutants at the source. In other words, BEV tailpipe emissions are 100 percent lower than tailpipe emissions from today's conventionally fueled vehicles. Even in the future, when diesel or natural gas vehicles may be much cleaner than today's vehicles (certified to a 0.02 gram per brake horsepower hour (g/bhp-hr) NOx standard, for example), BEVs still will provide additional tailpipe emission benefits, which may be crucial for attaining ambient air quality standards.

However, there are emissions associated with BEV operations when the electrical grid is used to recharge vehicles. A well-to-wheel analysis of BEV operations attributes emissions associated with electricity generation to the BEV. The magnitude of criteria and GHG emissions reductions associated with BEV operations on a well-to-wheel basis will depend on the emissions characteristics of the power plant(s) that provide the electricity. ARB is developing a separate fuels technology assessment that will evaluate overall well to wheel emissions from various transportation fuels. Preliminary results from that assessment indicate that battery electric vehicles have substantially lower well to wheel emissions than diesel- or natural gas-fueled engines.

10. What next steps are necessary to foster the expanded use of medium- and heavy-duty on-road BEVs?

There are a number of actions by government, academia, and industry that will help to promote the widespread deployment of medium- and heavy-duty BEVs. Range and cost are the two main barriers to widespread deployment. Actions to address range and cost, as well as other barriers, are summarized in Table ES-4 and discussed further below.

Improve Range

The first approach for addressing limited range is the continued identification of fleets wherein current 100 mile ranges may be adequate or where opportunities exist to fast-charge or charge en route. The currently available ranges are typically adequate for those operating over an optimal BEV duty cycle (i.e., lots of starts and stops, significant idle time, and relatively low average speeds). A second approach involves increasing

Table ES- 4: Heavy-Duty BEV Action Items and Likely Lead Parties

	Action Item	Lead Party		
		Gov't	Academia	Industry
1	Improve vehicle range		✓	✓
2	Reduce incremental cost		✓	✓
3	Improve non-battery components		✓	✓
4	Standardize charging		✓	✓
5	Demonstration Projects	✓	✓	✓
4	Improve/continue incentives	✓		
5	Regulatory activity, such as Advanced Transit and Last Mile Delivery regulations, and the development and adoption of other regulations	✓		

Gov't = Government, and includes public entities such as ARB, CEC, DOE, air districts, and ports
Academia = Academia and National Laboratories, Researchers
Industry = vehicle manufacturers, battery manufacturers, component manufacturers

range. Range generally can be increased by light-weighting, increasing battery pack size or by improving battery chemistry, including improving energy density of existing batteries, identifying and developing new battery types, and other improvements to new or existing battery technologies. Increased battery pack size has negative impacts on weight and payload capacity, so improving battery chemistry is likely a preferable approach. The U.S. DOE reported in its Quadrennial Technology Review that even using existing lithium-ion technology, battery energy density could be doubled with improvements in anode and cathode materials and higher-voltage electrolytes. Work in this arena may fall under the aegis of academia, research laboratories, and vehicle manufacturers. ARB and other public agencies can promote these efforts by providing research and development funding, where available.

Reduce Costs

Reducing costs may involve a combination of technology improvements and economies of scale. The predominant contributor to the incremental cost of BEVs is the cost of the battery pack. As battery costs decline, largely due to savings from increasing manufacturing volume with increased penetration of light-duty zero emission vehicles (ZEV) and plug-in hybrid-electric vehicles, the incremental costs of BEVs will also decline. Where possible, selection of battery chemistries that are also used in the light-duty fleet will help to reduce BEV costs.

Battery technology, the learning curve, and economies of scale found in the light-duty sector will readily transfer to the medium- and heavy-duty vehicle segment. Other components such as inverters are less transferrable, but economies of scale can also be obtained simply by using components developed for medium- and heavy-duty vehicles across several vehicle types, such as BEVs, fuel cell-powered vehicles, and hybrid trucks and buses. California’s light-duty ZEV mandate encourages technology improvements in BEVs in the light-duty sector, which in turn, will benefit technology advancements in heavy-duty sector. The role of ARB and the public sector in reducing costs primarily involves identifying new applications that may be suitable for transition to BEV technology and promoting them through demonstration, incentives, policies, and regulations.

Improve Non-Battery Components

Additional research needs to focus on the electrification of vehicle auxiliaries such as electrically driven air conditioning systems, and electrified power steering, and the demonstration of their robustness in BEV operations. Much of this research is being completed for conventional trucks and buses to reduce the significant power demand these auxiliaries now place on internal combustion engines, so economies of scale will quickly ramp up as these technologies are developed. In addition, ruggedization of battery packs and systems may be required. Most electric motors today use rare earth metals. Manufacturers should continue to work on developing motors that are not dependent on rare earth metals. The prime leader in this area will be vehicle and component manufacturers.

Standardize Charging

In addition, as initially seen in the light-duty fleet, charging approaches have not been standardized. A standardized charging infrastructure would reduce costs through increasing volumes, and increase opportunities to charge away from the home base. Standardization will likely be achieved through cooperative agreements between manufacturers of components and vehicles, with the assistance of the Society of Automotive Engineers (SAE).

Continue Demonstration Projects

Government encourages the introduction of improved battery technologies through its investment in technology demonstration and deployment. Demonstration projects were initially funded for delivery vehicles, transit buses, and school buses. In general, these incentive-funded EVs were well-accepted, and demonstration and pilot deployment projects continue while further demonstrations have been initiated for more difficult applications, such as drayage and refuse trucks. Demonstrations allow manufacturers to fine-tune their products, and showcase products that are in an early commercial readiness stage. ARB, and other demonstration project funders such as CEC, U.S. DOE, Ports of Los Angeles and Long Beach, SCAQMD and other California Air Districts can help foster broader BEV adoption by continuing demonstrations of BEVs in the medium- (8,501 to 14,000 lbs. GVWR) and heavy-duty (>14,000 lbs. GVWR) truck and bus arena.

Demonstration projects that focus on specific aspects of BEV technology that need to develop further to allow deeper penetration of BEVs into additional vocations, such as robust power electronics, broader range of electrified auxiliaries, standardization of a charging infrastructure and a better understanding of the economic realities of BEV operations, will all contribute toward the continued commercialization of BEV trucks and buses. Robust demonstration projects are needed to showcase a favorable economic argument for BEV operations to fleet purchasers and vehicle operators.

Provide Market Certainty

Market certainty can be built through a combination of incentives and regulations. Incentive programs can assist with offsetting the recognized increased cost seen with battery electric technology. This incremental cost difference between electric and traditional vehicles can be substantial. Some, if not all, of this cost differential can be repaid over time from the reduced operating and maintenance costs anticipated for a BEV (payback). For example, the West Coast Collaborative has found a three to five year payback period for medium-duty BEVs (WCC, 2011). However, the up-front capital-cost difference can still make the BEV option cost-prohibitive. By providing suitable incentives, agencies can reduce this cost so that the buyer can afford to make the most environmentally beneficial decision. As the incremental costs of BEVs are reduced, the use of incentives can be phased down.

As discussed above, ARB currently has several incentive programs (e.g., Proposition 1B, AQIP, low carbon transportation, etc.) that encourage the development and adoption of new BEV technologies. Most important of these is the HVIP voucher program, funded by AQIP and low carbon transportation funding. HVIP helps offset the incremental cost of eligible hybrid and battery-electric trucks and buses through a purchase voucher on a first-come, first-served basis. HVIP helps ensure California fleet acceptance of the nation's first commercially-available hybrid and zero-emission trucks and buses, and helps drive production economies of scale and lower technology costs. ARB's new pilot projects, discussed previously, will support larger-scale commercial deployments aimed at increasing production volumes to the point where significant economies of scale can be realized. These programs will be continuously improved over time to better ensure the transformation to a cleaner truck fleet.

Develop/Adopt Regulations

ARB can employ policies that increase stringency of vehicle and emission performance standards, which in turn, will help accelerate development and deployment of zero emission technologies. In 2016, ARB plans to propose requirements for zero emission transit buses; initial workshops were recently held. If needed, additional incentive support to promote their adoption will be included. Also, in 2017, ARB plans to develop a proposal to increase deployment of BEVs in last mile freight delivery applications (delivery vans/trucks). Those trucks typically operate over the optimal BEV duty cycle, and are well suited for BEV applications. That same year, ARB also plans efforts aimed at initiating deployment of zero emission airport shuttle buses.

I. INTRODUCTION AND PURPOSE OF ASSESSMENT

The ARB's long-term objective is to transform the on- and off-road mobile source fleet into one utilizing zero and near-zero emission technologies to meet established air quality and climate change goals. The purpose of the BEV technology assessment is to take a comprehensive look at the current status of BEV technology in the medium-duty (8,501 to 14,000 lbs. GVWR) and heavy-duty (14,001 lbs. GVWR and up) truck and bus market and the 5 to 10 year outlook of the medium-duty and heavy-duty on-road vehicle technologies that are being employed in BEVs. This technology assessment will support ARB planning and regulatory efforts, including:

- California's Sustainable Freight Strategy planning;
- State Implementation Plan (SIP) development;
- Funding Plans;
- Governor's ZEV Action Plan; and
- California's coordinated goals for GHG and petroleum use reduction.

This BEV technology assessment is broken into the following elements:

- Chapter II explains how BEVs work and describes the components of BEVs;
- Chapter III discusses BEV chargers and vehicle charging mechanisms;
- Chapter IV examines in-use medium- and heavy-duty BEVs;
- Chapter V examines BEV costs, holistically and at the component level;
- Chapter VI estimates the emission benefits of BEVs;
- Chapter VII presents the optimal duty cycle for BEVs; and
- Chapter VIII discusses the next steps needed for BEVs to significantly penetrate the medium- and heavy-duty market.

BEVs by definition are vehicles that utilize batteries as the sole source of power for vehicle locomotion, vehicle auxiliaries, and equipment used on-board the vehicle such as lift gates or wheel chair lifts. Since batteries are used for all the vehicle's power needs, there is no on-board source of criteria pollutant or GHG emissions from the vehicle. The only source of emissions associated with BEV operations is from power generation used to recharge the batteries, which is typically from the electrical grid. Without the direct consumption of fuel on-board the vehicle, there is a significant potential to reduce GHG emissions when using a BEV in place of a conventional diesel truck or bus. In fact, if recharged using renewable electricity sources, such as solar or wind power, BEVs will not only have zero tailpipe emissions, but the potential for zero total emissions, which will be key to achieving GHG reductions in the long term.

The elimination of criteria pollutants from a vehicle's tailpipe can have a significant positive effect in communities that are burdened by the emission of pollutants associated with conventionally fueled vehicle operations. In the medium- and heavy-duty arena, diesel fueled engines are commonly used; utilizing BEVs in traditional diesel fueled truck and bus applications can yield significant reductions in people's exposure to pollutant emissions. BEVs can be quieter than conventional trucks and may not vibrate as much as their diesel fueled counterparts, which may provide a more pleasurable environment for truck and bus drivers or vehicle passengers. This reduction in sound and vibration from diesel engines is especially valuable in school bus applications that involve special needs student transportation. In addition, electric motors are generally more efficient overall than conventional vehicles because their motors and transmissions more effectively convert the potential energy in the fuel source (in the case of BEVs, the battery) into kinetic energy, or motion, and maintenance requirements for electric motors are substantially less than their combustion-powered counterparts. The estimated emission reduction from BEVs is explored in Chapter VI Emission Benefits of BEVs.

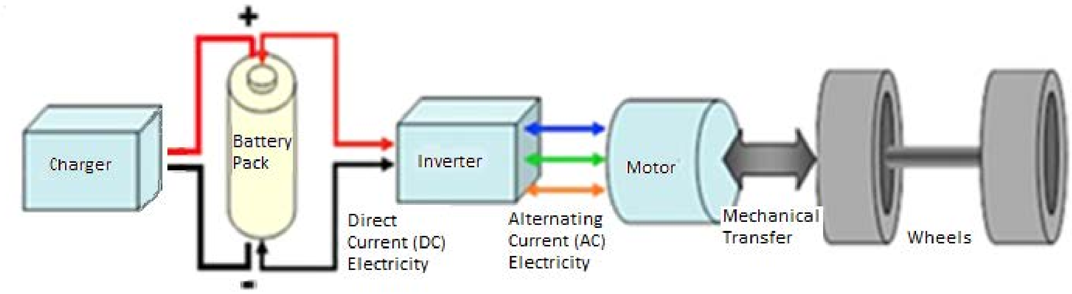
Medium- and heavy-duty BEVs have made significant in-roads into several market segments, notably transit buses and delivery vehicles. These two applications are ideally suited for BEV application based on their duty cycle, which is discussed in Chapter VII Optimal BEV Duty-Cycle, and the nature of fleet operations, which has vehicles returning to a home base every day and typically conducting refueling there.

II. OVERVIEW OF BEV COMPONENTS

BEVs have some unique components that are not typically found on conventional trucks and buses such as high voltage battery systems and regenerative braking systems. BEVS also have some common components that can be found on hybrid-electric and fuel cell-electric trucks and buses, like larger traction batteries or high capacity components such as inverters or electric motors. BEVs require the use of electrified accessories, which are just now beginning to be developed. Accessory electrification is being investigated by conventional truck manufacturers in their quest for more efficient and clean truck and bus engines, which will allow for more efficient vehicles and more wide-spread BEV acceptance.

Since BEVs utilize electricity as fuel, the recharging of batteries requires the conversion of alternating current (AC) power from the electrical grid to direct current (DC) power for battery storage. Further, the on-board conversion of DC power back to AC for use in AC motors (if employed) to provide energy for tractive effort is done by manipulating electrical current into a phase and power that can be utilized by the electric traction motor. Figure II-1 below illustrates in a simplistic representation the typical components that are found on a BEV.

Figure II- 1: Simplistic Overview of BEV Components



(modified from CAAT, 2015)

A description of some of the common vehicle components found on BEVs is provided below:

- Energy storage systems, including batteries, controllers, and the battery management system (BMS) (section A);
- Inverters, rectifiers and converters (section B);
- Electric motors (section C); and
- Vehicle auxiliaries (section D).

Vehicle chargers and charging are discussed separately in the next chapter, Chapter III BEV Charging Systems.

A. Energy Storage Systems

The energy storage system includes batteries, controllers, and the BMS.

1. Electric Vehicle Batteries

There are a number of considerations when selecting appropriate batteries for a particular EV use; the amount of energy that can be stored in the battery and the ability to discharge the stored power to produce useful work in a controlled and understood manner are just some of the issues that need to be evaluated.

Some battery considerations for use in vehicle applications are:

- Energy-to-weight ratio, or specific energy (gravimetric energy density), which reflects how much energy is available in watt-hours per kilogram of battery weight (Wh/kg);
- Energy-to-volume ratio, or volumetric energy density, which is similar to specific energy but addresses how much volume will be taken up to provide the needed energy in watt-hours per liter (Wh/L);
- Specific power, which reflects the amount of current that can be provided (W/kg)
- Expected lifetime of the battery, both calendar life and charge cycles;
- How long it takes to recharge the battery and whether fast charging can be employed;
- Specific temperature management requirements (heating or cooling); and
- Battery safety, both in-use (thermal runaway potential) and disposition at the end of its useful life in vehicle operations.

As a battery ages in-use, its capacity to do useful work will decline. The battery manufacturing industry generally determines the useful life of a battery based on the number of charge/discharge cycles the battery can sustain until it degrades to 80 percent of its original capacity. There are other factors that affect battery life, such as the depth of discharge encountered, potential overcharging concerns, and environmental conditions during operations. At the end-of-life, consideration must be given to reusability and recyclability of the battery and its components. Partially spent batteries can theoretically be restored or refurbished to new-battery performance levels. A battery no longer suitable for motive application may still function adequately in the secondary market as an energy storage system for electrical grid stability or as wayside power to facilitate vehicle recharging. Once the secondary useful life is over, recycling to recover high value materials will provide cost savings and conserve finite resources as well as avoid the costs and environmental concerns associated with battery disposal.

Many different motive battery chemistries have been developed over the years, but batteries generally have the same basic components:

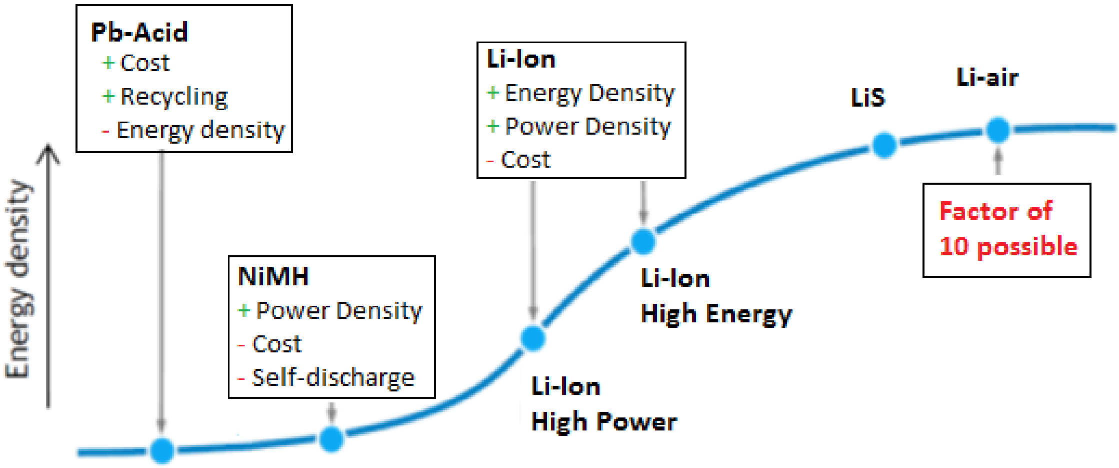
- Anode: Negative electrode where electrons are generated;
- Cathode: Positive electrode where electrons return to the battery after doing work external to the battery; and
- Electrolyte: Ionic substance that separates the anode and cathode.

Lead-acid (PbA) was the motive battery of choice for automobiles in the early part of the last century and beyond. However, vehicle manufacturers investigated other battery chemistries in the last few decades of the 20th century. In this BEV Technology Assessment, staff investigated six battery chemistries:

(a) PbA;
(b) Nickel-metal-hydride (NiMH);
(c) Various lithium-ion batteries such as lithium titanate, lithium-iron-phosphate ($LiFePO_4$), and nickel cobalt manganese (NCM);
(d) Lithium-air batteries;
(e) ZEBRA molten salt battery; and
(f) Flow batteries.

These six battery chemistries are each described further below, with a comparison of the energy density of some of these chemistries illustrated in Figure II-2. Staff believes that in the near term, lithium-ion batteries are most likely to be used in zero-emission medium- and heavy-duty truck and bus applications. This is because of significant investment from industry in the manufacture of these batteries, and a wide range of lithium ion chemistry options that provide vehicle manufacturers with battery choices for specific vehicle applications. In the long-term, more advanced chemistries may be introduced that significantly increase battery capacity while reducing weight and volume.

Figure II- 2: Energy Density of Different Battery Chemistries



(CALSTART, 2013)

a. Lead Acid Batteries

Lead-acid batteries powered the earliest electric cars, and still power neighborhood EVs, electric golf carts, and many light-duty EV conversions, due to their relative low cost and availability. PbA batteries use lead as the anode, lead oxide as the cathode, and sulfuric acid as the electrolyte. Thus, PbA batteries are both toxic and corrosive, but readily recyclable. According to the United States Environ-mental Protection Agency (EPA), 96 percent of PbA batteries are recycled. At around 35 Wh/kg, PbA batteries have too low an energy density to be useful for heavy duty applications. The weight of PbA batteries would be too great for the ranges that medium- and heavy-duty trucks and buses would require for commercial operations.

b. Nickel-Metal Hydride Batteries

The negative electrode for NiMH batteries is a form of a metal hydride. Typically, the positive electrode is nickel oxyhydroxide, and the electrolyte is potassium hydroxide. These materials have low toxicity, and the batteries are considered safe. The higher specific energy of NiMH batteries, at around 70 Wh/kg, allows for increased range, and they demonstrate relatively good cycle life when compared to PbA batteries. NiMH-based EVs have reportedly achieved over 100,000 miles on the original battery pack. NiMH batteries have a tendency to self-discharge, losing up to 20 percent of their charge per month. This can be an issue for applications with occasional usage, but is not an issue for a vehicle that sees regular use. The batteries can provide useful power down to 50 percent depth of discharge. However, cost remains an issue. While these batteries have been effectively used in the light-duty vehicle market, they are not highly suitable for medium- and heavy-duty vehicle applications because the specific energy is still too low to provide an adequate range without dramatically increasing the weight of the vehicle, thereby reducing cargo capacity of commercial vehicles.

c. Lithium-Ion Batteries

Lithium-ion batteries are currently the battery of choice for light and heavy-duty BEVs and are commercially widely available. There are a variety of chemistries that fall under the lithium-ion label. Table II-1 (p. II-11) lists several of the available lithium ion chemistries with their associated specific energy densities.

It is important to note that the energy density data presented in Table II-1 represent the total nominal capacity of the batteries when they are manufactured and not the accessible power of the batteries. Lithium batteries should not be completely depleted and therefore a buffer is needed to protect the battery from over-discharge. This protective buffer is typically 20 percent of the batteries' manufactured capacity. Several reasons for buffering battery pack's state of discharge are:

- Extends battery life;
- Allows for sufficient power for BEV operations at lower states of charge;
- Mitigates the risk associated with cell-to cell variations in higher voltage battery packs; and
- Builds in engineering margins to enable BEV manufacturers to state with confidence an anticipated range for the vehicle.

Further, overcharging of the batteries should be avoided to protect battery health, to prevent oxidation of the electrolyte, and to ensure that regenerative braking regimes can be utilized even with a fully charged battery.

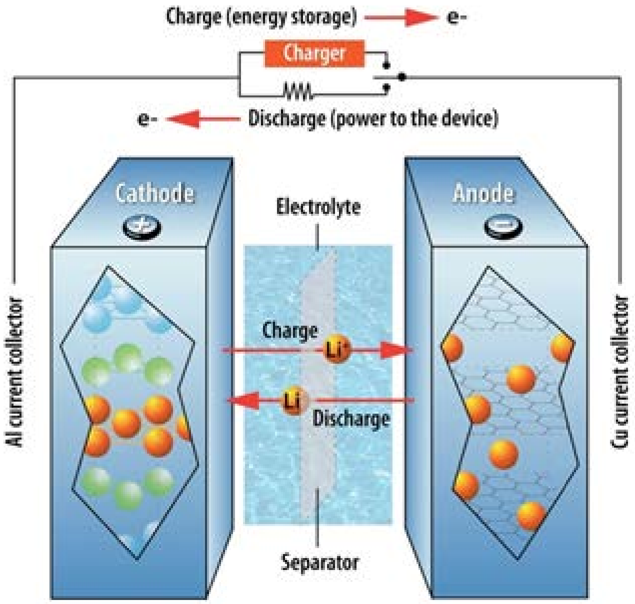
Lithium-ion batteries provide energy by shuttling lithium ions between the electrodes, as shown in Figure II-3. The cathode chemistry varies, but is lithium-based, such as Lithium Cobalt Oxide or Lithium Iron Phosphate. The anode is typically graphite, although it may also be metal-based, such as a tin/cobalt alloy, or use nanocrystals as with lithium titanate, which dramatically increase the surface area of the anode and facilitate fast charging (Graham-Rowe, 2005). The electrolyte is usually a lithium salt dissolved in an organic solvent, which does present some risk of fire if the battery is heated above its operating temperature. BYD, an electric bus and battery manufacturer, uses "fire safe" Iron Phosphate batteries; the safety claim is based on a very limited amount of lithium being used in the cathode. This approach does slightly reduce the power density of the battery compared to the conventional lithium iron phosphate battery (BYD, 2014). According to BYD, these batteries do not experience any thermal runaway even when pierced, submerged, baked, crushed, or exposed to flames (BYD, 2015). Lithium ion electrochemical cells have high nominal cell voltages, up to 3.7 volts depending on the specific chemistry used. Therefore fewer cells and connections are needed than for other battery chemistries like PbA or NiMH. These batteries are typically good for many cycles, with BYD claiming up to 7,200 charge/discharge cycles, corresponding to nearly 20 years if cycled once daily, to degrade the battery to 80 percent of its original capacity.

Lithium battery function may be limited by calendar life. These batteries do self-discharge, but at a lower rate than NiMH batteries, at around 1 to 2 percent per month (Sanyo, 2003). There are potential cost and safety issues as well, but the relatively high specific energy of around 150 Wh/kg may make lithium-ion chemistry a good choice for battery electric trucks and buses. Table II-1 (p. II-11) presents a comparison summary of lithium-ion batteries, while Figure II-4 (p. II-8) presents such information graphically.

Lithium iron phosphate batteries use graphite as the anode, and $LiFePO_4$ as the cathode. The electrolyte is a lithium salt in an organic solvent (McDowall, 2008). In addition, the use of phosphate as a positive electrode significantly reduces the potential for thermal runaway. This battery technology is used in the TransPower BEV drayage truck and electric school bus demonstrations.

Lithium-titanate batteries are also a type of lithium-ion batteries. The anode is lithium titanate, and the positive electrode is usually manganese-based. They use a non-aqueous electrolyte. The battery has a long cycle life of over 5,000 cycles. While the

Figure II- 3: Lithium-Ion Battery Flow Chart



(Argonne, 2010)

energy density is lower than other lithium batteries shown in Table II-1, they can be safely operated over a wide discharge range, so the effective available energy is comparable to lithium-iron phosphate batteries. The batteries also have increased stability, and hence more overcharge protection. Lithium-titanate batteries are used on the Proterra electric bus.

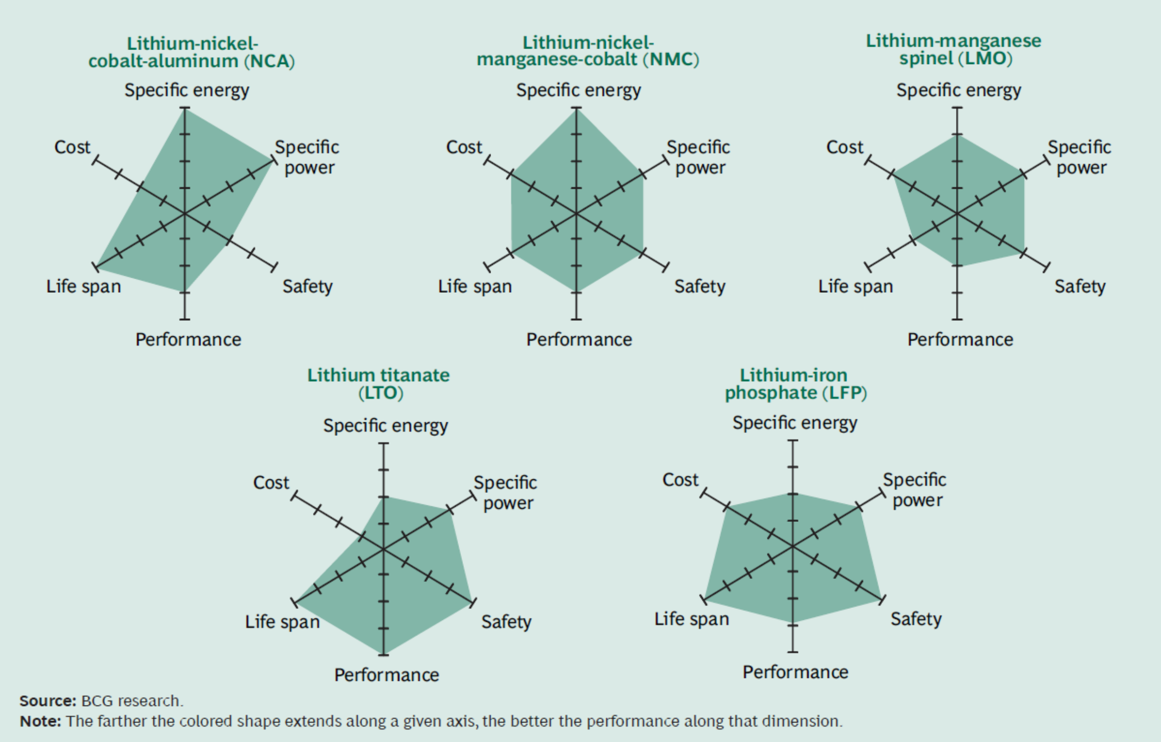
Another type of lithium-ion battery that shows promise is the nickel cobalt manganese battery. These batteries have a better specific energy and longer lives compared to many other lithium-ion approaches. The increased energy is associated with a longer range. For the same range, this chemistry allows the battery pack to be lighter and take up less space. This approach is used in many light-duty plug-In electric vehicles such as the new Chevrolet Volt, Chevrolet Spark EV, and Hyundai Sonata plug-in hybrid electric vehicle.

As can be seen from Table II-1 and Figure II-4, there are trade-offs for each lithium battery type. One may have better energy density but a shorter life expectancy. Another might have a good life expectancy but have potential safety issues. Figure II-4 visually compares different lithium battery technology. Six characteristics are included for all the battery chemistries to allow for an easy comparison:

- Battery safety;
- Life span (measured in terms of both number of charge/discharge cycles and overall battery age);
- Performance (peak power at low temperatures, state-of-charge measurement, and thermal management);
- Specific energy;
- Specific power; and
- Battery cost.

Figure II-4 makes the case that there is not a single battery chemistry that can be used in every on-road application. When BEV manufacturers are considering different lithium battery chemistries for vehicle usage, the vocation of the BEV must be considered. This is different from the approach used in conventional diesel trucks, where a diesel engine can end up in a multitude of vocations. It is important to note that when analyzing Figure II-4, the farther the shape extends along a given axis, the better the performance is in that dimension (Deutsche Bank, 2009). As an example, lithium titanate can be considered to be more expensive than lithium iron phosphate batteries but provide better performance.

Figure II- 4: Tradeoffs Among Lithium-Ion Battery Technologies



Source: BCG research.
Note: The farther the colored shape extends along a given axis, the better the performance along that dimension.

(Deutsche Bank, 2009)

d. Lithium-Air Batteries

Lithium-air batteries are still in the research and development phase, but, if they prove out, will be a very useful tool for EVs of all sorts. The negative electrode is lithium, but the positive electrode is atmospheric oxygen, allowing a theoretical specific energy similar to that of gasoline, at over 5200 Wh/kg. Lithium is oxidized at the anode and oxygen is reduced at the cathode (Imanishi & Yamamoto, 2014; Zhong, 2011). Further, significant reductions in battery weight can be realized by using the atmosphere as a cathode. Lithium sulfur and solid state lithium-ion batteries also show promise.

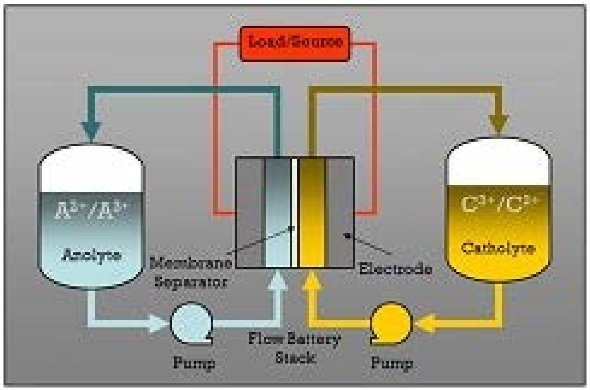
e. Molten Salt Batteries

The ZEBRA battery is one of the more popular molten salt battery chemistries and is currently being used in several medium-duty (8,501-14,000 lbs. GVWR) and heavy-duty (>14,000 lbs. GVWR) vehicle demonstrations. It uses molten sodium as a negative electrode and nickel chloride as a positive electrode. The electrolyte is beta alumina (Zebra, 2005). These batteries have a modest specific energy of 90-120 Wh/kg and have a long cycle life. In fact, durability of over 8 years has been demonstrated. The batteries can also recharge to 80 percent in only 75 minutes. Although the power density is relatively low, it is sufficient, and these batteries have been demonstrated in medium- and heavy-duty applications, such as the Motiv Power Systems' refuse truck discussed in Chapter IV In-Use Medium- and Heavy-Duty BEVs. They are also under consideration for rail operations. Molten sodium batteries operate above the melting point of sodium, which is 208 F. While the hot battery does use power when not in operation, the heat is self-maintaining in use, and no vehicle energy is required to keep the battery hot. If the battery is to sit unused for more than 3-4 days, however, it will begin to cool and will need to be reheated before it can be used. This battery is not affected by external weather conditions while in use as are other battery chemistries.

f. Flow Batteries

Flow batteries are another innovation that could revolutionize the EV field if they can be developed for use in mobile sources. Flow batteries are currently only used for electrical grid energy storage. A flow battery is akin to both a fuel cell and a battery. The liquid electrolyte holds the energy rather than the electrodes, and spent electrolyte can be drained and replaced in a similar fashion to current liquid or gaseous fuels used for conventional trucks and buses "at the pump" and be re-energized externally for re-use. Most flow battery systems have two electrolytes and rely on oxidation/reduction reactions; an example is presented in Figure II-5, Overview of a Flow Battery. Range is determined by the size of the tanks. Flow batteries produce a high power density in the lab, about 10 times higher than typical lithium batteries (Nguyen & Savinell, 2010).

Figure II- 5: Overview of a Flow Battery



- Discharge reaction
  - $C^{3+} + e^- \rightarrow C^{2+}$ (reduction)
  - $A^{2+} \rightarrow A^{3+} + e^-$ (oxidation)
- Charge reaction
  - $C^{2+} \rightarrow C^{3+} + e^-$ (oxidation)
  - $A^{3+} + e^- \rightarrow A^{2+}$ (reduction)

(ESA, 2014)

Redox flow batteries rely on electroactive couples. Most common currently are vanadium redox and polysulfide bromide. For a redox flow battery, an electron is released during discharge via an oxidation reaction from a high chemical potential state on the negative side of the battery. The electron moves through a circuit to do work, and is then accepted via a reduction reaction at a lower chemical potential state on the positive side of the battery. During re-energization of the electrolytes, the reactions are reversed. The electrodes do not take part in the reaction but serve as substrates for the reactions, so cycling does not cause any issues for anode or cathode durability.

Power rating is determined by the size and number of electrodes in the cell stack, and the stack size is tailored to the system needs. The system energy is stored in the volume of electrolyte, which can be very large and easily changed out. At the moment, cost is still a major issue. While a redox flow battery allows for flexible layout, quick response time, and no need for equalization charging, the system is more complex than traditional batteries, due to the need for sensors, control units, and containment vessels. These batteries are still at the development and demonstration stage, with use in grid storage, but long-term, flow batteries may be an excellent choice for long range and nearly transparent EV operation.

In the redox flow batteries, there is an ion exchange membrane to keep the two electrolyte solutions separate. Avoiding a membrane brings down cost and increases reliability, as well as allowing more chemistry options. For example, liquid bromine and hydrogen are both inexpensive, but cannot be used with a membrane since the resulting hydrobromic acid would destroy it. In the bromine-hydrogen membraneless system, liquid bromine flows through the channel over a graphite cathode and hydrobromic acid flows under a porous anode. At the same time, hydrogen gas flows across the anode. The reaction is reversed to recharge the system. Membraneless systems rely on laminar flow to stop the two liquids being simultaneously pumped through a channel from mixing (Braff et al., 2013).

Still in the research and development stages, organic flow batteries are another option. In this variation, the organic molecule can be tailored to obtain needed energy and power characteristics. These flow batteries are metal-free. Quinones are one of the charge carriers currently being investigated, and could potentially contain twice the energy in a given volume as that seen for inorganic flow batteries (Huskinson et al., 2014).

Table II- 1: Summary of Battery Chemistry Characteristics

Battery Chemistries	Specific Energy [Wh/Kg]	Life span [Cycles]
Nickel Cobalt Aluminum or Li NCA	160	2000+
Lithium Manganese Oxide or LMO	150	1500+
Nickel Manganese Cobalt Oxide or NMC	150	2000+
Lithium Iron Phosphate or LFP	140	5000+
BYD’s Iron Phosphate or LFP	120	7000+
Lithium Titanate or LTO	90	5000+
Lead Acid or PbA	35	500
Nickel Metal Hydride or NiMH	70	3000+
Molten Sodium or ZEBRA	110	2000+
Lithium Air or Li Air	>5200	Unknown (long)
Flow Battery	Unknown	Unknown (long)

(See text, Chapter II A)

2. Battery Management System (BMS)

The BMS manages battery charging, maintains proper voltages for use in different systems, and is involved in battery cell balancing. Further, the BMS can collect data on the battery's state of charge (SOC), battery temperature and rates of change in temperature and voltage, as well as track battery performance and health.

BMS in a simple form is a battery monitoring system that keeps track of the key operational parameters during charging and discharging. There are three main objectives to all BMSs:

- Protect the battery cells from damage;
- Prolong the life of the battery; and
- Maintain the battery in a state in which it can fulfil the functional requirements of the application for which it was designed.

For BEVs, the BMS is very complex, and it presents a significant challenge since it affects all aspects of vehicle performance. The BMS is tightly integrated within the battery and battery charging systems. It monitors the key battery operating parameters such as voltage, current, and temperature as well as controls the charging rate to provide the required charging profile. It triggers protection circuits if the battery's operating limits are exceeded, isolating the battery if needed.

One of the primary functions of the BMS is to monitor and protect the cells from extreme operational or ambient conditions. Taking into account ambient conditions is very important in commercial medium- and heavy-duty vehicle applications because of the vehicles' harsh work environment. Batteries used for BEV applications are made up of long strings of cells in series to achieve higher operating voltages. BMSs incorporate a cell balancing scheme to prevent cells from becoming overstressed during charging. These systems monitor the SOC of each cell string. Switching circuits control the charge applied to each individual cell in the chain during the charging process to equalize the charge of all the cells in the pack. Since it is impractical to provide independent charging for all the individual cells simultaneously, the balancing charge must be applied sequentially. Cell balancing regimes are being developed that minimize balancing time requirements. The BMS is designed to cope with the repetitive high energy charging pulses such as those from regenerative braking as well as the normal battery charging process.

Determining the SOC of the battery is the second major function of the BMS. The BMS uses a battery model that is characterized in the software algorithm to predict the behavior of the battery in response to various external and internal conditions, and uses these inputs to estimate the status of the battery at any given time. SOC estimates are complicated by the fact that the useable capacity of a cell is not necessarily constant but can vary significantly with temperature, charge discharge rates, and the age of the cell.

B. Inverters, Rectifiers and Converters

Inverters, rectifiers and converters all act to manipulate electrical current to do useful work on-board an EV. Inverters act to change batteries' DC power to AC power for use in motors or for exportable power for work-site needs. Rectifiers convert AC power to DC power: this is needed to charge battery systems from grid power. Converters allow for DC to DC conversions to ensure that the correct voltage is seen by subsystems in use on the vehicle. For example, a converter is used to step down the voltage from the traction battery for use on vehicle accessories, replacing the traditional low voltage PbA system battery currently in use with conventional trucks and buses.

BEV power electronics such as converters and inverters do not generally benefit from the increased production and deployment of light-duty zero-emission and plug-in hybrid electric vehicles. Though light-duty vehicle utilize similar types of power electronics as found in medium- and heavy-duty BEVs, they are not generally suitable for use on medium- and heavy-duty truck and bus applications due to the higher power equipment for truck and buses. In addition, significant hardening or ruggedization of power electronics is needed to withstand the harsh working environment of medium- and heavy-duty trucks and buses in commercial applications.

Significant advances in the durability of power electronics is needed for wider spread medium- and heavy duty BEV penetration. Commonality of power electronics among different truck and bus platforms would reduce the overall cost of BEVs and allow for wider penetration of BEVs into medium- and heavy-duty truck and bus segments.

C. Electric Motors

Electric motors convert electrical energy stored in the batteries into mechanical energy to propel the vehicle. Electric motors are used in all BEVs, replacing the internal combustion engine found in conventional trucks and buses. Further, the transmission can be eliminated in some applications where high speeds are not needed. Electric motors have been designed to use AC or DC power depending on the vocation that the vehicle is designed to fulfill.

Electric motors typically use rare-earth permanent magnets. Rare earth metals are costly, and increasing demand is likely to increase their costs. Much on-going research is focused on ways to reduce the use of rare-earth materials in electric motors; new approaches are regularly discussed in the literature.

AC motors have the advantage of not losing torque at higher revolutions per minute (RPM) like DC motors and therefore do not require the use of a transmission to facilitate higher vehicle speeds. However, transmissions in use with AC motors can allow for more efficient operations at higher speeds. Table II-2 below compares some attributes of AC and DC motors.

Electric motors can either be mounted in the driveline before the transmission (if used) to provide energy to the axles via a drive shaft or can be installed directly in wheel hubs. Wheel hub mounted motors can simplify the electric powertrain of a BEV, reducing future maintenance costs but can prohibit the use of a transmission, which typically is needed for higher highway speeds.

Motor controllers are used to govern the performance of an electric motor, such as starting or stopping the motor, regulating motor speed and torque, selecting forward or reverse, and protecting the motor from overloads or other harm. All types of electric motors use some form of controller.

Table II- 2: Comparison of AC versus DC Motors

AC Motor	DC Motor
Transmission Not Required	Multispeed Transmission Required
Light Weight	Heavier for Equivalent Power
Less Costly	Higher Cost
95 percent Efficiency at Full Load	85-95 percent Efficiency at Full Load
Expensive Controllers	Simple and Less Expensive Controllers
Requires Inverters	No Inverters Required

D. Vehicle Auxiliaries

In conventionally-fueled trucks and buses with reciprocating internal combustion engines, auxiliaries typically pull power away from rotating engines using pulleys and belts. Even if the air conditioning on a vehicle is not in use, it is still pulling power away from the reciprocating engine due to the pulley and belt system employed. BEVs still require the use of typical auxiliaries, such as power steering and air conditioning. The electrification of auxiliaries facilitates the draw of power for auxiliary operation only when needed and minimizes the parasitic load that these devices impose. Electrically-powered auxiliaries such cooling fans or air compressors can be operated as needed and can run at speeds that are independent of a conventional engine’s speed, reducing power requirements. Further, by increasing the efficiency of electrified auxiliary systems, power stored in on-board batteries can be used to maximize the range of the BEV, rather than powering auxiliaries, therefore reducing the size of the needed battery, and reducing overall vehicle cost. Auxiliary loads can represent up to nine percent of the energy used on a conventional truck; therefore any efficiency that can be realized in any BEV system need to be exploited (CalHEAT, 2013a). Auxiliary electrification is currently in the research and development stage with the major truck manufacturers, and has limited commercial availability from specialty manufacturers.

Advances in auxiliary electrification and on-board hydraulic pump controls can increase BEV range without adding larger batteries and increasing cost.

III. BEV CHARGING SYSTEMS

This chapter provides an overview of different charging approaches and strategies, various types of chargers, power delivery methods, and charging infrastructure found in BEV operations.

It is important to note that currently for medium- and heavy-duty trucks there is not a standard charging infrastructure that is used across different truck and bus platforms. Instead, each electric transit bus company has developed charging options for their product lines, such as Proterra's on-route overhead conductive system and BYD's bus yard-based wall mounted chargers. All charging systems for BEV trucks are project-specific, and installation issues will be very site-specific.

A. Conductive and Inductive Charging Systems

1. Stationary Vehicle Charging

All BEVs require charging systems to replenish the energy that has been used by the vehicle's propulsion system (electric motors) and ancillary systems. There are two main ways that the battery can be charged. First, and most typically, the vehicle can be "plugged in" via a conductive connection and energy delivered directly into the battery pack/battery management system. Conductive charging requires a physical connection, generally a cord and plug. The physical connection provides an efficient transfer of energy, typically about 95 percent.

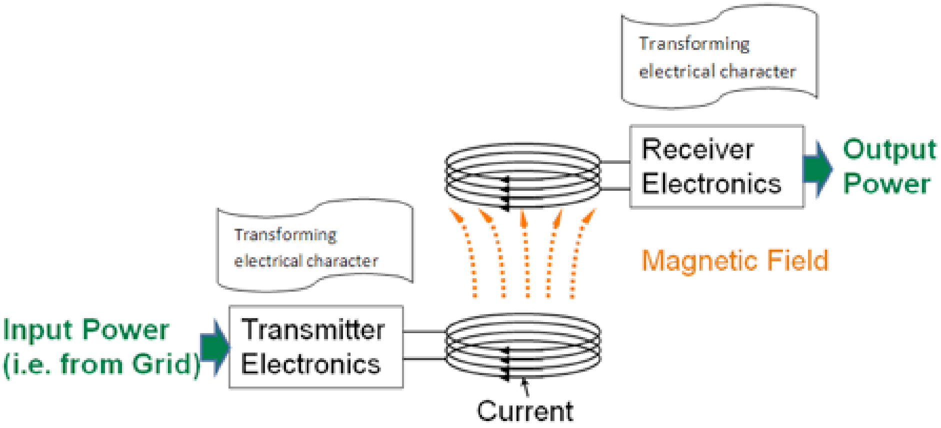
Figure III-1 shows TransPower's electric yard tractor utilizing conductive charging. Notice the blue plug just aft of the front wheel, which is connected to a mobile power supply that is providing AC current to the yard tractor.

Alternately, the energy can be delivered inductively. With inductive charging, there is no direct connection. Figure III-2 includes the basic components of an inductive charging system. Although currently less efficient, the inductive system does not require a physical connection to be made. The battery (in its vehicle) is simply moved into close proximity to the inductive coils, and the charging occurs automatically by magnetic resonance coupling. Inductive chargers are typically located overhead or in the roadbed beneath the vehicle. Inductive charging systems are very convenient and require little driver attention. However, they generally have an energy transfer efficiency rate of around 70 percent, and are more costly than conductive systems. Progress is being made on the efficiency front, however, and some systems now achieve a transfer efficiency of approximately 80-90 percent. In fact, Qualcomm is developing an inductive system (Halo WEVC) that is more than 90 percent efficient (Harris, 2013).

Figure III- 1: TransPower Yard Tractor Demonstrating a Conductive Charging System

(Transpower, 2013)

Figure III- 2: Basic Components of an Inductive Charging System



(Mick, 2012)

2. Dynamic and Semi-Dynamic Vehicle Charging

BEVs are usually charged while stationary. Stationary charging involves plugging into the energy source (conductive) or parking the vehicle over a pad with inductive coils embedded in the road or overhead. But there are also methods to provide power to vehicles "on the move." This type of charging is termed Dynamic Electric Vehicle Charging (DEVC). Conductive DEVC can use a catenary system with overhead wires to transfer electricity, while inductive DEVC can use inductive coils embedded in the roadway.

A new demonstration project is beginning in Southern California that will utilize overhead catenary wires to conductively supply power to three demonstration trucks that utilize retractable pantographs to access the overhead wires. One of the three trucks that are to be demonstrated will be a heavy-duty BEV drayage truck while the other two will be hybrid trucks with battery packs that allow for some zero-emission range (Siemens, 2014). This new demonstration is for Siemens eHighway system and is being funded by the SCAQMD and the U.S. DOE. Figure III-3 below shows an eHighway-equipped truck under the catenary lines.

Figure III- 3: Siemens' eHighway Demonstration Truck

(Ridden, 2012)

It is also possible to inductively charge during slow-movement scenarios, as when the vehicle is in a slow moving queue. This type of semi-dynamic inductive charging could be utilized at intermodal yards, weigh stations, and other places where vehicle movement is slow. Charging is activated when the vehicle is aligned above each pad; pads activate and deactivate as the vehicle moves over them. Semi-dynamic charging could also be implemented at traffic lights or road junctions where vehicles are slowly moving or stationary for a few minutes.

3. Combination of Conductive and Inductive Charging

Though not currently employed in a commercial truck or bus, a combination of inductive and conductive charging may be the best option for vehicles like buses with pre-set routes. Locating an inductive charging station at the end of the route, where buses stay for a few minutes, can provide a top-up charge. Full conductive charging would take place overnight and be performed at a bus depot. This combination would allow the battery pack to be downsized, which reduces the cost of the pack, reduces the weight of the bus, and increases bus capacity, thus reducing the total cost of bus ownership.

4. Opportunity Charging (Charging en route)

Opportunity charging is a stationary charging system where the battery is charged wherever power is available or between partial discharges rather than waiting for the battery to be completely discharged. Opportunity charging can be subject to wide variations in energy availability and power levels. Special control electronics are needed to protect the battery from overvoltage. Employing opportunity charging can reduce the size of the needed battery pack, provide for an increased range since charging can take place away from a truck or bus yard, reducing overall cost of ownership and allay range anxiety fears of commercial truck and bus operators. Though opportunity charging is not currently employed as a range extending strategy in commercial trucks and buses, Proterra’s electric buses do utilize en route charging to essentially allow for continual usage of their buses on fixed transit bus routes.

En route charging for BEVs can mean a system analogous to the gasoline station or it can mean specialized systems that will require fixed routes that may be expensive to modify later.

B. Battery Swapping Strategies

There is another option to replenishing the charge of on-board BEV batteries. Battery swapping systems utilize a standardized battery conformation and connection that allows for fully charged reserve battery packs to be stored and ready for use at strategic locations. The exhausted battery pack is removed and the charged pack installed in its place. This strategy has been demonstrated in China for a fleet of 100 buses operating on fixed routes. The Chinese system is automated and takes about 8-10 minutes to replace the packs (CALSTART, 2013). Battery swapping systems enable off-peak charging and a rapid return of the vehicle to active service. However, battery swapping requires battery standardization and ruggedization of battery packs, significant storage and operational space, and could increase equipment costs because extra battery packs would need to be on-hand to meet operational needs. Battery swapping could introduce creative battery leasing schemes, with spare batteries that are charged but standing by to be used for grid stabilization or grid storage further reducing battery ownership costs.

C. Classification of Chargers

Chargers for trucks and buses have not been standardized to allow for interoperation between different manufacturers of medium- (8,501 - 14,000 lbs. GVWR) and heavy-duty (>14,000 lbs. GVWR) vehicles. Chargers are classified by the level of power they deliver to the battery pack. Level 1, 2, and 3 chargers use AC power from the grid and convert it to DC power at a suitable voltage for charging the battery. DC fast chargers deliver DC directly to the vehicle. In BEV applications, level 1 and level 2 chargers can be completely contained within the vehicle. On-board chargers are limited in power output because of size and weight restrictions dictated by vehicle design, while off-board charges are only limited in power output by the capability of the batteries to accept the charge. Their higher power delivery ability allows a faster charge, and no additional weight or design constraints exist for the charging system since it is external to the vehicle. However, there are some battery considerations that need to be understood to utilize fast charging.

In DC fast charging systems, the charging functions are split between the charging station and the vehicle's on-board charger. Because of the high power requirements in wayside level 3 and DC fast charging systems (up to 240 kW per station), both systems can only be connected to the grid where utilities can provide a dedicated supply line capable of delivering the very high currents demanded.

It is important to note that charging speed can impact battery life; with lithium ion batteries, fast charging can cause lithium dendrites to form between the anode and cathode. This phenomenon is more pronounced with some battery chemistries than in others. For example, lithium titanate batteries are very durable in fast charge applications, and are being utilized by Proterra in their transit buses because of this trait.

Vehicle charging classifications are summarized in Table III-1.

Table III- 1: Charging Classifications

	Current Type	Amperage	Voltage	Kilowatts	Charge Time in Hours*	Primary Use
Level 1	AC	Up to 15	120	Up to 1.8	6-20	Residential Charging
Level 2	AC	Up to 80	240	Up to 19.2	3 to 8	Residential and Public Charging
Level 3 **(Under Development)**	AC	up to 200	up to 600	TBD	Less than 0.5	Public Charging
DC Fast Charge	DC	Up to 200	480	Up to 240	Less than 0.5	Public Charging

(AFDC, 2015)

- **Level 1:** Common household circuit rated at 120 volts AC and 15 amps. These chargers use the standard three-prong household connection.
- **Level 2:** Permanently wired EV supply equipment rated up to 240 volts AC, up to 80 amps, and 19.2 kilowatts. Level 2 chargers are used specifically for EV charging. In the light-duty vehicle segment a standard already exist, Society of Automotive Engineers (SAE) J1772, and is used by most domestic zero-emission or plug-in hybrid vehicles (SAE, 2001).
- **Level 3:** SAE is currently developing standards for three-phase conductive charging with a primary source voltage of up to 600 volts AC and up to 200 amps. This type of charging is expected to provide a fast AC charging option.
- **DC fast charging**: Uses a 480-volt connection to provide 50 kW or more to EV batteries.

D. Charging Infrastructure

In order to successfully deploy electric trucks and buses in California, there has to be a robust charging infrastructure in place to satisfy a variety of BEV charging needs. In the early stages, BEVs will be used in vocations that operate in the optimal BEV duty cycle discussed in detail in Chapter VII. Important infrastructure challenges to overcome include developing a regional charging infrastructure and incentivizing private companies to install charging stations on their premises and encouraging them to share with other companies with BEVs to maximize equipment utilization. The current rollout of light-duty BEV charging may benefit truck and bus charging needs in the short term by allowing emergency opportunity charging to trucks and buses that have depleted battery packs and in the mid- and long-term, by showing that supplying vehicle charging infrastructure can be a part of a profitable business model.

It is likely that both conductive and inductive charging infrastructure will be needed. The conductive charging infrastructure will probably evolve to a “gas station model” for BEVs with random routes that need to charge during the day or at the end of their shift. The inductive charging infrastructure could play a major role for BEVs with designated routes, like transit buses and drayage trucks, where charging stations can be located at the end of the route and can be used for a few minutes to top-off the batteries.

Advanced technologies such as Piezo Electric Generators (PEGs), utilizing the piezoelectric effect, may one day be used to harvest parasitic mechanical energy that is now being absorbed by roadways and bridges. By placing PEGs in a roadway, the compression of the imbedded PEGs by passing vehicles can generate electricity. If such generators are sited near where BEVs are housed, such as school bus yards, then energy generated from such systems could be used to provide power to charge wayside battery packs that can then be used to recharge traction batteries on-board BEVs regardless of the time of day, therefore avoiding any peak demand charges. A project was proposed to demonstrate this technology in Israel that claimed to be able to generate 400 kW of power from a 1 kilometers length of 2-lane roadway (Hanlon, 2008). Though this technology may not be feasible in the near term, creative concepts to harvest parasitic energy can provide a significant reduction in criteria and GHG emissions associated with a specific BEV fleet that can utilize such technologies, while reducing wear on transportation infrastructure.

It is important to realize that the obstacles needed to be overcome for installation of charging infrastructure are site specific and that each installation will have its own unique issues that need to be addressed, such as optimal location, electrical transformer limitations, other utility components competing for space at the truck or bus yard, burying of electrical conduit, and other site specific issues that may not be fully realized until work starts on charger installation. These obstacles may be significant.

As medium- and heavy-duty BEVs become more widely used, their charging infrastructure needs and impacts on the grid must be considered and addressed. Some of the site-specific issues affect the system costs, discussed in Chapter V.

IV. MEDIUM- AND HEAVY-DUTY TRUCK AND BUS BEVS

The focus of this Technology Assessment is on BEVs in the medium- and heavy-duty on-road vehicle classes. While relatively few medium- and heavy-duty BEVs are on the road to date, light-duty EVs are becoming increasingly popular. Some but not all light-duty technology can be transferred to the medium- and heavy-duty sectors, with the caveat that the technology often needs to be ruggedized, and that energy demands are higher. Reliability for medium- and heavy-duty BEVs is even more critical than for light-duty vehicles, since business depends on the reliability of these vehicles.

BEVs have been used in medium- and heavy-duty applications as follows:

- Transit buses (33,000+ lbs. GVWR); Urban Class 3-8 Vocational Bus
- School buses (14,000-33,000 lbs. GVWR); Urban Class 3-8 Vocational Bus
- Shuttle buses (14,000+ lbs. GVWR); Urban Class 3-8 Vocational Bus
- Medium-duty trucks (8,501-14,000 lbs. GVWR); Rural/Intercity Trucks
- Heavy-duty trucks (> 14,000 lbs. GVWR); Over the Road Trucks

Each of these applications is discussed further below. Section A discusses transit buses while Section B examines current efforts for the electrification of school buses. Section C focuses on medium-duty trucks and shuttle buses. Finally, heavy-duty trucks are the focus of Section D.

A. Transit Buses

Battery all-electric transit buses are in limited commercial availability; volumes of battery all-electric buses worldwide are in the couple of thousand bus level, with nearly 40 buses in service in California. Some of the earlier demonstrations of these buses, now underway or near completion, help to illuminate the operational and maintenance savings that BEVs can yield when compared to conventionally-fueled transit buses, and have proved the viability of electric bus technology.

Battery all-electric transit buses utilize an all-electric drive powertrain powered solely by an onboard battery storage system along with other electric components and features such as regenerative braking that are common in medium- and heavy-duty BEVs. Urban transit buses are an ideal application for battery all-electric heavy-duty vehicles because they operate on fixed routes of normally short distances, perform frequent stop and start driving which is needed for regenerative braking, maintain low average speeds which helps to preserve the battery power, and return to a general base or facility at the end of the day which enables overnight charging.

Many transit bus manufacturers have been reluctant to enter the battery all-electric market, resulting in smaller domestic and foreign companies entering the market.

Currently in the US, there are three manufacturers that offer battery all-electric transit buses for sale: Proterra; BYD; and New Flyer. Nova is currently demonstrating a prototype. Figure IV-1 below illustrates Proterra's first generation bus aligned with its overhead conductive charger, and the more recent 40 foot model.

Figure IV- 1: Proterra Battery Electric Bus

(Piellisch, 2014) (Proterra, 2015b)

Proterra's battery all-electric CATALYST™ transit bus operates with on-route fast charging technology. This fast charging is done through the use of a 500kW overhead charging station that recharges the batteries in less than 10 minutes. The overhead charger utilizes wireless bus identification that detects the bus when it is within range from the charger; it then automatically assists the bus in the charging process by lowering the speed of the bus and guiding the charge head into place to make physical contact with the lithium titanate batteries. The buses can operate for approximately 30-50 miles on a single charge before needing another quick charge (Proterra, 2014). In transit applications, the fast charge technology works by installing various charging stations along a transit bus route where a bus normally has a layover for a few minutes. By taking advantage of this layover and charging the bus in this time period, the bus' daily range is significantly increased. In cases when the bus cannot use the overhead charging station, the bus design allows for the use of a slower charging option. The current model is a 40 foot bus which is the most common bus size relied on by transit agencies to meet their needs. This Proterra bus has a 100kWh battery pack and a 220kW electric motor, although the new Extended Range model increases the pack size up to 321 kWh, allowing up to 180 miles per charge.

Figure IV-2 shows a BYD battery bus in service. BYD's battery all-electric transit bus operates with slow charge technology, typically charging over a period of a few hours utilizing a plug-in conductive charger as discussed in Chapter III BEV Charging Systems. The BYD bus uses Lithium-Iron-Phosphate battery chemistry typically

Figure IV- 2: BYD Electric Transit Bus on Route

(Strauch, 2014)

referred to as “Iron-Phosphate” and has large battery packs with a capacity of 360 kWh. The long life of these batteries is attested to by their 12 year standard warranty. BYD bus charges these battery packs by plugging into a wall mounted AC charger, similar to other EVs on the road today. The charging time varies depending on the type of charger; a 60kW charger takes 5 hours to fully recharge the batteries while a 200kW charger recharges the batteries in less than 2 hours. The bus has an operating range of up to 155 miles on a single charge which is reported as a sufficient operating range to allow buses to be used all day without requiring a recharge. In addition to the large battery packs, the bus employs wheel hub mounted electric drive AC motors that come in two sizes, 90kW or 180kW. BYD offers the standard 40 foot transit bus model and has a 60 foot articulated bus model that is in development (BYD, 2014a). Showcasing the new model is currently underway in California.

New Flyer’s Xcelsior XE40 electric transit bus, shown in Figure IV-3, can utilize en route or yard charging. Two buses are in use in Chicago, undergoing a year of testing before potentially exercising a purchase option for additional units. The buses have a 80-120 mile range from a 300 kWh NMC battery pack. Given the Chicago winters, the buses delivered in 2014 do have diesel heaters and so are not wholly electric. However, models sold in California will utilize electric heaters. New Flyer also has four Xcelsior buses in operation with Winnipeg Transit. The buses are available in 100, 200, 250, and 300 kWh configurations, and use an overhead pantograph charging system; a 10 minute charge will allow 2 hours of operation (New Flyer, 2014).

Figure IV- 3: New Flyer Electric Transit Bus On Route

(New Flyer, 2015)

Figure IV- 4: Nova Electric Transit Bus Prototype

(Novabus, 2015b)

Nova has also developed an electric transit bus. Montreal will begin a demonstration project involving three Nova electric buses later this year. The 40 foot bus uses $LiFePO_4$ batteries to power a 230 kW motor. Fast charging is completed via an overhead inverted pantograph. The bus requires 6 minutes of fast charge time per operating hour (Novabus, 2015a). This bus, shown in Figure IV-4, is not yet available for purchase.

Table IV-1 summarizes the vehicle specifications for BEV transit buses that are currently available for sale in the United States. Prices listed are current as of early 2015, but have been on a significant downward trend over time. Even at current prices, the payback period for these buses is estimated to be only a few years after application of available incentives and full 80 percent federal funding, as discussed in Chapter V E. When coupled with O&M savings, the payback period may little more than a year. Note that the payback calculations do not include infrastructure costs, as these are highly variable and site-specific. Including these costs will increase the payback period; however, these costs are spread out over the fleet of electric buses, and are not on a per bus basis. In addition, the expected life of the charging station may exceed the useful life of the bus.

The costs for 40 foot all-electric buses are around \$800,000, compared to \$485,000 for 40 foot clean diesel buses. 30 and 35 foot buses are also available from BYD, starting at \$350,000. BYD's new 60 foot articulated model is expected to cost \$1.2M, compared to \$600,000 for a conventional clean diesel articulated bus or \$800,000 for a comparable natural-gas articulated bus (Masunaga, 2014). Note that many transit agencies do require the use of natural gas buses, so the incremental cost may be best assessed based on a natural gas baseline, rather than diesel bus baseline.[3] Each bus will use about \$5-10,000 per year in electricity costs, compared to around \$50,000 annually for diesel fuel buses and \$30,000 in fuel for buses using natural gas (Borinson, 2014). Over the bus's 12 year lifetime, these fuel cost differences add up to significant savings for the all-electric buses. Proterra has calculated that electric buses will save \$500,000 in fuel costs alone over the 12 year life, as well as \$70-95,000 in maintenance costs. Nonetheless, purchasing an all-electric bus does result in additional upfront costs compared to a standard diesel transit bus, even after federal and HVIP funds have been applied. There are a number of financing options that can help with the remaining differential, including grants and various lease options.

Domestic transit buses typically receive funding from the FTA, offsetting a significant portion of the buses' total cost. To be eligible for FTA funding, the buses must undergo testing at the Altoona Bus Testing and Research Center in Pennsylvania. The test program at Altoona currently does not give a pass or fail for buses that participate, however, a pass or fail system is expected to be introduced soon. The goal of the program is to ensure better reliability and in-service performance of transit buses by providing an unbiased and accurate comparison of bus models through the use of an established set of test procedures (Altoona, 2014). Both Proterra and BYD's buses

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[3] The Discussion Document for the advanced transit bus proposal provides an incremental cost based on existing natural gas technology, since the majority of transit buses in California currently are powered by natural gas (ARB, 2015a).

Table IV- 1: Battery All-Electric Transit Bus Specifications

Make	Proterra	BYD	BYD	New Flyer
Model	40 foot	40 foot	60 foot	40 foot
Price	$800,000	$800,000	$1.2M	Not available
Battery Size (kWh)	100	360	590	300
Motor (kW)	220	90 or 180	360 (180 kW wheel motors)	160
Charge Time	<10 minutes	2 - 5 hr*	2 - 3 hr**	10 min gives 2 hours of operation***
Range on Single Charge	30-40	155	170+	80-120

*using a 200 kW charger or a 60kW charger respectively
** using a 200 kW charger
*** using a 300-500 kW charger; 1.6 hours to fully charge 1ith 100 kW shop charger
(See Chapter IV A for sources of data.)

have completed the Altoona tests and those reports are available on-line at: http://www.altoonabustest.com/ (Altoona, 2014). New Flyer began its Altoona tests in late 2014.

Studies of reliability of BEV transit buses have not been published in the literature. However, Proterra (Proterra, 2015a) reports a dispatch availability of 95-96 percent, comparable to conventional fuel bus availability. This is based on over one million miles in revenue service.

Lab tests results reported by BYD in the media indicate that BYD's battery packs will have a useful life of 20-25 years in transit application. This is greater than the anticipated lifespan of the buses powered by the batteries. Thus, the batteries should not need replacing during the useful life of the all-electric bus. The Proterra battery pack is not warrantied for as long a period as the BYD battery pack, though an extended warranty is available. The battery cycle data indicates that the batteries would be anticipated to last the life of the bus; if not, a replacement battery pack is said to be available for under $60,000, and likely less in the future when the replacement may actually be needed. When considering this possible battery replacement need, it is useful to consider that diesel buses often need engine overhaul or replacement at mid-life.

Table IV-2 shows battery all-electric transit buses that currently have been deployed by manufacturer, location and volume. The vast majority to date have been placed in China. As a point of interest, Seoul plans to have half of its bus fleet be electric buses by 2020.

There are currently over 18,000 transit buses in operation in the state, with an additional 4,000 medium-duty shuttle buses representing 35.7 million metric tons (MMT) of carbon dioxide (CO_2) annually. Many of those transit and shuttle bus routes could employ BEV technologies, significantly reducing the total GHG emissions from this sector. To this end, ARB is holding workshops to discuss potential fleet requirements for zero- and near-zero-emission transit buses. The current discussion document for the advanced transit bus proposal is available at http://www.arb.ca.gov/msprog/bus/bus.htm (ARB, 2015a).

B. School Buses

School buses which operate in urban or suburban environments typically operate in the optimum BEV duty cycle as discussed in Chapter VII: defined routes; high incidence of start and stops; lower average speeds; and high idle times. School buses typically may do one or two routes in the morning and again in the afternoon, but otherwise can be connected to charging infrastructure in the late morning and early afternoon. This makes the use of cost saving technologies that reduce the overall cost of ownership such as V2G particularly amenable to school buses. Using V2G generates a revenue stream for the bus owner during the day by selling surplus power back to the grid during peak energy demand hours.

School buses are not yet as commercially available as transit buses. This is due to a number of factors. First, California Highway Patrol (CHP) safety certification is required prior to any school bus transporting children and each model needs a separate approval. This is the case even for a BEV retrofit of a previously approved model. Further, the large school bus manufacturers in the US, Bluebird, IC Bus, and Thomas

Table IV- 2: BEV Transit Bus Deployments

Manufacturer	Location/Customer	Number of Buses
Proterra	Stockton, CA - San Joaquin RTD	2*
	Pomona, CA - Foothill Transit	15*
	Reno, NV - RTC	4
	San Antonio, TX - VIA	3
	Louisville, KY - TARC	10*
	Nashville, TN - MTA	9
	Tallahassee, FL - StarMetro	6
	City of Seneca, SC - CatBus	6
	Worcester, MA - WRTA	6
BYD	Los Angeles, CA- LA Metro	5
	Stanford, CA- Stanford University	13**
	Lancaster, CA - AVTA	2
	Gardena, CA	1
	Netherland	45
	Malaysia	15
	South America	15
	China	2500
	Israel	1
New Flyer	Winnipeg – Winnipeg Transit	4

*There are a total of 25 more buses on order for these customers as well as 22 to 5 new customers.
**There are a total of 10 more buses on order for this customer, as well as 19 to 4 new customers.
(Customer data was provided by manufacturers and was current as of mid-1015.)

Built, are not involved in electric bus production. The TransTech SSTe type A school bus is available for purchase, however, and Lion, a Canadian company, has recently released the eLion type C school bus, priced at $335,000 including tax and delivery. This makes the electric school bus in early commercialization. TransPower developed the eTrans, but has failed to get FMVSS certification to date, so is not yet approved by CHP. TransPower has completed at least one conversion of a Thomas Built school bus which has been approved by CHP.

Electric school buses have the potential for significant market penetration in the next 5 to 10 years. ARB has funded three electric school bus demonstrations to date (Table IV-3), starting in fiscal year 2011-12 and those projects have been completed, with buses now transporting children daily. The final reports from these projects are posted on ARB's AQIP Advanced Technology Demonstration Project webpage at: http://www.arb.ca.gov/msprog/aqip/demo.htm (AQIP, 2014a).

These buses constitute 3 of the 4 operational, CHP approved, electric school buses in California. All four of the electric school buses are in service transporting students. Two were manufactured by Motiv/TransTech, and one was a Type D (>33,000 lbs. GVWR) conversion by TransPower (see Figures IV-5 and -6). The fourth is a Type-D conversion by Adomani, discussed below. The CEC has recently funded a new electric school repower bus project with NSI/TransPower that incorporates Vehicle to Grid (V2G) on six Type C school buses (CEC, 2013), as mentioned in Chapter V BEV Costs. Further, there is another funding opportunity for electric school bus pilot projects in the new FY 14/15 AQIP's Truck and Bus Pilot Project (AQIP, 2014b).

Table IV- 3: ARB Funded Electric School Bus Demonstration Projects

Make	Weight Class	Range Miles	Battery Size kW-hr	Motor Size kW
TransPower School Bus	Type D (Heavy-Duty)	50-75	108	150
Motiv/TransTech School Bus	Type A (Medium-Duty)	60-80	88-110	150

(AQIP, 2014a)

Figure IV- 5: TransPower Type D Electric School Bus

(Transpower, 2013)

Figure IV- 6: Motiv/TransTech Type A Electric School Bus

(Motiv, 2014a)

The new eLion class C school bus, shown in Figure IV-7, holds 71 passengers, and has a 70 mile range, using a 105 kWh battery pack. This school bus is on a wider-than-normal chassis allowing for a more roomy interior. The bus recharges in 5 hours. With its anticipated savings of $13,000 in fuel each year and up to $3,000 in annual maintenance, Lion anticipates a payback in less than 6 years.

The Adomani bus, pictured in Figures IV-8 and IV-9, is in operation with Gilroy Unified School District. It utilizes an 83 kWh battery pack, and a 150 kW motor, and has an anticipated range of approximately 40 miles (Adomani, 2014). Several of the battery packs can be seen in the bus' luggage compartment in Figure IV-9. The charging system employed at Gilroy Unified School District is rated at 20 kW, with energy from the electrical grid supplemented by a solar array that reduces the criteria pollutant and GHG emissions associated with the use of this bus.

Electric school buses are also planned in Chicago and New York. The electric buses have twice the cost of a baseline school bus but cost an eighth as much to fuel and a third as much to maintain. Given that two to three times the vehicle cost is typically spent on fuel and maintenance over the life of a school bus, it is clear that the payback economics are in place.

Figure IV- 7: eLion Type C Electric School Bus

(Lion, 2015)

Figure IV- 8: Adomani Electric School Bus

(Adomani, 2013)

Figure IV- 9: Adomani Electric School Bus Charging Using Two Light-Duty J1772 Conductive Connectors

(Adomani, 2013)

Figure IV-10 is of a solar array that is deployed at Santa Clara Unified School District. This array is not part of an electric school bus project, but illustrates that many school districts are now deploying solar systems, which could be used to recharge electric school buses once the technology becomes more widespread. Such solar arrays could be used to reduce the impact of daytime bus charging on the electricity grid.

Figure IV- 10: Santa Clara Unified School District Solar Array

(Borregosolar, 2014)

As previously mentioned, the use of BEVs reduces or eliminates criteria pollutant emissions from the vehicle. When charged using renewable energy, emissions are reduced even further. BEV school buses completely eliminate diesel PM and NOx emissions from the bus thereby reducing children’s exposure to these pollutants.

Further, these buses have very quiet operations compared to conventional diesel buses and they lack the typical vibrations of a conventional diesel fueled bus. These quiet operational attributes are of particular benefit for special needs student transportation.

C. Medium-Duty Trucks and Shuttle Buses (8,501-14,000 lbs. GVWR)

The medium-duty category already has hundreds of EVs operating on California's roads; such vehicles are in the early commercialization stage. Vehicles in this category are being utilized in an optimal duty cycle for BEVs, urban delivery, and have ARB incentives to promote adoption. It is expected that widespread penetration into the market place will occur in the next 5 to 10 years. Figure IV-11 shows the EVI fully electric delivery van now in service with UPS. UPS received 17 of these vans using CEC demonstration funds; there are others that have been deployed as well. The CEC-funded vans cost around $143,000, including the purchase of the chassis and decommissioning of the existing powertrain. No performance or reliability issues have been reported to date (CEC, 2015).

As mentioned in Chapter V, ARB’s HVIP program has an incentive to help buy down the costs of BEV trucks and buses and will see further incentives beyond HVIP in FY14/15 with AQIP’s Truck and Bus pilot project. Most HVIP vouchers that have been issued for BEVs have been in the medium-duty vehicle weight class as shown in Table IV-4.

Figure IV- 11: Electric Vehicle International UPS Parcel Delivery Van

(CEC, 2014)

The medium-duty weight class has benefited from technology transfer from light-duty applications to a larger degree than heavy-duty trucks and buses, since these trucks require less power and typically drive fewer miles than heavy-duty BEVs. Medium-duty trucks that fall into the optimal duty cycle such as delivery and food distribution are ideal candidates for electrification.

Table IV- 4: HVIP Vouchers for BEVs by Vocation and Vehicle Class as of April 2015[4]

Vocation	Class 3	Class 4&5	Class 6	Class 7	Class 8	Total
Parcel Delivery	30	50	100	-	-	**180**
Beverage Delivery	3	-	26	-	-	**29**
Other Truck	-	-	6	-	-	**6**
Food Distrib.	1	1	96	-	-	**98**
Buses	-	-	-	-	10	**10**
Total	**34**	**51**	**228**	**-**	**10**	**323**

HVIP program statistics from CALSTART HVIP's project administrator

Figure IV-12 shows the Motiv Power Systems electric shuttle bus. Electric shuttle buses have the capability to fill many market niches currently occupied by conventionally-fueled medium-duty buses. Shuttle buses that service airports for rental car fleets or airport parking can be readily converted to electric operations, due to the well-defined routes. The use of opportunity charging can reduce the size of the needed battery system in this vocation, thereby reducing overall BEV costs and decreasing the return on investment timeframe. Further, hotel shuttles, or shuttles for special events can see significant BEV penetration. Simplification in maintenance requirements and

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[4] This table includes only vouchers actually paid for and issued. The July 2014 version of this table presented at ARB's September 2014 workshop included all vouchers requested; some requests were ultimately cancelled.

minimal regulatory requirements from an air pollution standpoint make these buses much simpler to operate than conventionally-fueled shuttle buses.

Zenith Motors offers an electric product line with configurations as delivery/work vans or as 12-passenger shuttles. The vans offer a range option of 90 or 120 miles, using $LiPO_4$ batteries, with around 6 hours required to recharge. With the available HVIP vouchers, Zenith is offering the 120 mile 350 cargo van configuration for a net cost of $40,400, which is comparable to the analogous Ram ProMaster gasoline unit. Figure IV-13 shows the Zenith Motors product line. Phoenix Motorcars also offers the Zeus electric shuttle bus. This 14 passenger shuttle bus has a 100 mile range and is also powered by $LiPO_4$ batteries.

Table IV-5 shows some of the specifications for several medium-duty trucks and shuttle buses that are discussed in this chapter. There are currently over 3600 shuttle buses in operation in the State, representing almost 5 MMT annual emission of CO_2; most of those bus routes could be serviced by electric shuttle buses.

Figure IV- 12: Motiv Power Systems Electric Shuttle Bus

(Motiv, 2014b)

Figure IV- 13: Zenith Motors Product Line

(Zenith Motors, 2014)

Table IV- 5: Medium-Duty (8,501 to 14,000 lbs. GVWR) Truck and Bus Vehicle Specifications

Make	Weight	Range Miles	Battery Size (kWh)	Motor Size (kW)
Motiv Shuttle Bus	Medium- Duty	80-100	110 or 132	150
Zenith Motors Cargo/Shuttle	Medium-Duty	90-120	52 to 62	135
EVI Walk-In	Medium- Duty	Up to 90	99	120
EVI Parcel Delivery Van	Medium- Duty	Up to 90	99	120

(See text, Chapter IV C)

D. Heavy-Duty Trucks (Over 14,000 lbs. GVWR)

Heavy-duty BEVs are now in the demonstration phase with two TransPower electric drayage trucks and one Motiv Power Systems electric refuse truck currently on the road engaged in the field demonstration phase of their projects. There are an additional 12 other Class-8 BEVs in varying stages of manufacture. As the hybrid truck market continues to expand with increasing market share in the regional trucking market, those increased production volumes may reduce common BEV/Hybrid component costs, further reducing the incremental cost of BEVs when compared to conventional diesel trucks.

Figure IV-14 shows the TransPower Class 8 all-electric drayage truck. This truck has a 70-100 mile range with its lithium iron phosphate battery pack (Transpower, 2015). TransPower's second drayage truck is just now entering demonstration service with a trucking company that services the Ports of LA and Long Beach. This demonstration project is being funded by the CEC and SCAQMD. U.S. DOE has awarded more funds to this truck project to expand the number of BEV drayage trucks that are being demonstrated to eight units. Additional funding, in the $25 million range, is anticipated for BEV demonstrations under ARB's Advanced Technology Demonstration Program for zero-emission drayage trucks. The solicitation will be released this Fall.

Heavy-duty truck operation can be a very demanding weight class for on-road trucks. Efforts to electrify vehicles in this category have begun with vocations that meet the optimal duty-cycle. There are not any commercially available heavy-duty BEVs outside the transit bus segment at this time, but there are several on-going demonstrations of BEVs in the heavy-duty vehicle sector with drayage trucks and refuse hauler projects underway, as previously mentioned.

Figure IV- 14: TransPower Electric Drayage Truck

(Transpower, 2015)

Motiv Power Systems, a Bay Area company that worked on AQIP's Type A/B electric school bus demonstration, has an all-electric refuse hauler in use in Chicago as shown in Figure IV-15. This refuse truck uses a 210 kWh molten sodium battery and has an 80-mile range. The City of Chicago has an option to order an additional 19 of these trucks pending the results of the demonstration. CEC recently approved funding to TransPower to demonstrate two electric refuse trucks in Sacramento County

Expanding BEV technology into most applications in the heavy-duty truck segment will require further developments in battery technology and lower vehicle component costs overall. It is not expected that BEVs can penetrate into the long-haul trucking vocation in the next several decades, where significant high speed steady-state operations dominate the vehicles duty cycle, without significant advances in battery energy density and BEV recharging technologies.

It is important to note that both of the heavy-duty trucks discussed above, the drayage and the refuse truck, operate in the optimal duty cycle for BEVs, as discussed in Chapter VII, which include shorter range, lower speeds, and high start and stops with lots of idle in an urban or suburban environment. Table IV-6 summarizes the vehicle specifications for the current drayage and refuse demonstrations.

There are other heavy-duty BEV demonstration projects underway. CEC has funded a project that includes Class 8 BEV truck being manufactured by Artisan Vehicle Systems that is being administered by CALSTART (CEC, 2013). Balqon, and U.S. Hybrid also have Class 8 BEVs under development utilizing 2012 U.S. DOE Zero Emission Cargo Transport funding, being administered by SCAQMD (Choe, 2014). New projects are approved in increasing numbers. Table IV-7 summarizes some heavy-duty truck demonstrations that are currently underway.

Figure IV- 15: Motiv Power Systems Heavy Duty Refuse Hauler

(Piellisch, 2013)

Table IV- 6: Summary of BEV Heavy Duty Vehicle Specification

Make	Weight	Range Miles	Battery Size kWh	Motor Size kW
Transpower (Drayage)	Heavy Duty	75	270	300
Motiv (Refuse)	Heavy Duty	80	220	230

(See text, Chapter IV D)

Table IV- 7: Summary of Heavy-Duty BEV Demonstration Projects Underway

Manufacturer And Vehicle Class	Total Number of BEVS	Trucks on the Road	Trucks Still Being Manufactured	Project Administrator
Transpower Class 8	8	2	6	SCAQMD
Motiv Refuse	1	1	0	Chicago
Balqon Class 8	3	0	3	SCAQMD
US Hybrid Class 8	2	0	2	SCAQMD
Artisan Class 8	1	0	1	CALSTART
Totals	**15**	**3**	**12**	

(See text, Chapter IV D)

V. BEV COSTS

BEVs have many common components with other conventionally fueled trucks and buses, such as chassis and driver comfort features, but have significant differences in powertrain and energy storage systems. Section A of this chapter addresses BEV truck energy requirements. Section B considers battery costs, which are a function of these energy requirements. Section C addresses component costs for BEVs, while Section D looks at operation and maintenance costs and savings. Section E uses these inputs to examine the vehicle payback period. Finally, Section F examines charging stations and infrastructure costs. Chapter IV also includes vehicle costs for some specific vehicles available for purchase.

A. BEV Truck Energy Requirements

The most significant cost component for BEVs, which drives the incremental cost of a BEV, is the energy storage (battery) system. It is thus important to understand what the energy needs are for a specific vehicle so the battery can be sized accordingly. The range of a BEV is dependent on the energy that is stored on-board the vehicle in its battery or batteries. ARB performed an in-house analysis to estimate the energy per mile needed for medium- and heavy-duty trucks and buses. Table V-1 shows the estimated energy needs on a per mile basis to be 1.8 - 2.8 kilowatt hours per mile (kWh/mile).

CALSTART, in their 2013 I-710 commercialization study, estimated the energy needs of a Class-8 drayage truck and found it to be 2.5 kWh/mile driven (CALSTART, 2013), which is generally consistent with ARB’s estimate. Based on the estimated BEV energy needs presented in Table V-1, battery sizes can be approximated for specific BEV applications with the consideration of a buffer to prevent over-discharge of the batteries, which is typically around 20 percent of the rated power output of the batteries (Van Amburg, 2014). Other considerations regarding battery size need to be considered such as allowing sufficient excess capacity to allow for different driving conditions and vehicle operator driving styles.

B. Battery Costs

Battery costs are currently high, but are anticipated to become less costly in the future. In addition to being a function of supply and demand, cost is also a function of the

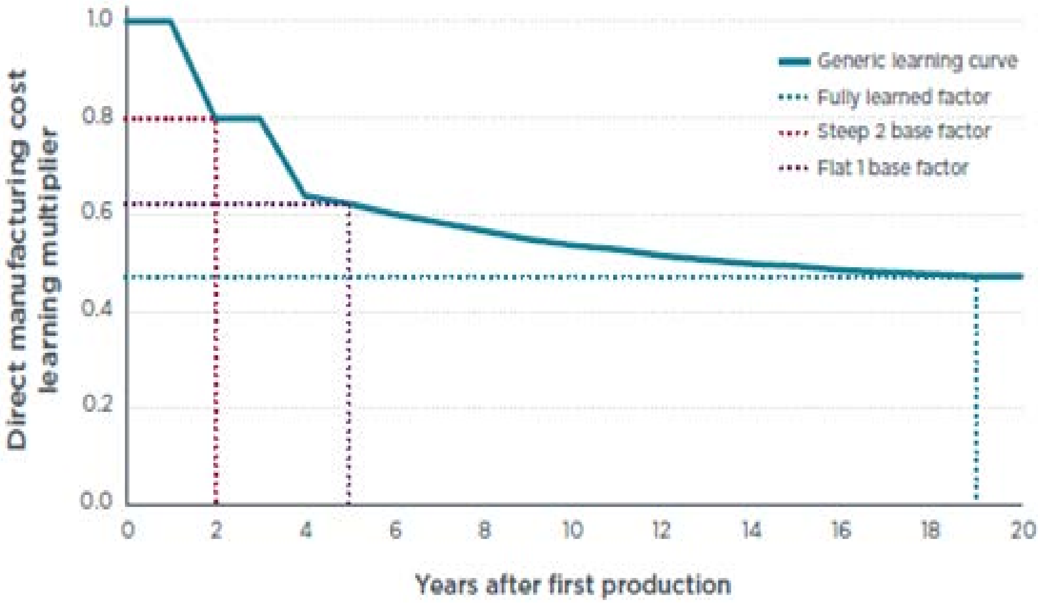
Table V- 1: Estimation of BEV Energy Needs

Estimate of BEV Energy Needs per Mile	
Weight Class	**kWh/mile**
Medium-Heavy (8,501 to 14,000 lbs. GVWR)	1.8*
Heavy-Duty (>14,000 lbs. GVWR)	2.8*

*ARB internal estimates, which do not include a buffer to prevent over discharge

manufacturing process and product distribution and retails network. The total cost of a technology, such as medium- and heavy-duty BEVs, is a composite of direct costs (e.g., raw material and labor) and indirect costs (e.g., research and development, overheads, marketing and distribution, and profit markups) (ICCT, 2015). For any new product, there is a learning curve associated with both direct and indirect costs that has a downward pressure on those costs over time as a manufacturer becomes more efficient with the production processes, as the in-field performance of the product improves (reducing warranty costs) and as other indirect costs are lowered through streamlining and improved efficiency. As shown in Figure V-1, the indirect cost multiplier generally reflects a 20 percent cost reduction after two years of production and another 20 percent after an additional four years of production. The indirect cost multiplier continues to decrease at a much slower rate up to about 20 years after the initial production, at which point the indirect cost multiplier stabilizes, as manufacturers are able to fully optimize and amortize both their direct and indirect costs by that time. By the tenth production year, the indirect cost multiplier has decreased to about 50 percent of the initial cost. This learning curve contributes to the rapid reductions in the prices of BEV transit buses, discussed in Chapter IV.

Figure V- 1: Direct Manufacturing Cost Learning Curve

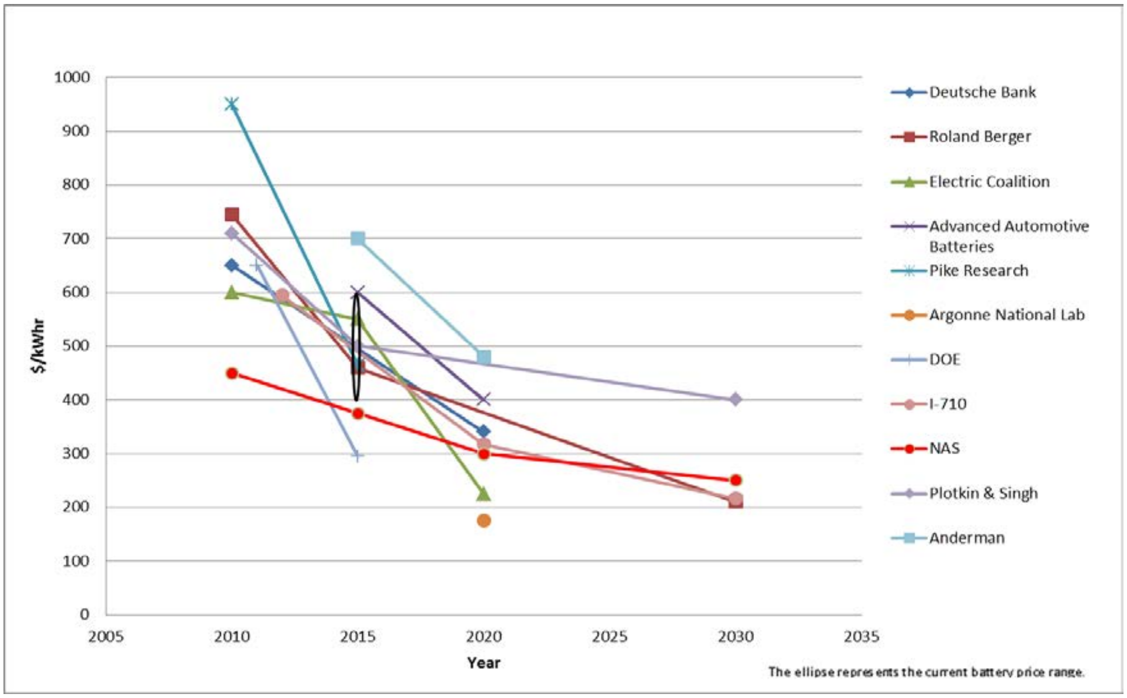


(ICCT, 2015)

Figure V-2 shows forecasts of battery costs ($/kWh) over the next several decades from a variety of sources. The figure shows declining battery costs; it is anticipated that these cost reductions will continue for some years. Some of the data presented in Figure V-2 are for light-duty applications, since that is where the majority of transportation batteries are destined to be used. However, battery pack technology, the learning curve, and economies of scale found in the light duty sector will readily transfer to the medium- and heavy-duty vehicle segment, more so than power electronics or charging infrastructure. Battery costs are falling even more rapidly for the light-duty fleet, with battery pack costs expected to approach $200/kWh by 2018 (Ayre, 2015; Anderman, 2014). Current medium- and heavy-duty batteries tend to use different chemistries than do light duty vehicles, which may account for some of the differences in current costs. For example, most light duty vehicles are currently using lithium-nickel-cobalt-manganese chemistries. In addition, the medium- and heavy-duty packs tend to be larger and require more rugged components, which also increase cost.

Batteries for medium- and heavy-duty trucks and buses are currently in the $400 to $600 per kWh range, consistent with the projections by Deutsche Bank. At $600/kWh, a 350 kWh system such as might be used in a Class 8 drayage truck would be expected to cost $210,000.

Figure V- 2: Forecasts for Battery Costs[5,6,7]



(CALSTART,2013; DOE, 2012; EEI, 2014; NAS, 2013; Sakti, 2015)

C. BEV Component Costs

Unique components for electric drive medium- and heavy-duty trucks and buses can be used across several vehicle types such as BEVs, fuel-cell powered vehicles and hybrid trucks and buses, and their costs would be expected to decline with economies of scale. Table V-2 is from the 2013 CALSTART I-710 commercialization study and projects the costs, rounded to the nearest thousand dollars, of BEV components for drayage trucks.

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[5] Battery cost estimates may be based on the cells only, on the battery stack, or on the entire pack. This, along with production volume assumptions and the year the projection was made, doubtless contributes to some of the range of battery costs and battery cost projections shown in this figure for a given year.

[6] The estimates from the U.S. DOE’s Quadrennial Technology Review (DOE, 2012) presume that U.S. DOE production targets are met; the I-710 study includes relatively aggressive reduction assumptions (CALSTART, 2013).

[7] Battery costs for the light-duty fleet are approaching the $200/kWh range. Costs for medium- and heavy-duty vehicle battery packs tend to be higher due to issues such as different chemistries for different duty cycles, ruggedization needs, and expected useful life.

The I-710 commercialization study is for the introduction of different technologies in drayage service coming from the Ports of Los Angeles and Long Beach to the warehouse districts that are located along the I-710 corridor in Southern California. As Table V-2 indicates, a BEV drayage truck currently costs about $200,000 more than a comparable diesel truck, which is nearly 200 percent more. By 2030, it is predicted that the incremental costs of BEV drayage trucks will have dropped to only about $60,000, or about 50 percent, more than comparable diesel trucks.

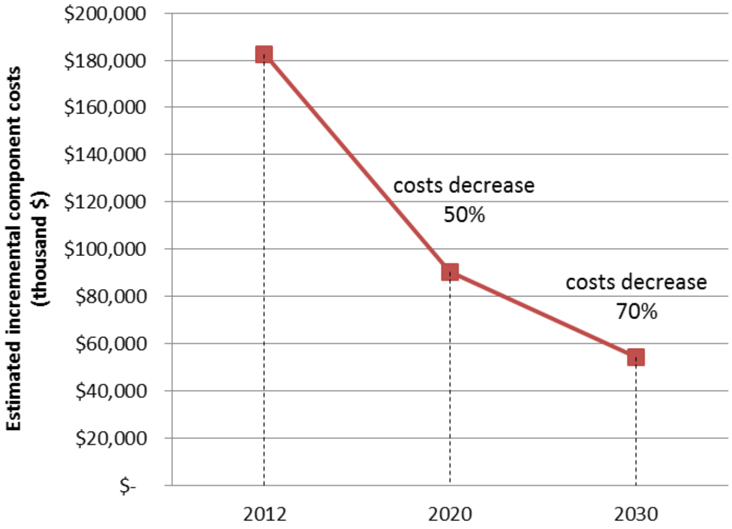
The I-710 project estimated the 2012 costs for motors, BMS, and power electronics at around $21,000. The table shows that the cost of these components is expected to decrease modestly over time, with a 14 percent cost reduction by 2020, increasing to a 29 percent reduction by 2030 compared to the 2012 baseline. Figure V-3 estimates component costs for a generic BEV truck, with the basic component costs including the

Table V- 2: CALSTART Estimations of BEV Drayage Truck Costs Over Time

Components	BEV (Year 2012)	BEV (Year 2020)	BEV (Year 2030)
Glider	$79,000	$79,000	$79,000
350 kW motor	$9,000	$8,000	$7,000
Power Electronics	$12,000	$10,000	$8,000
350 kWh Battery System	$210,000	$111,000	$74,000
Total Vehicle Cost	$308,000	$208,000	$169,000
Baseline Diesel Truck Cost	$104,000	$108,000	$111,000
Incremental Cost	$204,000	$100,000	$58,000

(CALSTART, 2013)

Figure V- 3: Estimated Incremental Battery Electric Component Costs Over Time



(CALSTART, 2013)

battery at $180,000 in 2012, decreasing to $90,000 by 2020 and to approximately $55,000 in 2030.[8] Economies of scale coupled with standardization of components across different vehicle platforms will lead to BEV costs declining over time.

D. Operating and Maintenance Costs

While there is an increased cost to purchase BEVs compared to conventionally fueled vehicles in the foreseeable future, BEVs have reduced operating and maintenance (O&M) costs. Thus, savings may be realized by employing BEV technologies in place of conventional fueled vehicle technologies. Maintenance savings are achieved for the following reasons:

- Battery, motor, and the associated electronics do not typically require regular maintenance;
- Significant reduction in brake wear due to regenerative braking;
- Fewer engine fluids to change;
- Fewer moving parts on a BEV when compared to a conventional fueled truck or bus.

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[8] Table IV-2 is specific to drayage trucks, while this figure reflects anticipated costs for a generic BEV. This is the reason for the observed differences between the Table IV-2 and Figure IV-3.

CalHEAT’s Report on BEV Parcel Delivery Trucks for the CEC issued in 2013 estimated that vehicle maintenance savings of Class 4 to 5 BEV parcel delivery trucks can be on the order of three to 10 cents per mile driven (CalHEAT, 2013b) when compared to conventionally fueled counterparts, which typically have maintenance costs of 12 to 15 cents per mile driven (a reduction of 20-80 percent). Greater maintenance savings would be expected for heavier trucks and buses.

BEVs are also more efficient than conventionally fueled trucks and buses, meaning that they use less energy to do work than do similar conventionally-fueled vehicles. There are many reasons for BEVs being more efficient, including employing regenerative braking and significantly less waste heat generation when compared to internal combustion engines, as well as more efficient motors and more efficient transmissions, if used. It has been estimated for light-duty BEVs that ‘fueling’ costs are about one-third that of a gasoline vehicle (NPC, 2012). This would be expected to also apply to medium- and heavy-duty gasoline, and to a slightly lesser extent, to diesel vehicles as well (because diesel engines are somewhat more efficient than are gasoline engines). In an analysis of diesel versus electric transit buses, AER (2014) found “fueling” costs for an electric bus were less than 20 percent that of a diesel bus. Historically, electrical power costs from the grid have not been as volatile as petroleum-based fuels and therefore, BEVs can be used to moderate the volatility traditionally seen in fossil fuel prices.

F. Vehicle Payback Period

The vehicle payback period reflects how long it will take for the savings in O&M costs to equal the additional incremental cost, such that the additional incremental cost will be “paid back” (independent of nonmonetary costs or benefits, such as reduced emissions). This calculation is a function of the total incremental cost and the savings to be achieved. An application with a low incremental cost and high O&M savings will have a quick payback period, while an application with a very high incremental cost and modest O&M savings may well have a payback period greater than the anticipated life of the vehicle. Once the payback period has been attained, benefits will continue to accrue due to lower O&M costs, reduced GHG emissions, and reductions in criteria pollutant emissions associated with charging BEVS using clean electricity.

After application of available incentive funds, calculations of payback are highly dependent on the remaining incremental costs, which can be determined for vehicles sold today and projected for the future, and O&M savings. Most O&M savings projections are estimates, as few medium- and heavy-duty BEVs have been in service long enough to ascertain actual O&M figures. Nonetheless, various entities have estimated payback periods for a variety of medium- and heavy-duty BEVs. The payback estimates below assume current incremental costs; as incremental costs fall, the payback period will also be reduced.

For medium-duty BEVs, incremental costs are currently in the $60,000 to $80,000 range, which is about a doubling of the cost of a conventional medium-duty vehicle. With this incremental cost, pay back is estimated by the U.S. EPA's West Coast Collaborative (WCC, 2011) to be between 3 to 5 years. It is unclear in this reference whether the West Coast Collaborative assumed that the medium-duty BEVs applied for and received available incentive funds which would decrease the net incremental costs for the payback analysis. Medium-duty BEVs are discussed in more detail in Chapter IV C Medium-Duty Trucks and Shuttle Buses.

The price for a BEV transit bus is up to $800,000 compared to $485,000 for a conventional diesel transit bus (ARB, 2015a). This high incremental cost is falling rapidly, with reductions of about 30 percent realized in just the past year or two, as BEV transit bus sales increase and battery electric components (battery pack, motor) costs decrease. For transit buses, there are substantial funds available to offset these costs. For example, ARB has estimated (ARB, 2015a) that the incremental cost of an electric transit bus compared to a clean diesel bus, after application of potential FTA Section 5307 monies, is about $57,000. Incentive funds from sources such as HVIP will reduce this incremental cost even further, potentially covering nearly all of the incremental costs, and enabling a payback with a few years. The cost differentials for all-electric transit buses are discussed in more detail in Chapter IV A Transit Buses.

Payback estimates cannot be readily made at this time for heavy-duty BEVs other than transit buses, as there is minimal availability and minimal costing data available. Heavy-duty BEVs are discussed in more detail in Chapter IV D Heavy Duty Trucks.

In addition to the incremental cost of BEVs compared to traditionally-fueled vehicles, payback calculations should also consider any needed infrastructure costs such as the purchase and installation of a charging system. These costs are vehicle- and site-specific. Charging stations will need to be built to accommodate these vehicles. Each charging station may be able to accommodate multiple vehicles, and much of the station costs would be anticipated to outlast a particular BEV. Thus, it does not seem appropriate to attribute the total costs of a charging station to each individual BEV, and they are not included in the assessment above. Such costs are discussed below.

In addition to federal, State, and local funding programs and incentives to offset incremental and infrastructure costs, there are a variety of financing options available to help with the upfront costs of BEVs, including California's AQIP funds, federal grants, and battery lease options; other federal, state, and local programs are also available.

G. Charging Stations and Infrastructure Costs

In order to successfully deploy electric trucks and buses in California, there has to be a robust charging infrastructure in place to satisfy BEV charging needs. This will be an expensive long-term project that involves the private sector as well as local and state governments. For example, CEC has funded $15 to $17M per year over the last two fiscal years for electric vehicle charging infrastructure (Smith, 2014; Smith, 2015). In the early stages, BEVs will be used for local transportation. Important challenges to overcome are developing a regional charging infrastructure and incentivizing private companies to install charging stations on their premises and encouraging them to share with other companies with BEVs to maximize equipment utilization. Light-duty charging infrastructure that is currently being deployed to satisfy the needs of light-duty vehicles could be used to charge trucks and buses, but there could be several issues that may inhibit this practice, such as reducing access for light duty vehicles and the extended charge times needed to recharge the larger battery packs needed for trucks and buses.

Typical costs of a conductive charging station include:

- The actual charging station hardware;
- Other hardware and materials associated with construction;
- Labor costs;
- Construction time including an initial on-site consultation; and
- Municipal permitting costs.

Level 2 charging stations are inexpensive, with costs range from $2,000 to $6,000 (Clean Technica, 2014). However, Level 3 charging station costs are currently much higher, beginning at around $50,000 per station, assuming no new transformer is needed (Clean Technica, 2014). A major portion of this cost is trenching to bury electrical conduit, which ranges from $25-$100 per foot. It should be noted that the cost for each charger installation is site-specific and costs can vary significantly depending on site characteristics. In addition, yearly maintenance costs are assumed as a percentage of installation costs to be $300 for level 2 and $1,000 - $2,000 for level 3 chargers (Clean Technica, 2014); this estimate may or may not be reasonable. The City of Santa Monica maintains a large number of Level 2 charge stations for the light-duty sector for which annual maintenance costs are quite low. Note that depending on charger technology, one charger should be able to service several BEVs. For example, the specialized Proterra fast charge system accommodates up to eight buses. Fast-charge systems such as those used by Proterra enable the use of smaller, lower priced battery packs, which increase vehicle pay-load capacity and reduce overall BEV costs (Wave, 2014).

An inductive charging infrastructure is significantly more expensive. Because it is in very early stages of development, costs are not well known and difficult to predict.

Utilities will have to play a major role in BEV commercialization and acceptance through participating in charging station infrastructure development. One of the most important new concepts developed by utilities is Smart Grid.

1. Smart Grid

Through the development of an advanced metering infrastructure, Smart Grid will allow utilities to charge "time-of-use" electricity rates. Instead of matching the supply to the demand, the objective of Smart Grid is to match the demand to the available supply. Smart Grid uses technology and variable pricing incentives to better utilize grid capacity. Consumers are encouraged to consume at specific times and to curtail their demand at others.

The main objective is to flatten the demand profile and allow pricing to reflect the availability of power from intermittent sources, like wind and solar, and to incentivize consumers to use it when it is available. To succeed, Smart Grid will require the implementation of a new level of intelligence in the distribution network with two way communications reaching down to the consumer level.

Smart Grid is one way to address the increasing daytime energy demands that a BEV fleet might pose by instituting demand pricing. A second approach, accessing other power sources, is Vehicle to Grid energy (V2G) transfer.

2. Vehicle to Grid Energy Transfer

A V2G energy transfer would allow electricity-generating utilities to level the demand on their generating capacity by drawing energy from the batteries of BEVs connected to the grid, via the charger, during the daylight hours of peak demand and returning it to the vehicles during periods of low demand during the night. It would require charging stations to be capable of bi-directional power transfer incorporating inverters with precisely controlled voltage and frequency output to feed the energy back into the grid. It would also require the support of a substantial communication network to manage the distributed power flows, the billing and feed-in buy back transactions. Inverters already in use for some transit buses are bi-directional and can discharge AC power from the buses to the grid, but also to other vehicles, and allow the bus to serve as a mobile generator. A vehicle-to-building option may be more widely viable in the near-term.

V2G has the capability to reduce the cost of ownership for BEVs by providing a revenue stream to the vehicle owner. Fleet operators, especially school bus fleets, may find

V2G operations a convenient way to reduce to overall cost of electric bus ownership due to the limited daily operations and the large amount of time spent at the bus yard during a typical school day or during summer breaks where the bus may not see much service.

V2G is being demonstrated in several areas in California; the US Air Force's V2G pilot project is now underway at the Los Angeles Air Force Base with a fleet of 42 V2G vehicles (USAF, 2014). Further, the CEC has funded a demonstration project for the electric retrofit of six heavy-duty Type C (19,000 to 33,000 lbs. GVWR) school buses with V2G that is now getting underway. Potential savings from V2G are not included in the payback assessments above.

E. Incentive Programs

Funding programs are available that can reduce the incremental costs of BEVs. ARB's allocation of funds from the Alternative and Renewable Fuel, Vehicle Technology, Clean Air, and Carbon Reduction Act of 2007 (AB 118; Núñez, Chapter 750, Statutes of 2007) have been directed to AQIP which includes incentives for the purchase of hybrid and zero-emission trucks and buses through the HVIP with a funding target of half of the incremental cost of the new technology when compared to conventional fueled trucks and buses (AQIP, 2014b). HVIP, which is funded by Low Carbon Transportation investments and AQIP, helps offset the incremental cost of eligible hybrid and battery-electric trucks and buses through a purchase voucher on a first-come, first-served basis. HVIP is intended to help encourage California fleet acceptance of the nation's first commercially-available hybrid and zero-emission trucks and buses, and helps drive production economies of scale and lower technology costs. So far, HVIP vouchers have been issued for over 320 EVs, with about 60 percent of all BEV HVIP vouchers issued, over 200 vouchers, for delivery vehicles. Over $10.7M of HVIP funds have been issued, averaging more than $33,000 per vehicle. In addition, California State Transportation Agency/Caltrans fund transit expansion and capital improvement projects with Greenhouse Gas Reduction Fund monies, some of which have gone to battery electric transit buses. Transit buses also can offset a substantial portion of their incremental costs using FTA grants.

Proposition 1B Goods Movement Emission Reduction Program funds may also be used to help existing truck owners who wish to upgrade to BEVs. For BEVs not yet commercially available, in addition, funds may be available from a wide range of sources through demonstrations by the agencies such as ARB, local air control districts such as the SCAQMD and the San Joaquin Valley Air Pollution Control District, ports of Los Angeles and Long Beach, and the CEC.

ARB is launching new pilot projects using AQIP and low carbon transportation funds to support larger-scale commercial deployments of zero-emission trucks and buses. These pilot projects are designed to help increase vehicle production levels to the point where significant economies of scale can be realized.

On October 1, 2015, ARB released a solicitation to fund larger-scale deployments of zero-emission trucks, buses, and school buses (including hybrid vehicles capable of operating in zero-emission mode within disadvantaged communities) and associated charging/fueling stations. Close to $24 million is available for these projects from fiscal year 2014-15 funds, with an additional $60 million from fiscal year 2015-16 pending approval by the California Legislature.

VI. EMISSION BENEFITS OF BEVS

BEVs have very low GHG emissions when the power to charge the batteries comes from renewable energy sources such as wind and solar. They also eliminate emissions of criteria pollutants from the tailpipe, as BEVs do not emit any criteria pollutants or GHGs from the vehicle directly. BEV tailpipe emissions are 100 percent lower than tailpipe emissions from today's conventionally fueled vehicles. Even in the future, when diesel or natural gas vehicles may be much cleaner than today's vehicles (certified to a 0.02 g/bhp-hr NOx standard, for example), BEVs will provide significant tailpipe emission benefits, which can be crucial for attaining ambient air quality standards. However, since power from the electrical grid is used to charge batteries, total well to wheel BEV emissions are only as clean as the power plants that supply their energy. If renewable fuels are used for electricity generation, then a closed carbon loop can be realized, significantly reducing the GHG footprint of BEVs.

While BEV efficiencies can result in reduced GHG emissions using standard grid power, further emission reductions can be achieved if solar, wind power, or advanced technologies such as parasitic energy harvesting utilizing piezoelectric generators implanted in roadways are used. Solar charging of wayside battery packs is one way to provide power to BEVs for recharging that has the potential for significant emission reductions. Bus or truck yards could also install solar arrays to provide clean renewable energy to charge the vehicles. Thus, to truly realize the maximum emission benefits potential from the use of BEVs, it is important to continue to strive to produce the cleanest power possible.

To compare vehicles powered by alternate fuels, well to wheel analyses are performed. These typically include only fuel-cycle and vehicle use (exhaust) emissions. They do not include vehicle-cycle emissions for any vehicle type, such as the emissions associated with the manufacture of the engine or motor, transmission, body, and batteries. Traditionally, these vehicle-cycle emissions are not included in well to wheel analyses because the differences are small. However, the differences may be more significant for BEVs due to the different components such as batteries contained in BEVs compared to the traditionally-fueled vehicles. A well-to-wheel analysis of BEV operations attributes emissions associated with electricity generation to the BEV. The magnitude of criteria and GHG emissions reductions associated with BEV operations will depend on the emissions characteristics of the power plant(s) that provide the electricity. The ARB continues to estimate emissions associated with power generation in California.

ARB is developing a separate fuels technology assessment that will evaluate overall well to wheel emissions from various transportation fuels. Preliminary results from that assessment indicate that battery electric vehicles have substantially lower well to wheel emissions than diesel- or natural gas-fueled engines.

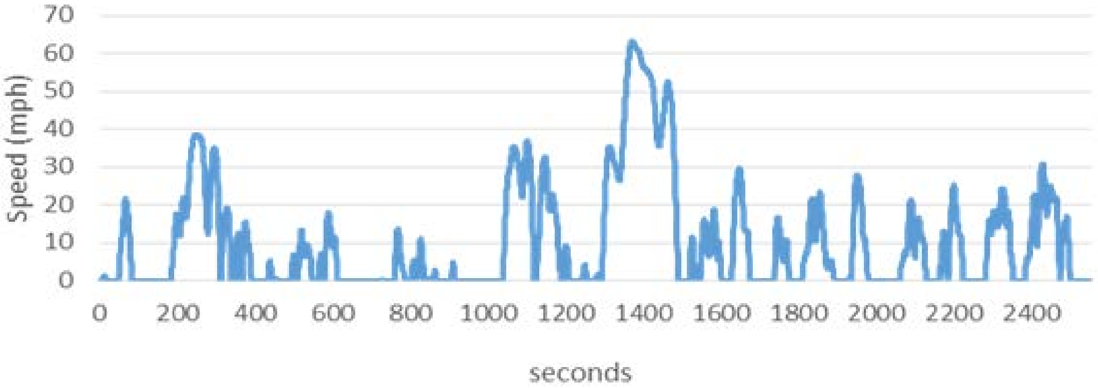
The question has been raised about the extent to which the carbon footprint of battery recycling would offset BEV well to wheel benefits. A cradle to grave assessment would include emissions associated with the end of the useful life. Such analyses can be very complex and have not been completed for medium- and heavy-duty BEVs. Generally, however, decommissioning of BEVs would be similar to decommissioning of conventionally-fueled vehicles, albeit with fewer waste fluids, except for spent batteries. An overview of the literature notes that battery recycling has a generally modest carbon footprint for the lithium-based batteries currently in use for electric transit buses, and would therefore have minimal impact on lifetime CO_2 emissions. Newer recycling processes have been developed that result in 80 percent of battery materials recycled into useful product while using minimal energy. In addition, spent vehicular batteries may enjoy a second life in applications such as electricity grid storage batteries. While this secondary use does not reduce the impact of eventual recycling, it does allow recycling emissions to be offset by greater accrued in-use emission savings.

VII. OPTIMAL DUTY CYCLE FOR BEVS

The preferred duty-cycles for BEVs take advantage of the unique operational characteristics in battery vehicles. BEV technology is ideally suited for applications with defined routes, lots of starts and stops, high idle time, and lower average speeds. Defined routes make route distance and placement of charging stations simple. Urban drive cycles allow for many stops and starts as vehicles negotiate traffic and stop lights. The stops and starts are ideal for BEVs, as they allow for regenerative braking, which recaptures mechanical energy, normally bled off as heat, and stores that energy as chemical energy in the on-board batteries for future use. However, they are typically a very inefficient duty-cycle for reciprocating engines since during idling, a conventional fueled truck is still using fuel and generating emissions while a BEV will be using very little of its stored energy. Duty cycles with lower average speeds have less power requirements than those with lots of highway driving. Generally, daily routes under 100 miles are optimal to limit the size of the battery. However, higher ranges can be achieved with larger battery packs or with en-route charging.

Some vehicle vocations stand out as fitting the optimal BEV duty cycle, such as parcel, linen, and food delivery vehicles operating in the urban and suburban environments. These are great opportunities for BEV penetration as are other urban vehicles that fit this same profile, like transit buses, school buses, and refuse collection vehicles. Figure VII-1, below shows the duty cycle (vehicle speed over time) for a representative parcel delivery vehicle, generated from the National Renewable Energy Laboratories, Fleet DNA data. The figure illustrates that these trucks typically have lots of starts and stops, with significant idle time, and relatively low average speeds.

Figure VII- 1: Representative Parcel Delivery Vehicle Duty Cycle



(NREL, 2014)

VIII. NEXT STEPS FOR BEVS

At the current state of BEV technology, market penetration in several vehicle vocations will continue to expand. BEV transit and school buses, urban delivery vehicles, drayage and refuse trucks will continue to increase in numbers with the assistance of robust demonstration projects and incentives for pilot deployments. In the near future, BEV short- and regional haul trucks will begin demonstrations, as will BEV shuttle buses. However, it is anticipated that BEVs will not be able to penetrate into the long-haul truck vehicle segment without further advances in the state of battery technology.

A. Demonstration, Pilot and Deployment Projects

For BEV technology to further penetrate into the truck and bus market there is a need to continue with medium- (8,501 to 14,000 lbs. GVWR) and heavy-duty (>14,000 lbs. GVWR) BEV demonstrations, pilot and deployment projects. BEV technology needs to be demonstrated in many different applications and weight classes. Future demonstration projects for heavy-duty should next focus on short and regional-haul trucking with an eye on expanding into trucking vocations that require higher mileage trucks, refuse haulers, and other urban vocation work trucks. Medium-duty vehicle demonstrations should focus on expanding the number of vehicles types available in this category with an eye on expanded vocational offerings and longer range trucks and buses. Pilot projects should help break down barriers to commercial acceptance of medium-duty trucks and buses and be focused on those vehicles that are currently in the demonstration and pilot stage. Deployment project funding should be focused on commercially available BEV transit, shuttle and school buses, and delivery vehicles that operate in the optimal BEV duty-cycle as discussed in Chapter VII.

ARB has allocated $25 million toward zero-emission drayage trucks and has another $20 million for the zero-emission truck and bus pilot project sourced from Greenhouse Gas Cap and Trade Auction proceeds to reduce carbon emissions from transportation sectors (AQIP, 2014b). Other public agencies have been funding medium- and heavy-duty BEV demonstration projects such as the CEC, SCAQMD, Port Transportation Advancement Programs, Federal funders like U.S. DOE and others, and it is hoped that these agencies continue to support demonstration projects focused at BEVs. These projects will help to determine the current boundaries of the application of battery-electric technology in the medium- and heavy-duty fleet.

These medium- and heavy-duty demonstration projects will help to better understand the economics surrounding BEV operations and therefore can increase fleet owners' confidence when making economic decisions to deploy BEV trucks and buses in their own fleets. We also hope to have a better understanding of other mechanisms to reduce the payback period, such as utilizing V2G technologies as CEC's V2G school bus demonstration program fields its fleet of buses and other V2G projects come on line.

B. Reduce Costs of BEV Components

Batteries are the most costly component of BEVs today. It is expected that battery costs will come down in the future due to economies of scale as the light-, medium- and heavy-duty EV market expands, and as general improvements in efficiencies are made as manufacturers travel the learning curve, as discussed in Chapter V BEV Costs. For the balance of components, however, there is not a direct technology transfer of power electronics from the light-duty sector to the heavy-duty vehicle sector, though advances in manufacturing technologies in light-duty power electronics will help the BEV truck and bus segment. The high power needs of medium- and heavy-duty trucks and buses require more robust power electronics such as inverters and converters. However, the standardization of vehicle components implies that a specific component could be used in many different truck and bus models and many different vocations. This standardization allows for reduced engineering costs compared to boutique components and allows for economies of scale to reduce individual component costs, reducing all medium- and heavy-duty BEV truck and bus purchase costs

Lithium battery technology is being advanced in incremental steps and continues to improve in ways that ultimately may be able to satisfy the needs of higher range BEV trucks, with lighter packs that have higher energy density; additionally, shorter charge times will also increase vehicle applicability to other duty cycles where BEVs are not currently present. Advances in battery technology reached as the result of light-duty EV needs can be applied to medium- and heavy-duty applications as well. In addition, to the extent that battery technology is similar, medium- and heavy-duty vehicles can benefit from the economies of scale present in the more robust light-duty market.

Primary research has shown that novel compounds being used in lithium batteries can significantly increase power density, provide ultrafast recharge times and increase the number of discharge/charge cycles that lithium ion batteries can endure before degradation. As an example, researchers in Singapore have reported that replacing the anode on a typical lithium ion battery with titanium oxide formed into nanotubes in a gel format can facilitate the recharge of lithium ion batteries to 70 percent SOC in only two minutes, with the potential for up to 10,000 discharge/charge cycles, using a technology that can be readily adapted to current production processes (Tang et al., 2014).

C. Vehicle Charging

Vehicle charging is a required element of BEV operations. Peak demand charges and limitations of available power at truck and bus yards need to be understood by commercial vehicle operators before BEV can significantly penetrate into the marketplace.

The standardization of truck and bus charging infrastructure would allow for any BEV truck or bus to connect to needed infrastructure to recharge its batteries. A standard conductive connector or inductive charging strategy, standardized software controls, and voltages can allow for widespread deployment of medium- and heavy-duty BEVs. Once medium- and heavy duty vehicle charging can become more ubiquitous with common conductive or inductive charging systems installed, smaller battery systems can be employed reducing the cost of the single highest cost component of BEVs which will reduce the overall cost of BEV ownership. There is a need for coordinated work between industry and the Society of Automotive Engineers (SAE). This process has already begun for battery electric buses.

The light-duty market is now undergoing widespread charging infrastructure installation in California utilizing the SAE J1772 conductive connector at standardized voltages to allow for any light duty ZEV to charge at any charging station. Medium- and heavy-duty BEVs charging infrastructure may be able to co-locate with light-duty charging stations, but the use of light-duty charging bays for trucks and buses should not be encouraged since it may hamper light-duty ZEV market acceptance if light-duty stations were commonly found to be occupied, charging large commercial vehicles for extended times.

D. Moving BEVs Forward

For wide-spread commercial adoption of battery electric technology, costs must come down (primarily by reducing battery costs) and range must come up (reflecting advances in battery technology). This will require further investments in battery research and development, as well as demonstrations of new technological approaches. In addition, if there is to be widespread penetration of any ZEVs, the power grid must be able to accommodate these vehicles. To the extent that daytime fast-charging is used, there could be possibly significant impacts on the grid that will need to be overcome. This may be where V2G can balance out the demands on the grid most effectively.

To encourage the development and use of BEVs for the medium- and heavy-duty fleet, ARB is actively funding demonstration projects and continuing to provide significant incentive funding such as HVIP, AQIP Truck and Bus pilot project, air district plus ups[9] for HVIP and other incentive programs (AQIP, 2014b), as discussed in Chapter VI. Programs such as these help to promote market certainty, and, in tandem with regulations, will help to drive the technology.

Widespread adoption of ZEVs is part of the sustainable freight strategy for California (ARB, 2015b). The goal of that strategy is to move goods efficiently, with zero emissions everywhere feasible, and near-zero emissions with renewable fuels everywhere else. The first step in a broader strategy to accelerate the deployment of zero emission technologies begins with zero emission transit buses that are already in the early commercialization phase. Staff is currently in the process of working with transit fleets and other stakeholders on an Advanced Clean Transit proposal (ARB, 2015a) that will use a combination of incentives and regulatory approaches to transition public transit bus fleets to zero emission technologies, while providing transit agencies the flexibility to continue to evolve to meet expanding needs for effective, efficient, and affordable regional transit services across California. The current proposal would include purchase requirements to phase-in zero emission buses beginning 2018 with a full transformation to zero emission buses by 2040. This item is scheduled to be considered by the Board in late 2016. ARB also plans to develop a regulation in 2017 to accelerate penetration of ZEVs in last mile freight delivery applications. ZEVs used in this application are nearing early commercialization, with a number of current demonstrations and early deployment programs in place. Airport shuttles are also likely to see a zero emission program, likely in 2017. Mandatory purchase requirements, coupled with appropriate incentives, will support increasing sales volumes. Government policies can encourage the introduction of zero emission technology through investments in research and development, technology demonstrations and deployments, and incentives to consumers and fleets to drive demand (ARB, 2015b). Regulatory actions, such as Advanced Clean Transit and last-mile delivery requirements, and regulatory and nonregulatory efforts aimed at initiating deployment of zero emission airport shuttle buses all will help California achieve its air quality and GHG emission reduction goals.

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[9] "Air district plus ups" are when an air district provides additional funds on top of incentive funds from another agency. For example, San Joaquin Valley will give additional funds for an HVIP eligible truck, above and in addition to the HVIP voucher amount, if the truck is bought and used in the San Joaquin Valley. These funds make the project more attractive, with a shorter payback period.

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