ZEMU Concept Feasibility Study

Detailed Evaluation of Battery and Hydrogen Technologies for the Arrow Service

July 10, 2019

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Information class: Standard

Definitions/Acronyms

AB .... Assembly Bill

AC .... alternating current

AMF……………Arrow Maintenance Facility

CalSTA .... California State Transportation Agency

Caltrans .... California Department of Transportation

CARB............... California Air Resources Board

DC.................... direct current

DMU................. diesel multiple unit

FCS……………fuel cell system

FLIRT............... Fast Light Intercity and Regional Train

GHG................. greenhouse gas

HFC……………hybrid fuel cell

HVAC............... heating, ventilation, and air conditioning

kWh.................. kilowatt hour

LHC.................. locomotive-hauled coach

mph.................. miles per hour

OCS .... overhead catenary system

OESS............... on-board energy storage system

ROW .... right-of-way

RPRP............... Redlands Passenger Rail Project

SOC……………State of Charge

SBCTA............. San Bernardino County Transportation Authority

TIRCP.............. Transit and Intercity Rail Capital Program

TPSS …………. Traction Power Substation

WESS ………… Wayside Energy Storage System

ZEMU............... Zero emissions multiple unit

1 Introduction

The San Bernardino County Transportation Authority (SBCTA) is expanding its public transit network in the San Bernardino Valley by building the Redlands Passenger Rail Project (RPRP). The RPRP or what will be known as the Arrow will be operated with Diesel Multiple Unit (DMU) rail vehicles and will serve the communities between Redlands and San Bernardino. In conjunction with public transit expansion, SBCTA is also seeking to reduce greenhouse gas (GHG) emissions on its systems by initially deploying a zero or low emissions train and ultimately converting the DMU vehicles on the Arrow. In 2018, SBCTA was awarded Transit and Intercity Rail Capital Program (TIRCP) grant for the development and purchase of an additional rail vehicle that will demonstrate the ability to provide zero emission service using multiple units train sets. The project will also explore the conversion of at least one DMU vehicle used on the Arrow service, so that regular revenue operations are provided by a zero emissions fleet, dramatically changing the corridor-level emissions of the new rail service.

The first phase of the project is intended to support the research, development, and eventual implementation of a zero emissions multiple unit (ZEMU) rail vehicle on the Arrow service. The purpose of this report is to refine the zero or low emission technology options, which have been identified as feasible for the Arrow service as part of previous technology evaluations done early on in phase 1. The results of the alternative technology evaluations were presented to the SBCTA Board in May 2019. Subsequently, two technology options have been analyzed further; the battery technologies and hybrid hydrogen fuel cells. This report describes the analysis of the two technology options, their application to the Arrow service, and their feasibility for future service expansion to Los Angeles Union Station (LAUS). This analysis will be the foundation for a recommendation to move forward with a preferred technology into engineering, design and eventually implementation.

Subsequent sections are organized as follows:

- **Section 2** provides a summary of preliminary technology evaluation.
- **Section 3** summarizes the evaluation criteria for the detailed evaluation, outlines the concept studies and highlights the critical assumptions and exclusions for the evaluation.
- **Section 4 and 5** present a detailed evaluation of the two vehicle technologies and how each would function in the RPRP corridor, examining aspects such as the operational performance, infrastructure requirements and energy requirements, costs, risks etc.
- **Section 7** documents high-level risks for further examination during future phases.
- **Section 8** provides the recommendations and conclusions of the evaluation.
- **Section 9** sets out the next steps.

2 Summary of Initial Evaluation of Technologies

In April 2019, SBCTA completed a technology review of zero or near-zero rail propulsion technologies. The purpose of the initial evaluation was to narrow down all potential technology alternatives to a core group of viable solutions that would be suitable for the Arrow service and meet SBCTA's objectives. This section summarizes the results of this initial evaluation and lists the technologies which were carried forward into more detailed study. For a complete review of the preliminary technology evaluation refer to the report titled *Review of Technologies for Zero or Low Emission Rail Vehicles,* dated April 2019.

The zero or low emissions technologies which were identified as suitable for rail vehicle operations with Arrow service were divided into three categories: wayside power supply, on-board energy storage, and hybrid systems. These technologies are summarized in Table 2.1 below.

Table 2.1: Low and Zero Emissions Technologies

Wayside Power Supply	On-Board Energy Storage (OESS)	Hybrid Systems
Electrification - Overhead Catenary System	Batteries	Hydrogen Fuel Cell - Battery Hybrid
Electrification - Third Rail	Supercapacitors	Diesel - Battery Hybrid
	Hydrogen Fuel Cell	Biofuel - Battery Hybrid
	Biofuels	Natural Gas – Battery Hybrid
	Natural Gas	

In order to evaluate the technologies uniformly, a set of evaluation criteria had to be established. In consultation with key stakeholders for this project, including SBCTA, Omnitrans, CalSTA and Metrolink the key evaluation criteria were identified. All technologies were considered against the criteria below to identify those which would be most suited for the Arrow service:

- Cost
- Additional infrastructure required
- Environmental considerations
- Operations
- Regulatory compliance
- Implementation schedule
- Risk

2.1 Initial Finding of Technologies for Low/Zero Emissions Vehicles

Electrification, for both **overhead catenary system (OCS)** and **third rail**, are considered energy efficient and widely deployed methods to provide power to a train. OCS is currently being adopted by Caltrain between San Francisco and San Jose and an extension to Gilroy is currently under environmental review. The San Francisco to San Jose segment will replace 75% of Caltrain's diesel vehicles with electrical multiple unit rail vehicles[1]. The corridor has a mix of passenger and freight rail, similar to the RPRP corridor. These systems typically require significant capital costs to implement and may have impacts to aesthetics near historic structures or districts (e.g. Redland Santa Fe Deport District). In addition, given the Arrow service corridor is also used by freight trains, overhead catenary wires are not desirable given the railroads past aversion to operating under OCS in addition to the high capital costs. While shown in the Caltrain project it is feasible to operate freight under OCS, it is a lesser desirable option to local freight operators. For third rail systems, these typically need to be grade separated for safety reasons and are not compatible with freight. Due to these factors, these technologies have not been carried forward for further consideration in this evaluation.

OESS technologies which include **battery**, **supercapacitor**, **hydrogen fuel cell**, **biofuel** and **natural gas**, do not need a continuous wayside connection to a power source. For biofuel there is minimal vehicle conversion effort to the procured DMUs as the fuel is put into the same diesel engine, but GHG emissions are not reduced to zero or sufficiently lowered compared to conventional diesel and therefore would not comply with the TIRCP grant. Natural gas systems would require changes to the vehicle aside from the engines and will require additional refueling infrastructure. While the combustion of natural gas will lead to positive air quality impacts and GHG emission reductions, the emissions would not be reduced to zero or near zero. As the TIRCP grant aims to identify technologies to convert to a low or zero emissions vehicle, these two technologies, biofuels and natural gas, do not sufficiently reduce emissions and therefore were not considered further in the process. For battery, supercapacitor, and hydrogen fuel cell, these technologies have different advantages and disadvantages, so their applicability to the Arrow service corridor and the Redlands-Los Angeles route were examined in more detail.

Hybrid systems examined in this study include **hydrogen fuel cell and battery**, **diesel and battery**, **biofuel and battery**, and **natural gas and battery.** The battery hybrid systems allow energy from regenerative braking to be captured and stored, which allows better management of the peak power requirements on a typical passenger rail trip while decreasing energy consumption and therefore GHG emissions compared to non-hybrids. While the diesel and battery, biofuel and battery and natural gas and battery systems can reduce GHG emissions, they do not reduce emissions to zero nor near zero and therefore are not considered further. Hydrogen fuel cell and battery do not emit GHGs but require additional supporting infrastructure and therefore these are examined in further detail for feasibility.

[1] http://www.caltrain.com/projectsplans/CaltrainModernization.html, 5/20/2019

The technologies that were selected for further review were:

Table 2.2: Summary of Propulsion Technologies Carried Forward from the Initial Evaluation

Technology	Advantages	Disadvantages
Battery	-Zero emissions from operation -Energy from regenerative braking can be captured and stored -Reduction in operating noise of vehicle	-May impact utility rates and capacity if charging at peak times -Longer dwell times possible at the ends of the route due to charging time required -Battery needs to be larger than power requirements to maintain long cycle life and require careful management
Supercapacitor	-Zero emissions at the operation site -Energy from regenerative braking can be captured and stored -Can withstand frequent and deep charge/discharge cycles	-May impact utility rates and capacity if charging at peak times -Do not store a lot of energy. They also have a relatively high rate of charge leakage and so do not hold their charge for a long period of time. -Can add additional weight to the vehicles without significant benefit to operations
Hydrogen Fuel Cell	-Zero local emissions (except water) from operation -Hydrogen is not toxic	-Fuel deliveries required or development of on-site hydrogen production facilities (potentially high capital costs) -Hydrogen tanks require a large volume to store fuel to achieve a range similar to a DMU -Hydrogen fuel cells may minimally increase the weight of the vehicle; resulting in potential for modifications to the vehicle structure, suspension or brakes
Hydrogen Fuel Cell + Battery	-Zero local emissions (except water) from operation -Technology approved for passenger service in Germany – viability has been demonstrated	-Fuel deliveries required or development of on-site hydrogen production facilities (potentially high capital costs) -Hydrogen fuel cells could increase the weight of the vehicle; resulting in potential for modifications to the vehicle structure, suspension or brakes -Battery will need replacement within the lifetime of the vehicle

2.2 Further Elimination of Alternatives

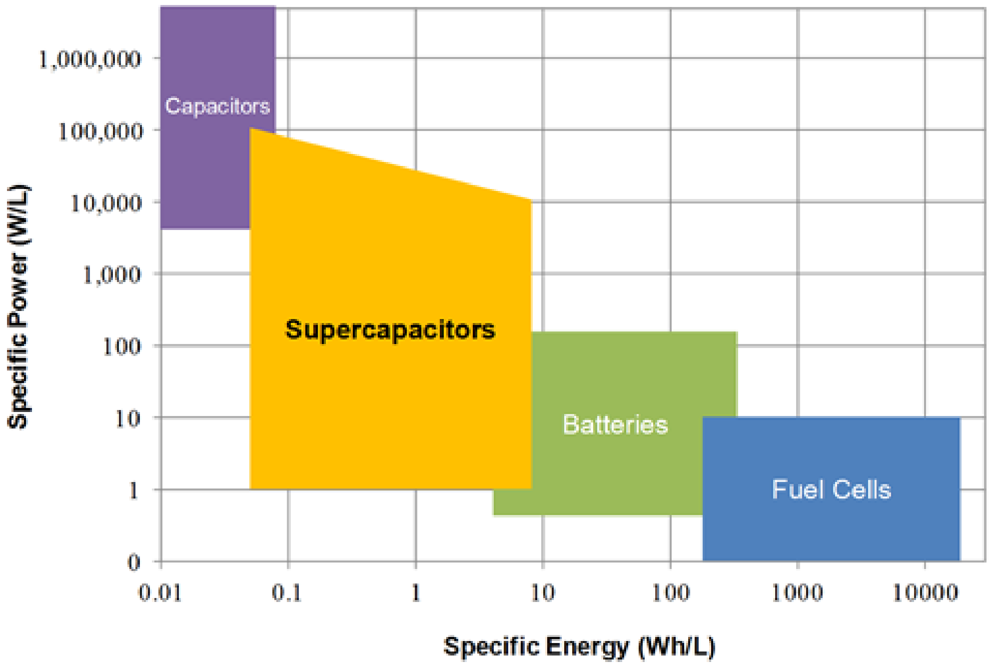
The four technology options in Table 2.2 were carried forward into the second round of evaluation. Upon further review and prior to the start of the concept studies, it was determined that only two technology options would be carried forward; batteries and a hybrid-hydrogen fuel cell. The following provides rationale for why supercapacitors and the hydrogen fuel cell option were not further considered.

2.2.1 Review of Supercapacitors

Following the high-level screening, the characteristics of supercapacitors were considered in more detail against the requirements of the Arrow service operations. The key characteristic of a supercapacitor is that it can charge and discharge quickly but in terms of power and energy densities, it does not hold as much power/energy as batteries or hydrogen fuel cells as shown in Figure 2-1.

For the distance between the stations that are furthest apart, Tippecanoe Avenue and New York Street Stations at nearly four miles, the volume and weight of supercapacitors required for this distance is anticipated to exceed the available space in the Stadler FLIRT vehicle or additional charging would be required in-route to complete this distance. Due to these limitations, supercapacitors have not been considered further for the Arrow service.

Figure 2-1: Comparison of OESS Power and Energy Densities



Source: "Energy Storage Technologies," CAP-xx, 2016. https://www.cap-xx.com/resource/energy-storage-technologies

2.2.2 Review of Hydrogen Fuel Cells

Hydrogen fuel cell technology alone would not be able to accept energy from regenerative braking. Considering the profile of the Arrow service, which has a noticeable gradient between New York Street and Tippecanoe Avenue Stations, there is opportunity to benefit from regenerative braking. By capturing the energy from regenerative braking in an on-board battery, it is possible to reduce the size of the hydrogen tank required and become more energy efficient.

Therefore, the hydrogen-battery hybrid is the preferred technology option, as we anticipate that there will be significant energy and emission savings potential by a hybrid and the results are shown in Section 5.2. Further consideration will be given to the trade-off between the size of the hydrogen fuel tanks and battery to determine the optimal size of both elements.

2.2.3 Technologies Carried Forward

Following the high-level screening set out in '*Review of Technologies for Low/Zero Emissions Vehicles'*, and the further review of the applicability of supercapacitors and hydrogen fuel cell technologies to the RPRP route, **battery** and **hybrid hydrogen fuel cell technologies** are identified as possible propulsion technologies for the Arrow service. These technology options were evaluated in detail for their feasibility for the Arrow service.

3 Detailed ZEMU Evaluation

The second round of evaluation aims to compare the preferred technologies in further detail, expanding on the evaluation criteria developed as a part of the high-level screening, as well as completing a planning level assessment of the feasibility the technologies for the Arrow service.

A detailed evaluation matrix has been developed with the same criteria and with weighting added, to identify criteria that are considered more important for operating a zero emissions Arrow service.

3.1 Evaluation Criteria

The same criteria that were established in the *Review of Technologies for Zero or Low Emission Rail Vehicles* have been used for further evaluation of the battery and hybrid hydrogen fuel cell technologies. Table 3.1 below provides an overview of the evaluation criteria and key characteristics for consideration.

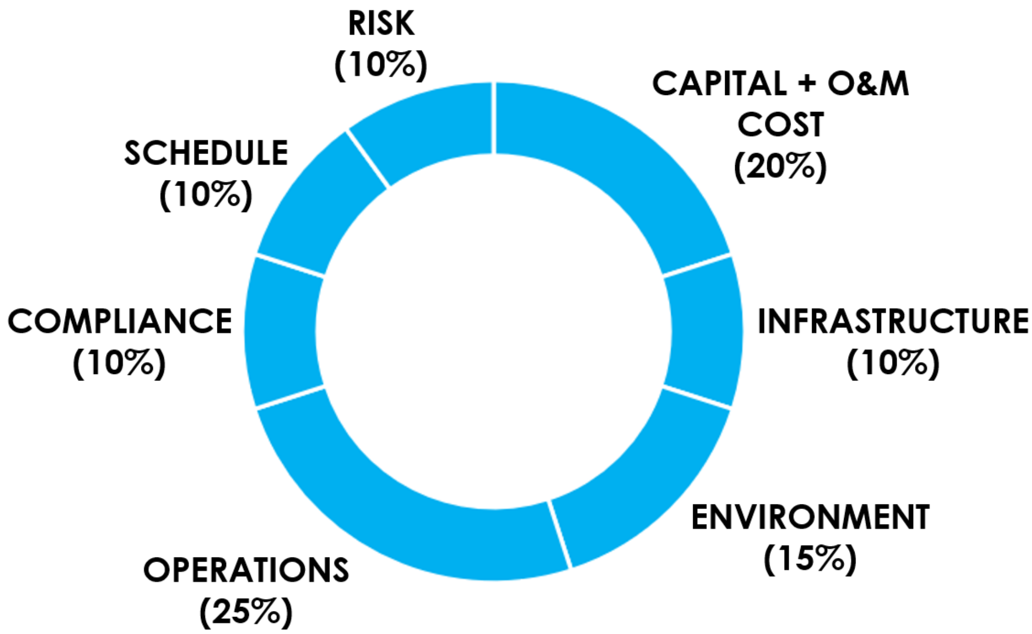
Table 3.1: Evaluation Criteria

Category	Characteristic
Cost	• Capital • Additional Operations & Maintenance (annual and vehicle life including propulsion technology)
Infrastructure	• Additional right-of-way or land acquisition required • Charging/Fueling infrastructure required • Utility/Fuel Availability
Environmental Considerations	• Land use compatibility • Potential greenhouse gas reductions (at vehicle) • High voltage clearance requirements • Socio-economic impacts of ZEMU vehicles and infrastructure • Aesthetics • Noise
Operations	• Frequency of major overhauls • Availability of warranty • Reliability • Maturity of technology • Range • Operational compatibility • Energy density (Wh/L) • Specific energy (Wh/kg) • Power density (W/L) • Specific power (W/kg) • Life span (before replacement) • Catenary free (when vehicle is in movement) • Energy recovery from regenerative braking • Scalability
Regulatory Compliance	• FRA, NFPA, CFR, electrical codes etc.
Implementation Schedule	• Time for planning, design, construction phases
Risk Analysis	• Identify and document risks for further analysis

Following on from the initial evaluation, the same criteria have been developed further to incorporate more detailed information of the technologies and to include a weighted scoring of the technology options.

With input from SBCTA, the criteria have been weighted to identify the ones most relevant to the implementation of a new propulsion technology. The cost and operations criteria are weighted higher than the other criteria, as the technologies being examined have not been used in passenger rail application in the United States before. These two criteria are essential for evaluating whether the technologies and their supporting infrastructure are capable of providing a reliable and financially sustainable zero emissions Arrow service. Figure 3-1 shows the relative weighting of the criteria used for the evaluation.

Figure 3-1: Relative weighting of criteria



Within these main criteria, different aspects are considered in more detail. These different aspects or sub-criteria are also weighted according to their relative importance and have been evaluated on a scale of 1 to 5, with 1 as low and 5 as high. With all the sub-criteria evaluated, a score is produced which ranks the technologies on a scale of 1 to 5 with 1 as low and 5 as high. The following section explains the concept feasibility studies carried out to evaluate the technologies against these criteria and the results of this evaluation.

3.2 Concept Feasibility Studies

Focused studies were completed as part of the second assessment to better understand the risks and costs associated with implementing each of the technology options into the corridor. These studies were as follows:

- Operational modelling and performance; including future expansion to LAUS
- Energy/Fuel Consumption
- Infrastructure Requirements; including fit into the RPRP Corridor
- Modifications to the Maintenance and Storage Facility
- Right of Way Impacts
- Market Availability
- Environmental Considerations

The findings and results of these studies were evaluated based on the criteria listed above and incorporated into the overall evaluation matrix, which can be found in Appendix L.

3.3 Exclusions and Assumptions

The following are exclusions and assumptions used when conducting the focused studies.

3.3.1 Energy Requirements

The relative power and energy densities of the technologies being compared, in both batteries and fuel cells are expected to provide the power and energy required for rail applications. It is expected that the on-board energy storage system (OESS) selected will be of sufficient capacity to supply power required by the subsystems and components installed on typical modern rail passenger vehicles, including but not limited to propulsion, braking, heating, ventilation, and air conditioning (HVAC), lighting, communications and signaling.

3.3.2 Vehicle Configuration – 2 Car vs. 4 Car Assessment

The diesel multiple unit rail vehicles which have been procured for opening day of the Arrow Service are 2-car consist DMUs. In addition, the stations and the Arrow Maintenance and Storage Facility (AMF) will be constructed to accommodate 2-car vehicles.

Key challenges for operating a 4-car vehicle were identified during this phase and while not infeasible, could result in additional effort during vehicle maintenance and operations. The following is a summary of some of the risks associated with procuring a 4-car ZEMU.

- Platform lengths do not accommodate a 4-car vehicle – until platforms are extended; the last two cars would remain inaccessible.
- Vehicle maintenance access within the AMF – track lengths only permit interior facility access (pit and roof platform access) to the front two cars in a 4-car consist. The consist would therefore either have to be broken up (requiring temporary accommodation trucks to support the unsupported car-ends) or the whole consist turned around to access these areas on the rear cars. Both options add significant complexity to operations as access to the underside of trucks (and potentially the roof of a ZEMU, depending on the final design) is typically required for routine maintenance. Though 4-car maintenance would be possible, this is anticipated to become a significant logistical constraint.
- 4-car vehicle storage – future expansion could be limited should 4-car vehicles be procured early on during operations as the AMF accommodates six (6) 2-car vehicles and introduction of a 4-car vehicle would reduce that to four (4) 2-car vehicles and one (1) 4-car vehicle.
- Vehicle lifting – lifting of vehicle for maintenance would need to be staged; inter-car connector would need to be disconnected requiring temporary accommodation trucks to support the unsupported car-ends.
- 4-car ZEMU design may not be similar to 2-car DMU conversion – additional effort on design and propulsion storage for 2-car converted ZEMU (batteries or hydrogen) which could impact regulatory approvals for DMU conversion.
- Increased costs for 4-car and potential delays to ZEMU Pilot Project due to anticipated longer design and construction timelines.
- No anticipated benefit to ridership during lifetime of pilot project

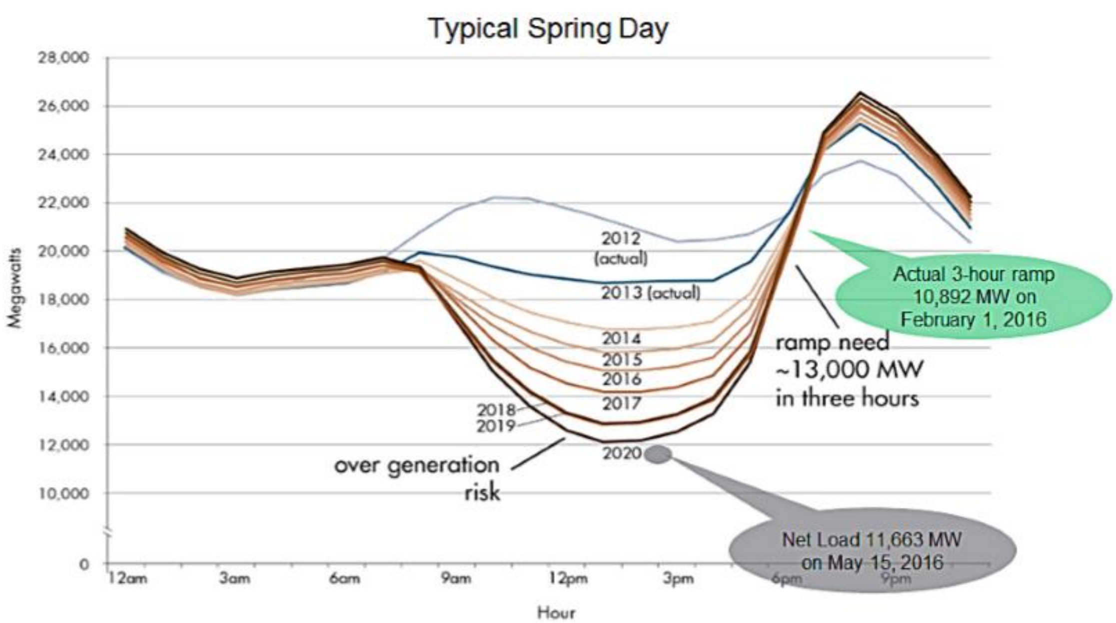
While it is ultimately feasible to operate and maintain a 4-car vehicle with the Arrow service and AMF, for the purposes of this evaluation, it will be assumed that a 2 car ZEMU will be utilized.

However, to provide a more thorough assessment of the feasibility of operating a larger 4-car vehicle using the preferred ZEMU technology, operational modeling has been completed for both the 2-car ZEMU and 4-car ZEMU to determine the increase in power demand. This can be referred to in Section 4.2 of this report, as well as in the operational modeling technical appendix entitled *ZEMU Performance and Energy Simulations*. The intent is for this information to be able to be applied to other corridors considering ZEMU vehicle applications state or nationwide. The 4-car modelling also investigated the feasibility of demonstrating 4-car operations by using a newly procured 2-car ZEMU coupled in-consist with an existing 2-car DMU. The study concluded that from a propulsion system perspective this is a feasible option on the RPRP corridor for a battery or hydrogen hybrid ZEMU. However, it is recommended that this scenario be written into the technical specification for procuring the ZEMU, particularly a hydrogen fuel cell hybrid ZEMU, to ensure the sizing of the fuel cell / battery hybrid considers the longer duty cycles where the vehicle will be demanding maximum tractive power output to accelerate the additional mass on the RPRP route, particularly on the uphill grades.

3.3.3 California Energy and Emissions

The evaluation of the technology alternatives for the ZEMU application considered the current energy and emissions landscape of California. The current landscape favors technologies that best assist in managing the state's power generation challenges based on assumptions relating to information published by the California Independent System Operator (CAISO) and the local electricity utility provider in the San Bernardino area Southern California Edison (SCE). CAISO have published data relating to the states power generation and demand "duck curve" which illustrates that the state sees peak power demand from 6pm until 10pm in the evening, and a significant power trough through the middle of the day, 9am until 6pm, when much of the state's renewable energy sources are generating power.

Figure 3-2: California "Duck Curve" – source CAISO Fast Facts Pamphlet 2016



The Arrow service is planned to offer peak service in the morning and evening, coinciding with the peak demand on the electricity grid. Technologies that offer a method to reduce or offset the demand on the grid to alternative hours when higher renewable sources can be utilized will be evaluated favorably as they will provide the dual benefit of reduced total system (well-to-wheel) emissions and reduced energy costs.

4 Battery Technologies

4.1 Technology and System Description

Batteries are individual cells that are combined in a pack to achieve the required power output and energy storage requirement. Several battery packs are typically configured to operate together to provide sufficient traction power and power for auxiliary systems. The battery packs need to be integrated into the train's power systems by an electrical management system together with the appropriate converters and inverters to ensure that the appropriate current is supplied when required. In addition, a thermal management and charge monitoring system are usually included to ensure that the batteries operate at a safe and optimal temperature and the charge/discharge is evenly distributed across all the battery packs and, ideally, individual cells.

4.1.1 Battery Chemistries

There are a wide range of different cell chemistries that offer different voltages, power and energy performances. Battery technologies in rail applications have historically been made of lithium compounds to provide both the power and ability to be recharged.

Lithium-ion cells have considerably greater energy density than previous chemistries (e.g. lead-acid, nickel cadmium, nickel metal hydride, etc.), making them particularly suitable for rail applications. They are also considered safer, less toxic, and are more energy efficient with a significantly longer cycle life. Table 4.1 demonstrates the characteristics of typical lithium ion batteries compared to other common battery types used in the rail industry.

Table 4.1: Comparison of different battery cell chemistries

Applications	Unit of Measurement	Lead Acid	NiCd	NiMH	Lithium-ion
Cell Voltage	Volts	2	1.2	1.2	2.4-3.8
Specific Energy	Wh/kg	30-40	35-80	55-110	100-300
Energy Density	Wh/l	50-90	50-70	160-420	125-600+
Power Density	W/kg	100-200	100-150	100-500	500-5000
Maximum Discharge	Rate	6-10C	20C	15C	80C
Useful Capacity	Depth of Discharge %	50	50	50-80	>80
Charge Efficiency	%	60-80	60-80	70-90	>95
Self-Discharge	%Month	3-4	15-20	15-30	2-3
Temperature Range	◦C	-40 to 60	-20 to 70	-20 to 65	-30 to 70
Cycle Life	Number of cycles	200-400	300-1000	500-1000	>2000
Memory Effect		No	Yes	Yes (<NiCd)	No
Micro-Cycle Tolerance		Deteriorates	Deteriorates	Yes	Yes
Robustness (Over/Under Voltage)		Yes	Yes	Yes	Needs BMS

Source: Johnson Matthey Battery Systems 3rd Edition 2017 | Our Guide to Batteries

Within the lithium-ion family of battery cell chemistries there are numerous variants. The following are the most appropriate chemistries for rail applications. These have been researched, assessed and compared to determine the most ideal battery solution for the ZEMU vehicle by evaluating each against the project criteria defined in Section 3.1. Figure 4-1 shows a condensed version of the evaluation matrix of battery chemistries. For the detailed evaluation, refer to the matrix in Appendix A.

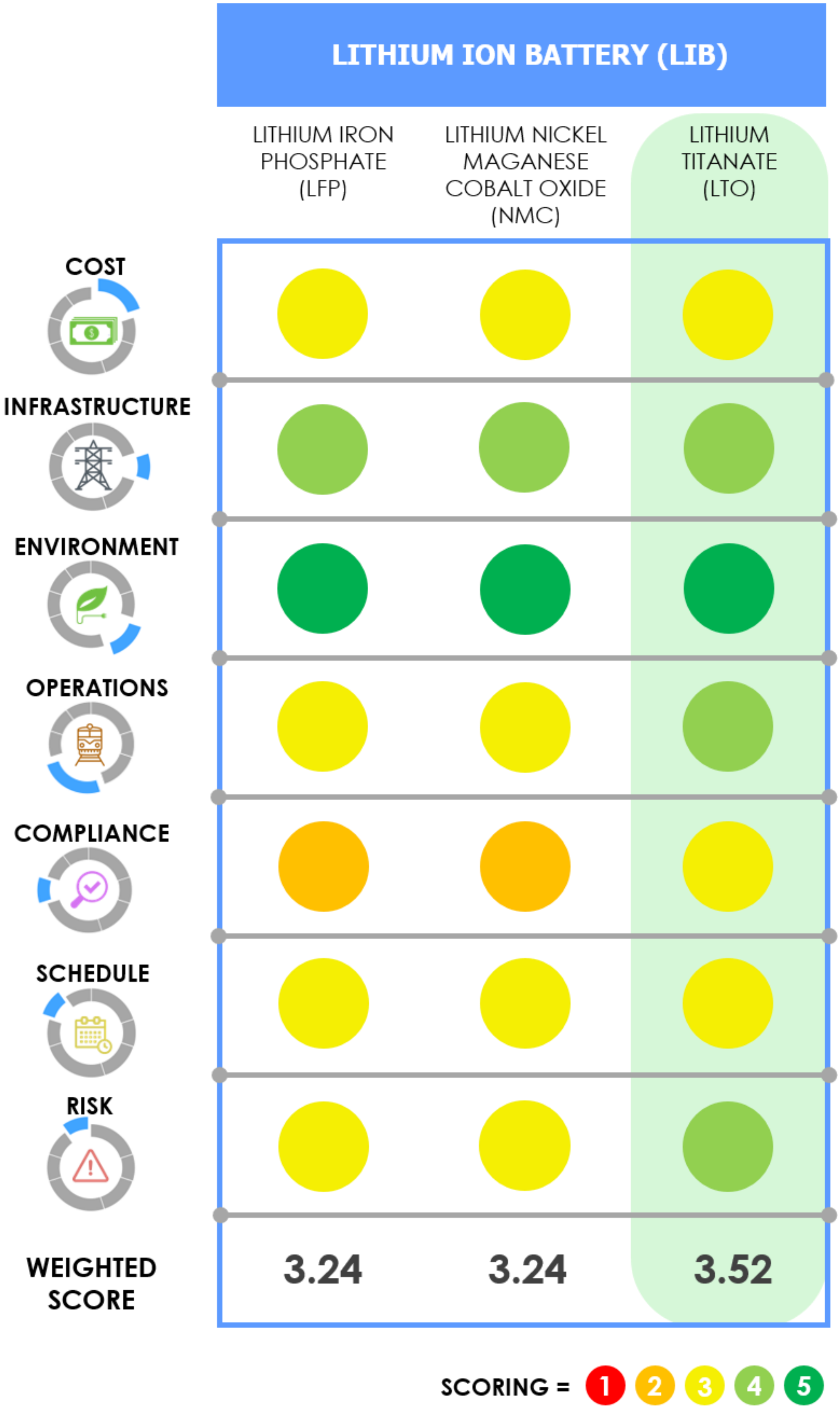
- **Lithium Iron Phosphate (LFP) $LiFePO_4$** – Phosphate-based technology lithium ion materials possess improved thermal and chemical stability than oxides and are generally perceived to be a safer cell chemistry than other lithium-ion technologies and less susceptible to thermal runaway under abuse conditions. The phosphate binds the oxygen more closely than in oxide systems providing a degree of inherent stability. Automotive lithium ion cells are also durable and stable to long term cycling. Although Lithium iron phosphate batteries have lower energy density than oxide systems they are typically able to support higher currents and thus suited to high power and longer life applications. They are a significant improvement over lithium cobalt oxide (LCO) cells in terms of the cost, safety and toxicity.
- **Lithium Nickel Cobalt Manganese Oxide (NCM) $LiNi_xCo_yMn_zO_2$** – Although no single cell chemistry currently ticks all the boxes of energy, power, cost, safety and life, the mixed metal oxide systems and in particular those based on NCM type chemistry can be optimized to give high specific energy and/or high specific power while being considered safer and more cost effective than LCO and LFP but with reasonable life expectation.
- **Lithium Titanate Oxide (LTO) $Li_4Ti_5O_{12}$** – These cells replace the graphite negative electrode with lithium titanate. This negative electrode material is compatible with any of the above positive electrode materials but is commonly used in conjunction with Manganese-based materials. They offer superior rate capability and power combined with wide operating temperature range. They are considered a safer alternative to the graphite material due to higher potential vs Li/Li+ than conventional Graphite and therefore have a degree of inbuilt overcharge protection. Also, they are a ‘zero-strain’ insertion material that does not form a large passivating Solid Electrolyte Interface (SEI) layer with the electrolyte, thus giving rise to high coulombic efficiency and long cycle life. However, lithium titanate batteries tend to have a slightly lower energy density than graphite-based systems.

The lithium ion family of batteries includes many other variants, some commonly used in transportation applications, such as:

- Lithium Cobalt Oxide (LCO) $LiCoO_2$
- Lithium Cobalt Aluminum Oxide (NCA) $LiNiCoAlO_2$
- Lithium Manganese Oxide Spinel (LMO) $LiMn_2O_4$

However, these were initially screened out as being much less ideal for the Arrow service application than LFP, NMC and LTO.

Figure 4-1: Lithium Ion Battery Evaluation Matrix



The evaluation determined that an LTO cell based battery system is the preferred chemistry owing primarily to the following considerations:

- Superior continuous charging/discharging rates (C-rates) enables the LTO to minimize charging times during station dwells and enables the battery to accept the full rate of charge generated by the vehicle motors during dynamic regenerative braking. This provides the maximum energy efficiency without needing the use of a supercapacitor system in hybrid. Supercapacitors would likely be needed for other battery systems to fully realize these efficiencies and therefore energy cost savings.
- Superior charge/discharge cycle life will provide greater reliability longer and will result in less frequent replacement/overhaul events through the life of the vehicle, this should aid in offsetting the higher up-front cost of the LTO;
- Superior stability and inherent resistance to overcharge and thermal runaway safety risks will be key to demonstrating to the regulating bodies that design decisions have been taken to make the system safe for passenger rail applications.

It is considered that the advantages of the LTO are sufficient to justify the slightly lower energy density and higher capital cost of these cells compared to other lithium-ion chemistries. While other chemistries could likely provide an adequate solution, LTO was assessed as currently the most suited for the ZEMU rail vehicle application on the RPRP Corridor. The follow evaluation and feasibility assessment take into consideration the weight, volume and other impacts of the full battery system (battery management, power electronics, thermal management system, and enclosure) for LTOs. These support systems for other battery chemistries will be very similar to the LTO system, resulting in minor impacts on the assessment of technology.

4.2 Operational Performance

4.2.1 Operational Range - Redlands to San Bernardino Transit Center

The range of a battery electric vehicle is dependent on numerous application specific factors. These relate broadly to the vehicle characteristics, the load it is carrying and the route it is traversing. The major factors regarding the vehicle are its mass, load carrying capacity, resistances to motion, propulsion system output power, energy storage, system efficiencies and auxiliary loads. The load the vehicle is carrying will typically either be freight, bulk materials or passengers; obviously for the ZEMU application it will be passengers. The route will then heavily influence the range that a given vehicle and load combination can traverse. The most influential characteristic is the grades present in the route as these determine whether the force of gravity assists or resists the vehicle's motion throughout a journey. The sectional speeds and runtimes are also important and to a lesser extent the horizontal curvature of the track will provide resistance to motion.

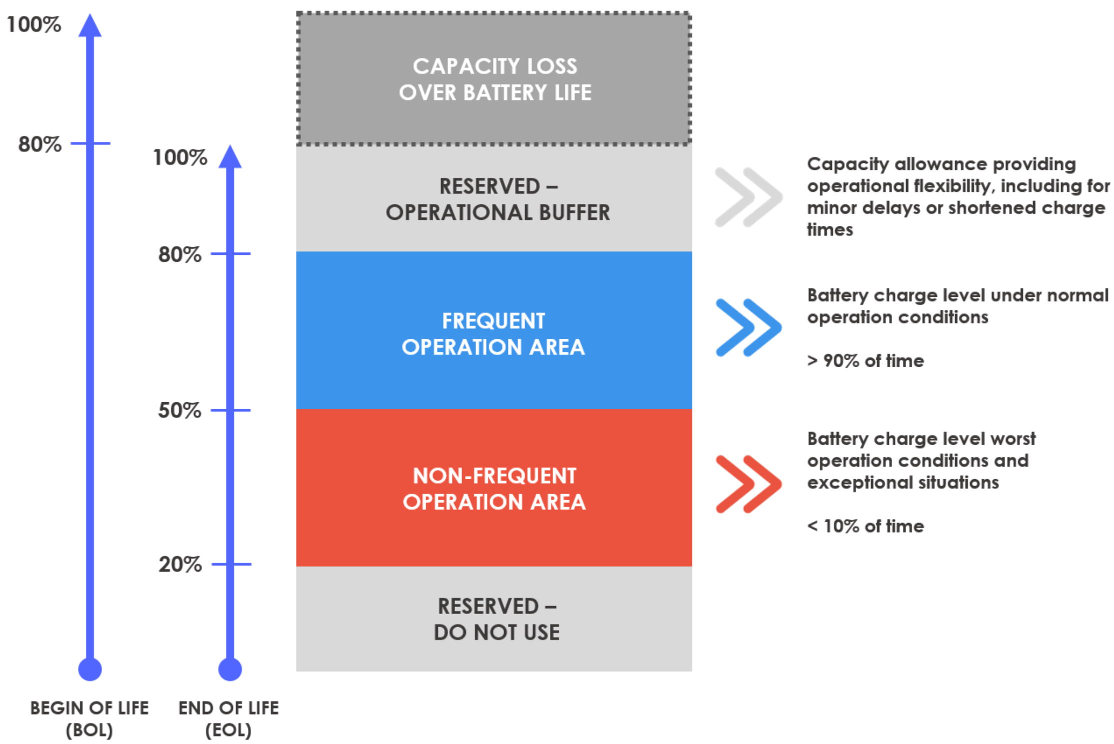
Through the supplier engagement process, numerous battery and vehicle suppliers were interviewed regarding the capabilities of their products that are currently in the marketplace or under development. As a result of this engagement it is anticipated that the maximum energy storage capability of a regional multiple unit vehicle, of a type similar to the Stadler FLIRT used for the Arrow service, will be approximately 1,000 kWh at the current level of battery technology. With this constraint as a baseline, the effective range of a battery ZEMU has been assessed.

In addition to quantifying the maximum energy storage capability that could fit on the ZEMU, there is a need to reasonably quantify the useable capacity for regular operations. It should be noted that there are many limitations to consider, as recommended by suppliers, for managing the health of a battery system in order to maximize its useful life. These include understanding that the following main factors influence the battery life:

- number of charge/discharge cycles
- charge/discharge rates
- state of charge and allowed depth of discharge
- balancing of supply current and charge levels to individual cells
- balancing of thermal loads between cells

The first three points are operational considerations, whereas, the second two are related to the internal vehicle system design. The key factor influencing the operational range of the battery is the state of charge (SOC). There are certain design criteria that should be followed to provide a reliable system that has the appropriate longevity and does not unduly inhibit day-to-day operations by requiring sensitive monitoring and management of the batteries by train operators. Good practice is to size the battery system such that the state of charge is maintained within an allowable window that maximizes the battery health and lifetime. This can be done by calculating the energy consumption likely to be required during operations between charging points, then factoring in allowances for reserve capacity, non-frequent or emergency conditions and the capacity loss that is expected as the battery ages. Figure 4-2 illustrates these allowances.

Figure 4-2: Battery sizing and State of Charge working levels

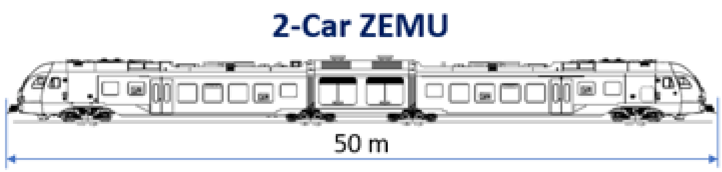


Source: Battery rail vehicle supplier

If following the guidance described above, a 1,000 kWh (when new) battery system has 1,000 kWh * 80% * (80% - 50%) = 240 kWh of useable energy capacity for frequent operations at the end of its life. It should be noted that with the advantages of the latest LTO technologies it may be possible to routinely use more of the battery capacity than described above; however, for the purpose of this feasibility study we have conservatively assumed this is the operational limit. Utilizing LTO's within these constraints should otherwise provide the benefit of even further improved battery life than other chemistries.

To quantify how this useable energy capacity limit translates into the operational range of a battery electric ZEMU on the RPRP corridor, computational simulations have been conducted. The simulations have used vehicle and route information provided from the RPRP project as well as battery system characteristics gathered through the supplier engagement process.

The results below illustrate the power and energy demands of a 2-Car ZEMU with the following vehicle parameters:



- 2-Car ZEMU vehicle weight with one power module, AW3 loading condition (6 standees per square meter as defined in SBCTA's DMU specifications) + 20 % contingency (170 metric tons total);
- 2-Car ZEMU with 8 axles, including 4 driven and 4 trailer axles;
- 3-phase induction motor and drive train efficiency of 85%;
- A combination of friction braking and dynamic braking from the traction motors, but with no regenerative braking as the energy created during dynamic braking is dissipated through on-board resistors (rheostatic) rather than being used to recharge the OESS, as well as friction brakes that offer no possibility of energy recovery. This is necessary in order to quantify the total energy consumption for each trip;
- Nominal maximum power at the wheels of 700 Kilowatt (kW) for traction and 1800 kW for braking; and
- Constant 132 kVA auxiliary power load at a power factor of 0.89, resulting in 117.5 kW of real load. This represents a worst case with heating, ventilation, or air conditioning (HVAC) in full operation.

Figure 4-3: RPRP Corridor – ZEMU Speed, Track Elevation, Curvature and Grade %

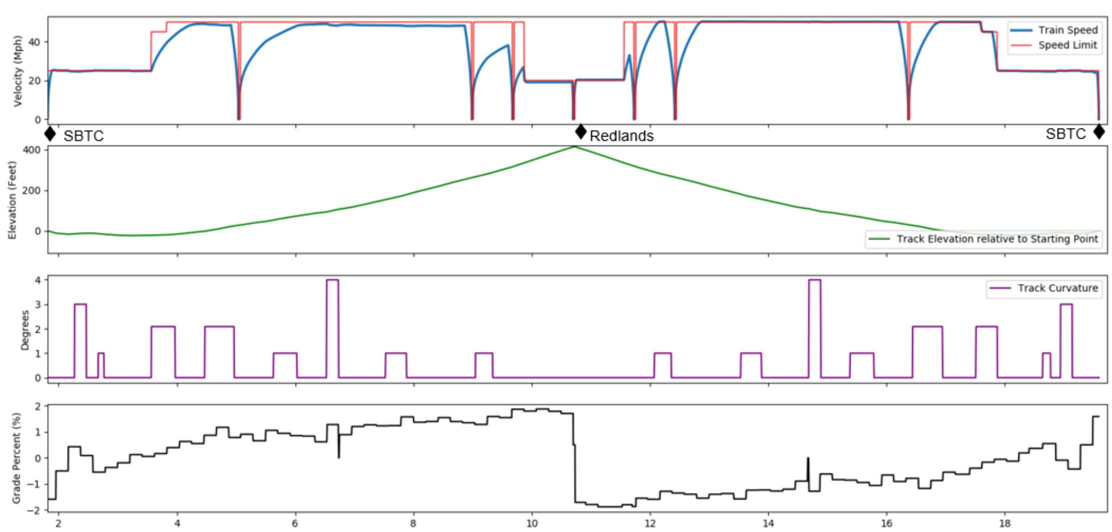
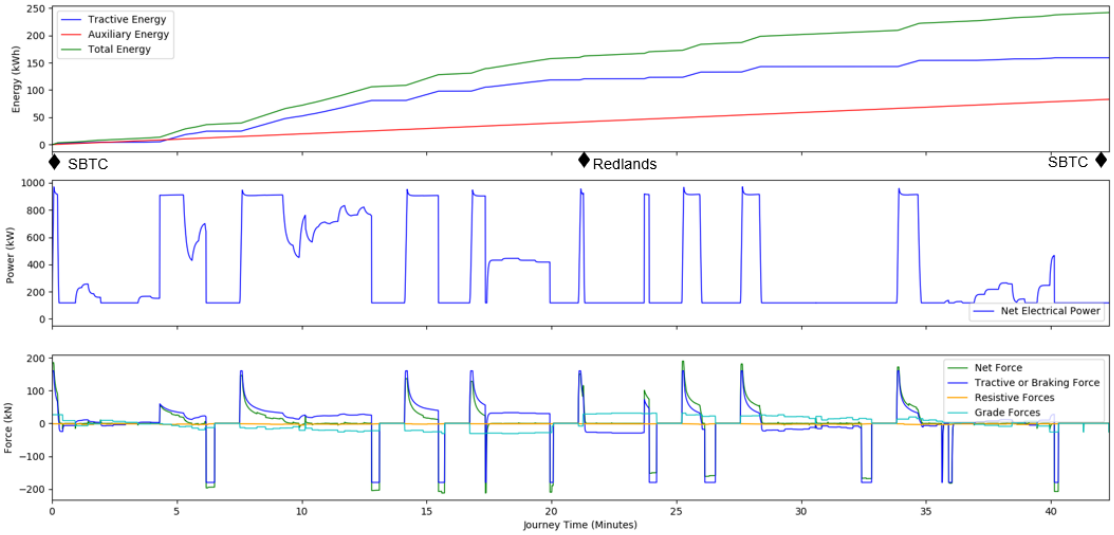


Figure 4-4: RPRP Corridor – ZEMU Energy, Power and Horizontal Forces



When tabulated by station the results are provide in Table 4.2.

Table 4.2: RPRP Corridor – Energy Required Between Stations

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)
SBTC	Tippecanoe	3.23	24.50	12.74	37.24
Dwell	1 minute	-	0.00	1.97	1.97
Tippecanoe	New York	3.95	56.28	10.95	67.22
Dwell	1 minute	-	0.00	1.97	1.97
New York	Downtown Redlands	0.69	17.06	3.13	20.19
Dwell	1 minute	-	0.00	1.97	1.97
Downtown Redlands	University Redlands	1.03	20.46	6.54	27.00
Sub Total		**8.89**	**118**	**39**	**158**
University Redlands	Downtown Redlands	1.03	4.96	6.14	11.09
Dwell	1 minute	-	0.00	1.97	1.97
Downtown Redlands	New York	0.69	9.58	2.63	12.21
Dwell	1 minute	-	0.00	1.97	1.97
New York	Tippecanoe	3.95	10.03	10.28	20.31
Dwell	1 minute	-	0.00	1.97	1.97
Tippecanoe	SBTC	3.22	16.17	12.66	28.83
Sub Total		**8.89**	**41**	**38**	**78**
Total Round Trip		**17.78**	**159**	**77**	**236**

The simulation results indicate that the range capability of the battery ZEMU roughly correlates with the total round trip of the Arrow service (18 miles) for a 2-Car ZEMU, i.e. 236 kWh consumption vs 240 kWh useable capacity. Note this assumes that there is no charging during the journey and is a conservative assessment as the payload is exaggerated and regenerative braking has not been considered, which would provide approximately 25% energy saving. Therefore, should charging occur at both the San Bernardino Transit Center (SBTC) and University of Redlands terminals the 1,000 kWh battery ZEMU has far more range than required to operate the Arrow service. In fact, if this is the only service SBCTA aims to operate, then a smaller battery could be chosen to reduce costs. It should be noted that the route characteristics (grades) cause asymmetric energy consumption while operating on the RPRP corridor depending on the direction of travel. The worst-case direction of travel is the predominately uphill route from SBTC to Redlands, being 158 kWh versus 78 kWh for the downhill route. For this reason, it is not realistic to halve the capacity of an on-board battery system by charging at both terminals. Even so, a system in the region of 600 - 660 kWh should be sufficient to comply with the battery supplier's general recommendations for the Arrow service application.

To further assess the potential operational range of a battery ZEMU along nearby regional corridors, simulations have been performed along Metrolink's San Bernardino Line from SBTC to LAUS. The speed, power and energy consumptions plots are presented in a separate operational modeling memo entitled *ZEMU Performance and Energy Simulations,* dated April 2019, also in Appendix B.

Combining the simulation data for both the RPRP corridor and Metrolink's San Bernardino Line, the following Table 4.3 describes the total energy requirements for the 2-Car ZEMU.

Table 4.3: University of Redlands to LAUS - Total Energy Required

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)
University Redlands	LAUS	66.5	552	209	761
LAUS	University Redlands	66.5	755	216	971
Total Round Trip		**133**	**1307**	**425**	**1732**

An analysis of the data presented in the modelling report shows that a battery ZEMU service with a useable energy capacity of 240 kWh originating at the University of Redlands terminal has a reliable range taking it to Fontana Station, a journey of just under 18 miles. A University of Redlands to Fontana trip consumes approximately 229 kWh, where as a Fontana to University of Redlands trip consumes approximately 262 kWh, this is slightly more than the 240 kWh however it is assumed that 20 – 25 kWh would be received through charging during the 1-minute dwell at SBTC.

The operational range of a battery ZEMU is therefore conservatively assessed to be 18 miles between charging points. As noted above, ignoring the benefits of regenerative braking and the exaggerated vehicle mass used for the simulations makes this a conservative evaluation.

The assessed range is heavily influenced by the need to plan routine operations with an aim of maintaining the batteries state of charge to be within their "frequent operations" area. Were this constraint to be ignored, say for the purpose of a maximum range demonstration, it should be possible for the 1,000 kWh ZEMU to operate the entire San Bernardino Line route between LAUS and University of Redlands, the worst case (uphill) journey consuming 971 kWh to go 66.5 miles. While this journey would be possible, it is not recommended for regular service as repeated occurrences would cause lasting damage to the internal chemistry of the battery, severely reducing its useful life.

4.2.2 Option for Increasing Range – In-route Charging

An option for increasing the range of a battery ZEMU service is to implement in-route charging. This provides the benefit of either reducing the size of the battery capacity for a given service, or alternatively increasing the range capability of that service. It should be understood however, that in-route charging may not be ideal for the ZEMU application as its ability to transfer energy to the vehicles can be constrained.

The most significant constraint to the benefits of in-route charging is that the available charging time during service stops is far shorter than that between services after a vehicle terminates. For Arrow service, the planned station dwell time is one minute, whereas the planned dwell at terminals between service is 10 minutes during peak service and up to 40 minutes during off-peak service. Additionally, it has been assessed through consultation with battery and infrastructure suppliers, that a likely maximum feasible charge rate for the vehicles is 1,500 kW. At this flat rate (excluding ramp up and constant voltage "trickle charging" when batteries are close to fully charged) a charger can transfer 25 kWh of energy to the batteries in one minute. In 10 minutes, a terminal charger could charge 250 kWh, replacing more than the frequent-use capacity of the system. During longer off-peak terminal dwell times, the terminal charger could lower the rate of charge which will have the benefit of lengthening battery life and reducing the power demand from the utility.

With these constraints in mind, the ability of a battery ZEMU to service the entire route between Redlands to LA Union Station has been assessed.

Figure 4-5 illustrates the effect of adding in-route charging to a battery ZEMU operating between LA Union Station and University of Redlands, a journey with total energy consumption of 971 kWh based on the conservative simulations (i.e. non-regenerative braking). The figure follows the state of charge (SOC) guidelines provided in Figure 4-2 where calculations take into consideration the capacity of the battery at end of life (EOL) and significant portions of the battery capacity are reserved for operational buffers and contingency (non-frequent) situations. As shown, that even with an in-route charging system at every station on the route providing 1,500 kW for one-minute dwell times, the net depth of discharge is still 521 kWh. Far greater than the 240 kWh design capacity and taking the battery below its non-frequent operation area into the reserve capacity. Regular operations of this nature will significantly reduce the life of a battery system.

Figure 4-5: Battery Charging Alternatives - LA Union Station to University of Redlands

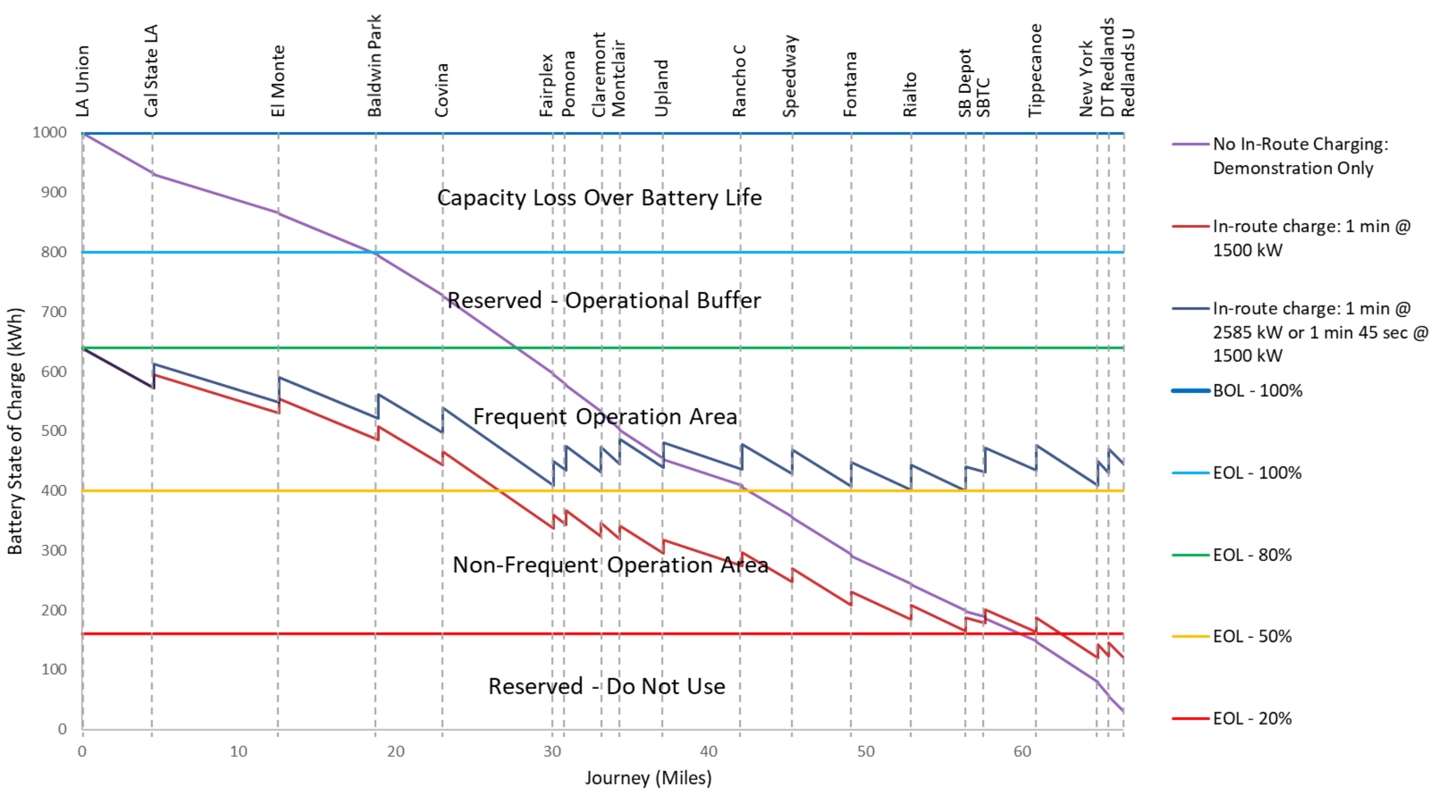


Figure 4-5 also demonstrates the amount of in-route charging needed to keep the battery ZEMU within the operational SOC parameters. To do this, each charging point needs to be able to deliver 43 kWh. This can be achieved within a one-minute dwell time by increasing the charge rate to 2,585 kW (excluding ramp up). Alternatively, the dwell times need to increase to 1 minute and 45 seconds if the charge rate remains 1,500 kW; however, this option obviously has the effect of delaying the service and would not be preferred.

As demonstrated, comprehensive in-route charging would be needed to provide a continuous service to the Redlands to LA Union Station corridor with a battery ZEMU, which has potentially significant cost implications. Power supply and vehicle interface infrastructure will likely be required at all stations, rather than only the terminal stations, unless longer dwells are allowed at specific stations along the journey. Given the fundamental constraints with this type of charging, it may not be the most cost-effective method of providing a zero-emission service for longer distance routes, this tradeoff is discussed in Section 8.

4.2.3 Energy Consumption – Design vs Duty Cycle Scenarios

The simulation results discussed above have taken conservative assumptions as they are used to quantify the design requirements of a potential battery system for the ZEMU, specifically, the sizing of the battery system should allow it to operate within its frequent operation range under the most unfavorable conditions that may occur on a regular basis. This is why regenerative braking was ignored. However, when assessing duty cycle energy consumption, the more likely day to day conditions should be assessed. For this reason, simulations were performed to quantify the energy reductions from capturing regenerated energy during braking. These should be used for duty cycle calculations and infrastructure utility energy demand costs.

The summary of both design versus duty cycle scenarios is presented in Table 4.4, by comparing simulations with and without regenerative braking. Typically, regenerative braking has less impact on the worst-case direction of travel (uphill) routes but does provide a significant energy consumption reduction for the total round trip.

Table 4.4: Effects of Regenerative Braking

Journey		Section Length (Miles)	Total Energy - No Regen Braking (kWh)	Total Energy - With Regen Braking (kWh)	Net Decrease in Energy (%)
SBTC	Univ. Redlands	8.9	158	141	11%
Univ. Redlands	SBTC	8.9	78	32	59%
LAUS	SBTC	57.6	812	672	17%
SBTC	LAUS	57.6	681	497	27%
LAUS	Univ. Redlands	66.5	971	815	16%
Univ. Redlands	LAUS	66.5	761	531	30%
LAUS to Univ. Redlands Round Trip		**133.0**	**1728**	**1342**	**22%**

4.2.4 ZEMU Battery Life

The LTO battery systems currently on the market have charge / discharge cycle life expectancies of up to 8000 full cycles. Based on this data, and the expected depth of discharge as estimated in the simulations completed above, a 660 kWh LTO battery is expected to be capable of a battery life (defined as reducing to 80% of original capacity) of 5 years while operating the full Arrow service timetable, i.e. 12 round trips per day on RPRP for 365 days per year or half of the planned 25 round trips per day. Should three ZEMU or DMU vehicles be operating the service on an even rotational basis (as is expected), the ZEMU battery life is expected to increase to be capable of 7.5 years due to the reduced duty of each vehicle.

4.3 Infrastructure requirements

The following section provides a summary of the infrastructure requirements to implement a battery ZEMU vehicle and an assessment of how these elements could be retrofit into the existing RPRP corridor. Construction impacts to the RPRP mainline contract and/or re-routing related to electrical services for the existing Arrow Service operations have not been considered in this assessment but will be incorporated in the risk evaluation.

4.3.1 Charging

To maximize battery health and lifespan, the state of charge of a battery must be maintained within an optimal window. This results in the need for charging infrastructure within the corridor to deliver adequate energy to the onboard batteries during operations to keep the charge within that preferred range. Battery charging systems for rail applications can be analyzed in three areas and are defined as follows:

1. **Power Supply** – A battery charging system has a power supply and in the context of a ZEMU there are two options; a Traction Power Substation or a Wayside Energy Storage System. Either of these technologies will contain transformers and rectification circuits responsible for stepping down Alternative Current (AC) power from the electrical grid to a suitable level and converting it to Direct Current (DC) power for battery charging.
2. **Power Transfer** – From the power supply, either overhead and/or underground power cabling will need to be implemented to send the power to the Station to Vehicle Interface.
3. **Station to Vehicle Interface –** The final charging equipment, which delivers the necessary power to the ZEMU onboard batteries either inductively or conductively.

4.3.1.1 Power Supply

Two options have been considered for power supply for the Arrow service, Traction Power Substations (TPSS) and Wayside Energy Storage Systems (WESS). The following provides a summary of the capabilities of each alternative to provide power to a ZEMU rail vehicle, as well as their applicability for the RPRP Corridor.

Traction Power Substation (TPSS)

A DC traction power substation is specifically designed to convert high voltage AC power from the grid to lower voltage DC power that is directly supplied to the vehicle charging interface.

In usual applications, a 1.5MW-3MW TPSS would supply current to multiple DC overhead catenary or third rail traction systems. For a ZEMU on the RPRP corridor, the substation would only be utilized for battery charging. This results in a smaller number of feeder cables, which would reduce the high upfront cost for a complete substation. In addition, the overall components of a substation require lighter maintenance which makes a TPSS advantageous in terms of life cycle costs.

While the capital expenditure of a TPSS for a ZEMU charging application may be comparatively less than for a typical rail application, a TPSS system will draw power during operational dwell (or turnaround) times only. This results in intermittent service from the grid, often at peak times. Electricity providers in the United States will typically incorporate energy fees measured in $/kWh and demand fees, measured in $/kW. Of the latter, customers demanding above 200 kW are often charged high demand rates, which can be well above $15/kW[2]. It is not

[2] U.S. Department of Transportation. Federal Transit Administration (2014). Peak Demand Charges and Electric Transit Buses.

uncommon for a local utility to utilize the highest instantaneous power in the billing calculation, which can further increase the monthly operational cost for rail operations[3].

Not only does drawing high power intermittently from the grid significantly increase the yearly operational cost, drawing megawatts of power for very short periods of time can also pose a higher risk of outages in the local area, resulting in a potential risk to operations if TPSS are not constructed on independent feeders.

While a TPSS is a reliable means of supplying power for batteries onboard a rail vehicle, the large intermittent power draw from the grid, increase in yearly operating costs and the potential challenges for future expansion (discussed further in Section 4.10 – System Expansion) result in poorer performance in comparison to a WESS system. For these reasons and considering the proposed Arrow Service timetable, a TPSS power supply is ultimately not recommended to provide the charging power for a ZEMU vehicle in the RPRP Corridor.

Wayside Energy Storage (WESS)

A Wayside Energy Storage System (WESS) is a bank of energy storage devices (battery, supercapacitor, flywheel) that receive power from the grid to be stored until transferred at high rates into the vehicle. Typically, these devices are combined in order to create an optimal power supply.

Similar to the onboard batteries, a WESS bank of batteries will always need to stay in a frequent operation range, which is recommended to be from 50-95% during Arrow service. The WESS bank would start service at near full charge, then be maintained in the provided operation window and would then be topped off at the end of the charging period. The maximum power required to sufficiently maintain a WESS bank within the operation window decreases if the charging period is longer. Often it is most efficient to provide slowcharging to the WESS from the grid as much as possible over 24 hours to keep it charged at the optimal level and to act as a power supply.

Utilizing batteries due to the energy density would be the most feasible option in comparison to supercapacitors. Many different battery chemistries could be utilized to form a larger wayside bank. Based on the battery assessment completed for the ZEMU vehicle, it is anticipated that a lithium-ion chemistry such as titanate oxide as a WESS bank would be able to accept the max charging current of 2000A (1500kW/750V) during Arrow service dwells (estimated to be 10 minutes at the terminal stations) with less risk of diminishing battery state of health.

Based on the recommended size of a WESS bank comprised of LTO batteries, the upfront cost of this power supply will likely be similar to the price of an individual substation due to the large energy capacity. The lifecycle costs for a WESS will be much higher than a combined system or a TPSS due to replacement costs which is an important consideration in the overall evaluation. Maintaining the battery SOC within the frequent operation area will help preserve the service life, which is estimated to be around 7.5 years based on duty cycle calculations in the same method as Section 4.2.4.

The key factor differentiating the cost of a TPSS compared to a WESS is the operational cost. A WESS can significantly reduce operational costs by lowering utility demand charges at peak

https://calstart.org/wp-content/uploads/2018/10/Peak-Demand-Charges-and-Electric-Transit-Buses.pdf. p.20-22.

[3] Southern California Edison. Time-Of-Use Charges (2019). https://www.sce.com/business/rates/time-of-use/Understanding-Time-Of-Use-Charges

times. The batteries are able to pull power at off-peak times, throughout the day in order to maintain their optimal SOC and supply power to vehicles when required.

The overall size of WESS implemented at terminal stations on the Arrow service should be minimized to offset the upfront cost as much as possible, yet large enough to reduce the peak power drawn from the grid and have enough reserve capacity in the case of a grid service outage. For this analysis, the power requirements for charging a WESS of LTO batteries in the range of 500-800 kWh at each terminal station are:

- 120 kW of max demand to charge a WESS at the SBTC over 24 hours; and
- 300 kW of max demand to charge a WESS at University of Redlands over 24 hours

Note that during the peak service (half hour service), the WESS would be recharged by the grid in 20 minutes. This results in a duty cycle of two thirds as the WESS bank must discharge the power (defined in table 4.5) needed to charge the ZEMU batteries and because batteries are not recommended to be charged/discharged simultaneously. However, for the non-peak-service, the recharging period for a WESS can be extended closer to an hour due to the longer dwell times. For instance, if the WESS discharged to store the energy needed maintain the ZEMU batteries in 6-7 minutes, then the WESS batteries could be charged by the grid for 53-54 minutes at a lower C-rate.

While the operational performance of a TPSS is generally preferred, it is ultimately recommended to implement a WESS for the RPRP corridor given that this type of power supply would draw a fraction of the power that a substation would intermittently demand at peak times from the grid. The ability for a WESS to be charged slowly throughout the day, at specified off-peak times, or at times when only renewable generated power is available has significant operating cost and socio-economic benefits. In addition, should the service be extended, it is generally easier to install WESS within the stations than a TPSS (discussed further in Section 4.10 – System Expansion).

4.3.1.2 Power Transfer

From the power supply location, energy will need to be transferred via overhead or underground cables to the point of vehicle interface. The overall performance and characteristics of overhead and buried power cabling are similar, as noted in the Power Transfer Evaluation Matrix in Appendix C. Depending on the voltage of the cabling, the upfront cost of an underground line could be double the cost of an overhead line. The life span of buried cabling is close to half the service life of overhead lines and maintenance performed on any buried lines poses the risks of either disrupting the Arrow service and/or impacting other utility related infrastructure.

The matrix summarizes and compares the characteristics of underground and overhead powerlines. Although the matrix shows that overhead cabling outscores underground cabling, it is recommended that the buried type be given preference due the reduced risk of electromagnetic interference and improved safety. The overall charging system will output a large amount of power, which may result in electromagnetic interference with other nearby systems. Installing cabling underground is a feasible way to isolate the large magnetic fields of the cabling from other systems that may be disturbed and will also keep the charging system better protected from hazardous weather conditions that may cause outages.

4.3.1.3 Station to Vehicle Interface

Power from the supply location is delivered directly to the vehicle within the station via an inductive or conductive charger. Unlike at the maintenance facility, where the vehicles could be charged using a conventional stinger type plug system, in route charging is required to operate automatically and for short period of time at a station or terminal. In the case of the Arrow service, the charging infrastructure will also need to accommodate larger vehicle clearances (i.e. Metrolink and freight rail vehicles) as well as function with the at-grade track infrastructure. The different types of charging systems are discussed below.

Inductive Charging

Inductive charging is a form of wireless charging, which involves transferring energy between objects through electromagnetic induction. Inductor coils located under the vehicle in the track bed produce an alternating magnetic field, which induces a current in the secondary pickup coils located onboard the train. Modern inductive charging technology includes resonant circuits in design to strengthen the inductive coupling between the primary and secondary pickup coils, which reduces the losses in the wireless power transfer. The current induced in the secondary coils is then rectified to DC current and utilized for charging the onboard batteries.

Implementing an inductive charging scheme for the station to vehicle interface does reduce some of the components in the power supply portion of a complete battery charging system as the power does not require rectification until current has been induced onboard the train. However, the advanced resonant circuit technology for the station to vehicle interfaces is very expensive and the wireless power transfer efficiency of inductive charging technology without resonant coupling is poor[4]. The technology is also not mature in relation to the rail industry. Inductive systems utilized for battery charging have thus far been successful and service proven for electric busses, but not for multiple unit trains. Bombardier’s PriMove system implements this type of technology as a continuous power supply to provide propulsion for a vehicle, but not as a static battery charging apparatus, noting that the power for electric buses and other electric vehicles is only a fraction of the power required for charging onboard rail vehicle batteries. Due to this, the overall components of inductive technology for the ZEMU would be much bulkier and have a high upfront cost.

Another concern with implementing inductive technology as the vehicle to station interface on the RPRP corridor is that the ZEMU will need to perfectly align above the primary pickup coils in the track while charging. If the ZEMU is not aligned, then the power transfer efficiency will be significantly reduced, resulting in less energy delivered to the onboard batteries. From discussions with different suppliers of this type of technology, it has been disclosed that around 6-8 sets of pickup coils in the track would be needed along with additional control technology to ensure that the train operator aligns the ZEMU such that max power transfer occurs during battery charging. Implementing multiple sets of resonant inductive circuits in the track bed may lead to increased installation cost, service interruption, and may pose higher risks of electromagnetic interference. The latter is also a concern as research in this area is limited and there are no current electro-magnetic compatibility standards for inductive charging systems specific to rail applications. Due to the above concerns about functionality, weight and cost, inductive charging is not recommended to be considered for the Arrow service at this time.

Conductive Charging

The alternative to inductive technology for a vehicle to station interface is conductive charging. In this type of charging, the vehicle makes physical contact with charging rails or charging bar at a specific stopped location.

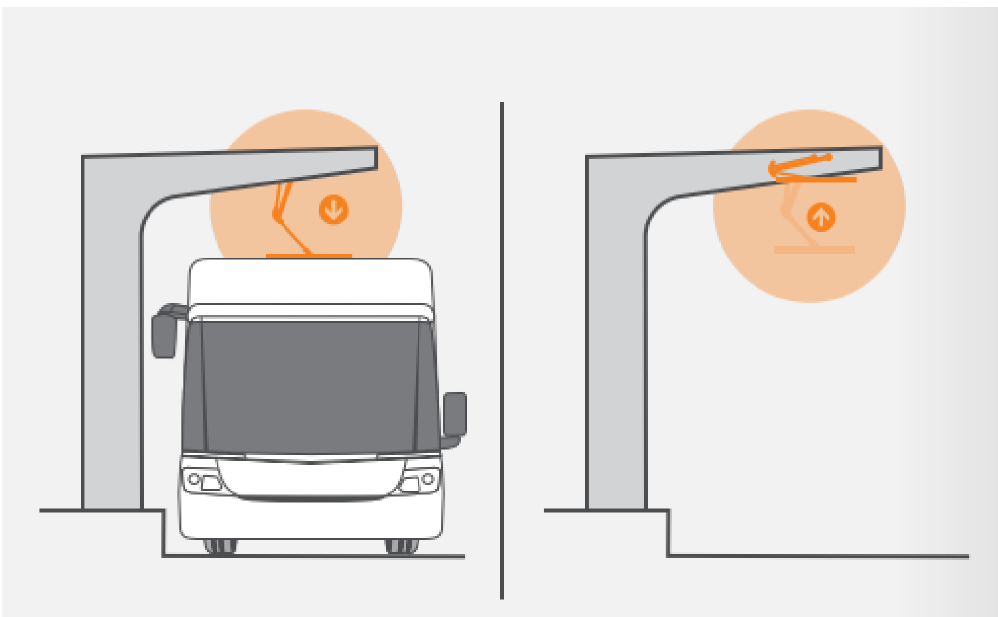
Conductive charging can be overhead or ground level. Charging rails are utilized in ground based conductive charging systems that are similar to inductive charging schemes, but the

[4] NaNoNetworking Summit (2012).
http://n3cat.upc.edu/n3summit2012/presentations/Resonant_Inductive_Coupling_Wireless_Power_Transfer.pdf

power transfer is not wireless. Ground based conductive charging has not been service proven for static battery charging, but Alstom has implemented this technology as a propulsion drive, like Bombardier's PriMove mentioned above. The overall upfront cost for this type of equipment and installation is not considered to be a feasible option for the Arrow service.

Overhead conductive charging within the terminal station platform is the preferred method of vehicle charging at the station interface for a ZEMU vehicle in the Arrow service. This type of vehicle to station interface is recommended given the reliability of technology when compared to inductive charging and/or ground based systems. While overhead charging is widely applied in rail operations, the application for the ZEMU corridor is unique given the mixed use of the corridor and variation in vehicle clearances between the ZEMU, Metrolink and freight vehicles. As a result, the conductive charger within the station will need to be designed to accommodate freight vehicle clearances. This will likely result in a charger design which extends from a higher clearance down to the ZEMU vehicle connection point. Figure 4-6 highlights the concept for this charger as applied for bus operations. Figure 4-7 also provides real world examples of how this has been applied. Given the uncertainty of this design, this will be captured in the project risk evaluation.

Figure 4-6. Example of overhead charging bar mechanism for bus operations



Source: Furrer and Frey (2017). All-In-One Charging System.

Figure 4-7. Example of Overhead Conductive Chargers for Rail

Source: Metro Report, 2019

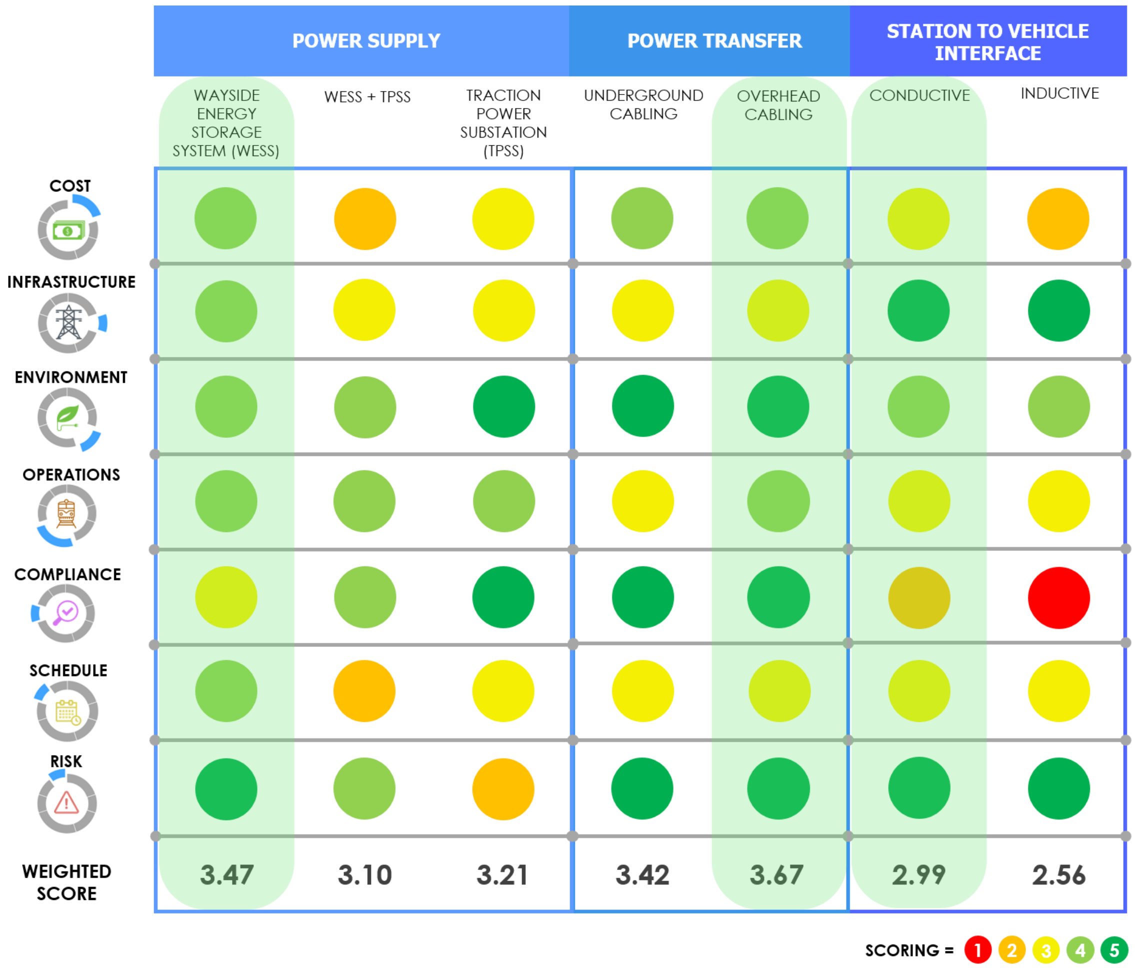
4.3.2 Recommended Charging Infrastructure for ZEMU on RPRP Corridor

The evaluation of the alternatives indicates the most adequate charging system would consist of a WESS power supply combined with overhead cabling and an overhead conductive charging technology. A WESS outranks the substation power supply mainly because this power supply system is able to reduce peak power demand from the grid, therefore reducing operating cost for a ZEMU. The WESS solution is also more reliable in situations where there are local power outages. If a substation at either terminal were to lose grid power, there would be no way for the ZEMU onboard batteries to be charged during dwells. The energy capacities of potential WESS should be large enough such that if one WESS bank fails the charging system at the other terminal can supply the onboard batteries the required energy. If utility power was lost completely along the RPRP corridor, the WESS power supplies should be able to maintain charging the ZEMU batteries for a few hours before service is interrupted but could likely supply adequate battery charging for a full day if the headways were decreased by half in this scenario.

For the method of power transfer, overhead cabling is generally preferred, but based on the physical layout near the platforms at the Arrow Service terminals, it is recommended to bury cables for ease of future maintenance and to reduce potential impact to operations. Additionally, an overhead conductive charging interface is the most feasible option in comparison to a ground based inductive charging scheme. Despite some risk associated with clearances as described in Section 4.3.1.3, this type of interface is not only more efficient in terms of power transfer but is compact, can be located on the platform and presents easier options for a ZEMU to connect to the interface with a single or two pole pantograph located on the vehicle.

The charging infrastructure evaluation matrix included in Appendix C provides a summary of the evaluation of the recommended charging system for a ZEMU on the RPRP corridor. Figure 4-8 show a condensed version of the matrix found in Appendix C.

Figure 4-8: Charging Infrastructure Evaluation Matrix



4.3.2.1 Charging Points Along the Arrow Service Route

In order to charge the ZEMU within the 1-minute dwell time at non-terminal stations, the power delivered from a charging system would need to be approximately 2,500-3,000kW. The increased power requirements to implement this type of rapid charging at intermediate stations would require bulkier and higher power transformer rectifiers for the charging power supply as described above, making the overall equipment cost too high to be a viable option for the Arrow service. Therefore, it is suggested that charging points be implemented only at the terminal stations.

4.3.2.2 Output Power Requirements at Terminal Stations

Section 4.2 summarized the energy usage for a 2-car ZEMU requiring full round-trip energy utilization of 236 kWh. A charging point at each terminal needs to charge the energy back into the onboard batteries that was drained during a half trip. However, the amount of energy to be delivered back into the batteries also depends on the type of service. Recall that during peak service hours, the dwell time is planned to be 10 minutes and that for non-peak service, the dwell time is planned to be 40 minutes as disclosed in section 4.2.2. Table 4.2 from section 4.2.1 illustrated that for every minute of dwell time, approximately 120 kW is needed to provide 1.97 kWh of energy for auxiliary loads, which equates to an additional 20 kWh and 80 kWh of energy= during the 10 minute and 40-minute dwells respectively. Therefore, the charging power source needs to deliver an extra 120 kW to meet the energy requirements of both the onboard batteries and auxiliaries during these stops at terminal stations. For longer dwells at non-peak hours, more energy will need to be fed from the charging point, but at lower power, while at peak service higher power will need to be delivered to charge the OESS. Separate electrical routing from the charging system to the onboard batteries and to the auxiliary power system (APS) respectively. It also assumed that the additional 120 kW of DC power provided from the charging system, will be converted back to AC power by the inverter of the APS.

The minimum requirements for the output power of a charging station at each terminal are summarized in Table 4.5. Note a conservative approach for the battery charging was utilized to account for additional ramp up in charging time, when battery charging switches from constant current mode to constant voltage mode.

Table 4.5: Minimum requirements for output power of a charging stations

	Charging at SBTC	Charging at University of Redlands
Energy to Store	78 kWh for a ZEMU trip from University of Redlands to SBTC Stations (downhill)	158 kWh for a ZEMU trip from SBTC to University of Redlands (uphill).
Peak Service	720 kW total to provide 100 kWh in 10 minutes. 600 kW of the total power must be fed into the onboard battery to store 78 kWh tand 120 kW of the charging power should be utilized to provide the 20-kWh for auxiliaries	1300 kW total charging power to deliver 180 kWh in 10 minutes. 1180 kW of the power is utilized for storing 158 kWh into the ZEMU battery, while 120 kW will provide the energy for auxiliaries.
Non-Peak Service	270 kW from the charging source is needed to provide a total of 160 kWh. 150 kW is needed to store 80 kWh into the battery and 120 kW for the 80 kWh of auxiliary energy.	400 kW of total charging power to provide 240 kWh. 280 kW for battery charging to store 158 kWh and the remaining 120 kW of charging power to provide the 80 kWh of auxiliary energy.

Based on the above information, each charging station for a battery ZEMU should be designed for a nominal 750 V DC, with a max rated power of 1,500 kW. Section 4.3.3 evaluates the feasibility of placing this size of infrastructure within the RPRP Corridor at the two selected terminal locations.

It should be noted that if there is a fault within a WESS battery bank, that there should be

4.3.3 Evaluation of Charger Locations and Clearances

As discussed in the previous section, the ZEMU will need up to a maximum charging power of 1,500kW at terminals where the dwell times are 10 minutes. The power requirements assessed pertain to charging stations located at the San Bernardino Transit Center and University Station utilized to charge on board batteries for a 2-car ZEMU, such that they always stay between 50-95% SOC.

Due to the immense power-demand required to fast charge a battery powered ZEMU, subsequently large footprints (assumed to be 20’W x 50’L x 15’H) may pose spacing issues. In some space-constrained locations, a right of way extension may be required if more than one access point to the structure is deemed necessary. A 3’ wide walkable access path around charging stations has been assumed but may change depending on location and proximity to utilities and vehicles. Protective fencing, requiring more clearance, may be necessary depending on the location and tamper-resistance of proposed structures. These concerns will be identified and addressed prior to the selection and further design of any specific location. Electrical lines connecting the charging system to the grid will be underground for safety and no apparent issues have been found within this consideration.

Two options for battery charging points have been proposed along the Arrow service at the terminal stations. See Appendix D for substation concept plans, which are also described below:

SBTC - Option 1: The substation is proposed approximately 350’-400’ to the southwest of the station platform between an existing crew house and a private lot. Access to the substation equipment would be via a new station parking lot. It would be relatively insulated from the public and have enough space for a 3’ walkway around the structure. There are existing electrical and communication lines within the proposed footprint. Further utility verification would need to be performed to determine the conflicts and potential relocations. The crew house also contains communication lines and cabinets which likely cannot be relocated.

SBTC – Option 2: The substation is proposed approximately 100’-150’ south of the platforms within the new station parking lot. No existing utilities would be impacted by this location, but approximately six parking spaces would need to be eliminated to accommodate the substation. Additionally, a perimeter fence or safety bollards may be considered to provide separation and protection from the adjacent sidewalk and parking lot driveway.

University Station – Option 1: The substation is proposed approximately 200’ to the northeast of the platforms adjacent to a future parking lot. Up to two parking spaces may need to be eliminated and perimeter fencing, or safety bollards may need to be installed. No utility conflicts are anticipated with this option.

University Station – Option 2: The substation is proposed on the east side of the station between the platforms and a future parking lot. Perimeter fencing, or safety bollards may need to be installed. No utility conflicts are anticipated with this option.

Overhead charging bars are being considered to provide charge to the battery-powered ZEMU vehicle at stations. One charging point per vehicle per track is assumed at each station platform. At the University station, the two platforms are long enough to each accommodate two trains. One charging point could be located on the western end and a second charging point could be located on the eastern end of the platform.

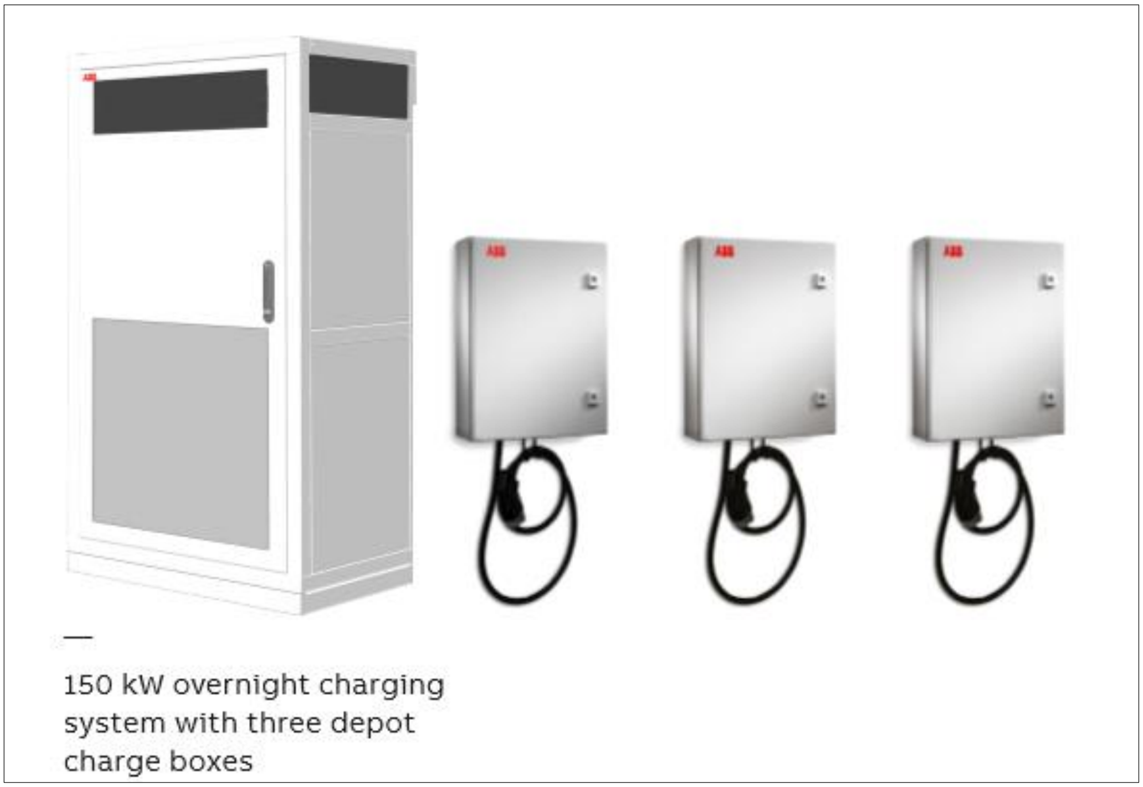
Various overhead charging bar and vehicle infrastructure configurations are available for consideration for the RPRP corridor. However, since freight trains also operate on the RPRP corridor the overhead charging bar would need to be located a minimum of 22.5’ from top of rail to be in compliance with the California Public Utilities Commission (CPUC) General Order 95, which governs minimum allowable overhead clearance of wires above railroads. The ZEMU vehicle is anticipated to be 14’ high, measured from top of rail, thus either the charging bar would need to be lowered or the charging infrastructure on the vehicle would need to be raised over 8’ if a deviation from the CPUC cannot be obtained. The pole supporting the overhead charging bars is assumed to be 2’ in diameter and must be located a minimum of 10’ from edge of pole to track centerline.

4.3.4 Maintenance and Storage Facility Modifications

Proposed charging infrastructure from ABB's product line is physically small (assumed to be 5'W x 5'L x 10'H) and will require only minimal modifications, such as installing underground electrical wiring. The charging infrastructure is anticipated to be located outside of, but adjacent to, the maintenance building.

Multiple charging units may be installed depending on the location and number of stored vehicles, however, this will likely not add any negative impact to the overall maintenance facility. Figure 4-9 below shows an example of typical charging infrastructure implemented for a bus which is anticipated to be similar for a ZEMU rail vehicle application.

Figure 4-9 . ABB Example of AMF Charging Infrastructure



Source: ABB, 2019

Some spare batteries need to be stored at the maintenance and storage facility to quickly swap out worn out or defective battery packs. These need to be stored in a designated area which is raised off the floor and in a locked area to avoid accidental discharge, as shown in Figure 4-10. These also need to be stored in a state of partial charge to ensure that the battery chemistry is maintained at an optimal state.

Figure 4-10: Battery storage area at Long Beach Container Terminal

Given the space programming and details of the storage areas and allocation is not available for the Arrow service maintenance facility, further configuration will be needed. This will be captured in the risk assessment and a more detailed evaluation of the AMF modifications will be completed in Phase 2 should a battery ZEMU option be selected. Given the size and storage requirements for the batteries, it is not anticipated to be a significant risk.

4.4 Utility Supplier Assessment

For a charging system to be implemented at the University of Redlands and SBTC terminals for a battery operated ZEMU, higher grid voltage will need to be tapped into. The power currently delivered to these terminals provided by Southern California Edison (SCE), is rated at 15kVA. This is significantly less than the 1,500 kW a substation would need to supply to a ZEMU and less than the 160 kW to 240 kW that would need to be delivered for 24-hours to charge a WESS.

Discussions with SCE or another local utility should be initiated in the next phase of the ZEMU Project to discuss feeder voltages and the distance these feeders are currently located from the University of Redlands and SBTC terminals. Drawing power from higher feeder voltages may result in lower electricity prices as the utility does not have to step down the higher voltage as much. However, drawing at higher voltages may result in increased distances away from the ZEMU charging stations, which will require more cabling and will increase the upfront cost for installation.

Ultimately, it is recommended that grid power be drawn from the closest feeder voltage that can supply the required charging power, but the construction of new voltage feeder lines at higher voltages that could be located even closer to University of Redlands and SBTC should also be discussed thoroughly with the utility.

4.5 Right of Way Impact and Land Use Evaluation

The potential for right of way impacts are contingent on clearance requirements around the proposed substations to be located at University Station. For the purposes of the infrastructure assessment, it was assumed that three feet of clearance around each substation would be required. The required clearances are available, and a substation would fit within the existing SBCTA right of way (ROW) adjacent to University Station. Should vehicle access and parking be required at each substation however, then additional coordination with the City of Redlands may be needed to dedicate up to two spots for maintenance parking.

While there may be additional land requirements outside of SBCTA ROW depending on access requirements, these impacts would remain within the project area as outlined in the final environmental impact report (EIR). Therefore, minimal to no impact is expected on the land use surrounding the corridor.

4.6 Market Availability

4.6.1 Provider dependency

Battery technology is already being used in the rail industry as an auxiliary power source with many suppliers producing batteries and some of these suppliers have also started research into battery technology for propulsion. As part of the initial technology selection process, a number of suppliers were interviewed to understand more about the technology, future developments, and suitability for the Arrow service. Combined with the power modeling carried out for this report and suppliers, it is confirmed that the power required for a standard round trip between SBTC and University of Redlands is feasible for the current state of battery technology and the charging equipment envisaged in-route.

To be used for the ZEMU on the Arrow service, the battery will need to be customized to fit within the available space of the Stadler FLIRT vehicle and the operational characteristics of the Arrow service. While the technology is well-understood and can be standardized, with a number of potential suppliers, it has only been a recent development that batteries have been used as a propulsion technology and significant amount of customized design work on the battery packs and the vehicle will be required to interface between the two aspects.

In terms of charging equipment, battery suppliers may also develop their own charging equipment for optimal charging or work with third party companies to develop charging equipment. Therefore, if battery technology is selected, charging equipment will also be available.

4.6.2 Technology Obsolescence

Battery technology is continually evolving with a trend for battery technology to generally become cheaper and more energy and power dense over time. While this offers opportunities for reduced life cycle cost and over time for a battery ZEMU, it also presents an obsolescence risk. The rapid advance of technology may cause battery system suppliers or their sub-suppliers to no longer support existing products for either spare parts or like-for-like system replacements at the end of battery system life. Care should be taken in SBCTA's contracting approach to procuring the battery ZEMU in that it requires the supplier to design the system with forward interoperability in mind. In the future, newer (smaller, lighter, cheaper, or more powerful) battery technologies should be able to be packaged into modules that fit common interface, management and space requirements such that SBCTA is not limited to a sole source battery supplier. This should mitigate both cost and obsolescence risks.

4.7 Safety

Modern batteries used for propulsion applications introduce unique safety hazards. Charged propulsion batteries store significant energy and, as they cannot easily be discharged, (in fact this may damage the battery, reducing its life) to render them harmless, they must be carefully managed. This is a major change compared to conventional vehicles, where for example, the diesel engine is turned off and no power is present across the powertrain. A similar function is achieved with a circuit breaker in a battery-powered system, but the battery itself remains 'live.' Access to the batteries, for either maintenance or storage, must be restricted to only those sufficiently trained to handle them safely and only then with appropriate safety measures in place.

In addition to the electrical safety considerations, batteries also present a fire risk that needs to be addressed. The risk of fire by thermal runaway of the batteries exists due to various failure modes such as overcharging due to poor charge management, overheating due to poor temperature management, physical damage, i.e. piecing of cell due to collisions, among others. Recent developments in lithium-ion battery chemistries (lithium titanates and lithium iron phosphates) eliminates the potential for thermal runaway, even in the event of control system failure or collisions mentioned above. It is expected and recommended that the specification for design of a battery ZEMU vehicle for SBCTA will require the use of chemistries that minimize fire safety risks.

In addition to basic requirements to use safer battery technologies, the project will include the requirement for the vehicle supplier to provide a full system safety analysis to demonstrate that the system is safe to use in passenger service and that all failure modes have been considered, including the protection of passengers from battery related hazards caused by collisions, fires or other events that may damage the on-board battery system. This analysis will be required to be verified by an appropriate test program per the requirements for FRA review and approval.

Electrical safety considerations will need to be addressed for the charging infrastructure implemented to charge a battery ZEMU. The primary hazards relate to the high voltage conductor that is required to be suspended above the running rails. The infrastructure design is required to include various electrical safety features such as insulators in the conductor support and high-speed circuit breakers at the power supply. Exclusion zones are needed whenever work is to be done nearby the conductors.

4.8 Cost

4.8.1 Capital Cost

The up-front capital costs associated with implementing a battery ZEMU service, including one (1) ZEMU vehicle and associated infrastructure, are summarized in Table 4.6 and Table 4.7. Costs are broken down by major components and estimated values. Note that this estimate currently excludes the costs of converting any of SBCTA's new DMU vehicles to ZEMU vehicles. Further detail on the items covered in this cost estimate can be found in Appendix E.

Table 4.6: Battery ZEMU Capital Costs for WESS

Item	Cost
Battery ZEMU vehicle, including: - Modified base vehicle designed to accept and integrate a battery powered propulsion system - Battery propulsion system assumed 660 kWh - Battery charging system including pantograph	$10,200,000
ZEMU Vehicle Non-recurring costs, including: - Project and engineering management / overhead - Engineering and Design - Testing and Commissioning - FRA Process Approval	$8,100,000
Battery ZEMU specific capital spares	$1,000,000
Charging infrastructure – WESS, including: - Charging units with 500-800 kWh energy storage - Station retrofit work - Utility connections - Maintenance facility modifications	$3,500,000
General costs, including: - Environment and Permitting - Project and Construction Management - Public Outreach Campaign	$3,100,000
Unallocated contingencies (20% of total)	$5,200,000
TOTAL – WESS Option	**$31,000,000**

Table 4.7: Battery ZEMU Capital Costs for TPSS

Item	Cost
Battery ZEMU vehicle, including: - Modified base vehicle designed to accept and integrate a battery powered propulsion system - Battery propulsion system assumed 660 kWh - Battery charging system including pantograph	$10,200,000
ZEMU Vehicle Non-recurring costs, including: - Project and engineering management / overhead - Engineering and Design - Testing and Commissioning - FRA Process Approval	$8,100,000
Battery ZEMU specific capital spares	$1,000,000
Charging infrastructure – TPSS, including: - Modular sub-station 1.5 MW - Station retrofit work - Utility connections - Maintenance facility modifications	$2,200,000
General costs, including: - Environment and Permitting - Project and Construction Management - Public Outreach Campaign	$2,700,000
Unallocated contingencies (20% of total)	$4,800,000
TOTAL – TPSS Option	**$29,000,000**

4.8.2 Operational and Maintenance Cost

The on-going operations and maintenances costs associated with implementing a battery ZEMU for the Arrow service requiring two (2) ZEMUs are summarized in Table 4.8 and Table 4.9. Operation costs are broken down by major components and estimated values. As a point of comparison, the total annual estimated equivalent DMU vehicle for fuel, service and engine overhaul is $750,000 per year.

Table 4.8: Battery ZEMU Operating and Maintenance Costs for WESS

Item	Quantity	Frequency	Unit Price	Equivalent Annual Cost
Energy / Power costs - WESS	1	Annual	$206,000	$206,000
Battery replacement / system overhaul – ZEMU	2 ZEMU	5 years	$800,000	$267,000
WESS replacement / overhaul	2 WESS	7.5 years	$980,000	$190,000
Station equipment maintenance	2 Stations	Annual	$10,000	$20,000
Station equipment overhaul	2 Stations	15 years	$50,000	$7,000
TOTAL ANNUAL ex contingency – WESS Option				**$690,000**

Table 4.9: Battery ZEMU Operating and Maintenance Costs for TPSS

Item	Quantity	Frequency	Unit Price	Equivalent Annual Cost
Energy / Power costs - TPSS	1	Annual	$451,000	$451,000
Battery replacement / system overhaul – ZEMU	2 ZEMU	5 years	$800,000	$267,000
TPSS replacement / overhaul	2 TPSS	15 years	$375,000	$25,000
Station equipment maintenance	2 Stations	Annual	$10,000	$20,000
Station equipment overhaul	2 Stations	15 years	$50,000	$7,000
TOTAL ANNUAL ex contingency – TPSS Option				**$769,000**

Note that these estimates assume two ZEMU vehicles are operating and perform the full Arrow service between SBTC and University of Redlands. For a discussion on the battery life assumptions refer to Section 4.2.4 and 4.3.1.1. No contingency is included. The items covered in this cost estimate are explained in further detail in Appendix E.

SBCTA is eligible to receive Low Carbon Fuel Standard (LCFS) credits through the operation of an electric fueled fixed guideway transit system.[5] The LCFS Program, administered by the California Air Resources Board (CARB), allows entities that use electricity as a transportation fuel to earn LCFS credits for each metric ton of reduced CO2 emissions. The credits can be sold for monetary value through CARB's Report and Credit Bank & Transfer System.

Additionally, two factors that would provide positive effects for battery replacement costs have not been factored into the estimates. These are: 1) the price of battery technology is expected to reduce over time; and 2) at end of life estimated for the cost calculations, LTO batteries will retain 70% - 80% of their original capacity, meaning they will retain some re-sale value and could be sold into the second-life battery market. These opportunities will benefit the WESS option more than the TPSS option as they apply to the wayside battery equipment as well as the on-board battery equipment. The opportunity for reducing O&M costs will be captured in the risk register.

4.9 Feasibility of Application for the Arrow Service

A battery ZEMU service is assessed as feasible for the Arrow service. The 9-mile corridor lends itself ideally to the vehicle and charging technology and products currently available. While the application of a new technology inherently has risks, a battery ZEMU also provides a potential for long-term operational cost savings for SBCTA in operating the Arrow service.

4.9.1 DMU Conversion

The Stadler FLIRT DMU vehicles currently on order for SBCTA are better suited to a propulsion technology conversion than most all other rail vehicles on the market. The configuration utilizing a central power-module should provide a relatively simple conversion program, particularly if SBCTA limits the energy storage capacity requirements of the OESS to the 600 – 660 kWh range. This is all that is needed to service the 9-mile corridor while maintaining an optimal battery state of charge, and therefore minimizing life cycle costs by maximizing battery life.

It is expected that a battery of this size could fit in the compartments currently occupied by the diesel engines on the DMU and could be mounted and integrated without major re-configuration or structural changes. However, note that the cost estimates provided above relate only to the procurement of a new ZEMU vehicle. It is expected that Stadler would charge a separate non-recurring design related cost, on top of the conversion kit and implementation costs, should SBCTA move ahead with a DMU to ZEMU conversion contract. Estimates for these costs have not yet been done, as they are highly dependent on understanding the final ZEMU design, as accepted by the FRA, and then assessing the significance of changes needed to convert a DMU to this final design solution.

4.10 System Expansion to LA Union

4.10.1 Vehicles

Section 4.2.2 provides a description of the likely maximum feasible operating range of a battery ZEMU. To provide a service between University of Redlands and LA Union Station, the vehicle would need to be configured to utilize the maximum available space on-board to install a battery system with maximized capacity. As stated above this will likely result in a battery ZEMU with a 1,000 kWh capacity, when new.

[5] California Air Resources Board. (2016). LCFS Electricity Program Regulatory Guidance.

Through the supplier engagement process, Stadler provided feedback that indicated that a battery of this capacity is conceptually possible, however it would likely result in significant structural configuration changes to the base power module design, as it is implemented in the current DMU design. The changes would be aimed at utilizing and maximizing the space available in the module to better accommodate battery propulsion equipment rather than the original diesel engine equipment. This would include, for example, removing the diesel fuel tank from the module structure and re-purposing that space for battery equipment enclosures. Therefore, if this solution were to be pursued for the ZEMU, the existing DMU power modules structures may not be able to be retained should SBCTA move ahead with DMU to ZEMU conversions. New power modules may need to be delivered with the conversion kit. While this may make the conversion technically simpler and faster, as Stadler may be able to supply a complete ZEMU power module to be “swapped” with a DMU power module, it will make the conversion more expensive.

For approximate cost estimate purposes, it is expected that this solution would add $500,000 - $1 million to the new vehicle price estimate above, due to the additional battery system size and complexity and a similar amount for the associated non-recurring design costs due to the changes to the power module and other flow on-effects that need to be re-validated due to the extra weight (suspension, brakes, etc.). Total approximate cost would be between $1 - $2 million for the entire project. Operating and maintenance costs will also be affected as the replacement costs of the larger batteries and auxiliary equipment will be higher.

4.10.2 Infrastructure

As demonstrated in the operating range calculations described in Section 4.2.2, in-route charging would be required at every station in order for a battery ZEMU to service the LAUS to the University of Redlands run. The power supply of these charging points would be of different design to those described for the terminal charging points, as the requirements would be for shorter duration but higher power transfer charging, i.e. 1 minute at 2.6 MW rather than 10 minutes at 1.5 MW. For infrequent headways, charging with these characteristics better suits supercapacitor based WESS systems, rather than batteries. Alternatively, a 2.6 – 3.0 MW substation could be effectively used if headways are shortened, such that the power demand cost is spread over many services. Either way, a cost similar to that estimated for the battery WESS (approximately $1.65 million) may be expected for these in-route charging stations at each of the 18 stops shown in Figure 4-5, on top of SBTC and University of Redlands. This would add approximately $30 million to the capital expenditure of the project.

4.11 Current applications

Battery technologies are already used in rail applications, including the Stadler FLIRT rail vehicle currently in use in Germany. Further information on this application can be found in Appendix F.

5 Hydrogen Fuel Cells

Hydrogen is the most common element in the universe and a common element here on Earth, where it primarily occurs in compounds such as water H_2O and hydrocarbons such as natural gas or petroleum. It has to be split from the compound to be used and, therefore, is an energy carrier (or vector) rather than an energy source; similar to electricity in this respect. At ambient temperature and pressure hydrogen is a colorless, odorless gas and the lightest element. It has the largest energy density by mass, ~120MJ/kg low heating value, of any fuel but a low volumetric energy density requiring compression or liquification to enable practical storage densities allowing attractive ranges for vehicle applications. Hydrogen is not a greenhouse gas itself and its combustion with air results in water and small amounts of NOx as emissions, but these can be avoided if hydrogen is used in a fuel cell. Currently, hydrogen is used in many industrial processes, such as petroleum refining and fertilizer (ammonia) production and available as a merchant gas. Hydrogen has also been transforming warehousing and distribution centers with more than 20,000 hydrogen fuel cell forklifts operating across the US.[6] Fuel cell vehicles are also available to consumers which are being manufactured by Toyota, Honda, and Hyundai. It is estimated that there are currently more than 6,500 fuel cell vehicles on the road in the US.[7] Increasingly, hydrogen fuel-cell buses are being rolled out in the US. Sunline Transit Agency in the Coachella Valley in California has been running hydrogen fuel-cell buses for over 15 years. Sunline makes its own hydrogen and invested in hydrogen fueling infrastructure to serve its growing fleet and reduce the cost of hydrogen. Another agency, the Orange County Transportation Authority (OCTA) is nearing construction completion of its hydrogen fueling facility. Unlike Sunline, OCTA will have liquid hydrogen delivered to its facility in Santa Ana, California, then vaporize the hydrogen to a high-pressure gas, which will then be pumped into the buses. In the U.S, there are a little over 30 HFC buses on the road most of which are operating in California[8].

5.1 Technology and System Description

Hydrogen is an attractive option for an alternative fuel as it does not contain any carbon and can be utilized in fuel cells, therefore avoiding all harmful emissions. As an energy carrier, it can be produced from many feedstocks enabling a zero-emission energy supply chain.

Fuel cells are electrochemical devices where a fuel, in this case hydrogen, is combined with oxygen from the air to produce electricity, heat, and as exhaust pure water, predominantly as vapor. Several different types of fuel cell technologies exist and the most popular option for vehicle applications is the proton exchange membrane also known as polymer electrolyte membrane (PEM)[9]. In almost all vehicle applications (aside from space craft), such as cars, buses, forklifts, and trains, PEM fuel cells are being employed. Their high efficiency, low operating temperature, start-up capabilities, and relatively long operating lifetime make them the preferred option. An illustration of the operation of a PEM fuel cell is provided in Figure 5-1.

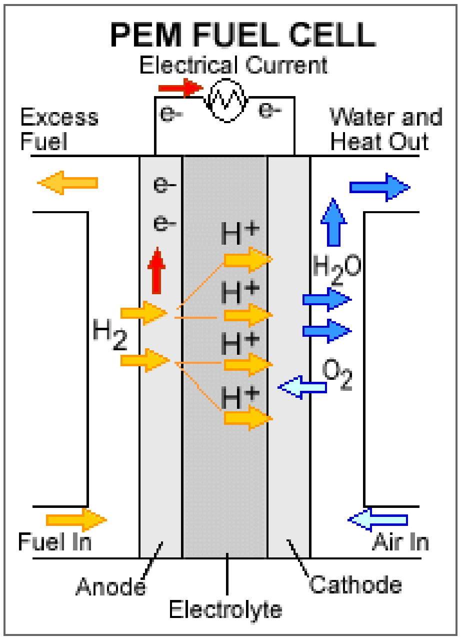
[6] Department of Energy. (2018). Fact of the Month.
https://www.energy.gov/eere/fuelcells/fact-month-november-2018-there-are-now-more-20000-hydrogen-fuel-cell-forklifts-use

[7] Department of Energy (2019). Fact of the Month.
https://www.energy.gov/eere/fuelcells/fact-month-march-2019-there-are-more-6500-fuel-cell-vehicles-road-us

[8] National Renewable Energy Laboratory. (2018. Fuel Cell Buses in U.S. Transit Fleets: Current Status 2018.

[9] Department of Energy. (2016). Comparison of Fuel Cell Technologies.
https://www.energy.gov/sites/prod/files/2016/06/f32/fcto_fuel_cells_comparison_chart_apr2016.pdf

Figure 5-1: Diagram of a PEM Fuel Cell[10]



The process can be explained in three stages[11]:

1. Hydrogen enters the cell at the anode side where the hydrogen molecule is split into atoms.
2. An anode catalyst separates the electrons from the atom creating hydrogen ions, which pass to the cathode, whereas the electrons have to move across an electric circuit to arrive at the cathode.
3. Oxygen is directed to the cathode, where it combines with the hydrogen ions and electrons to form water, which then leaves the cell.

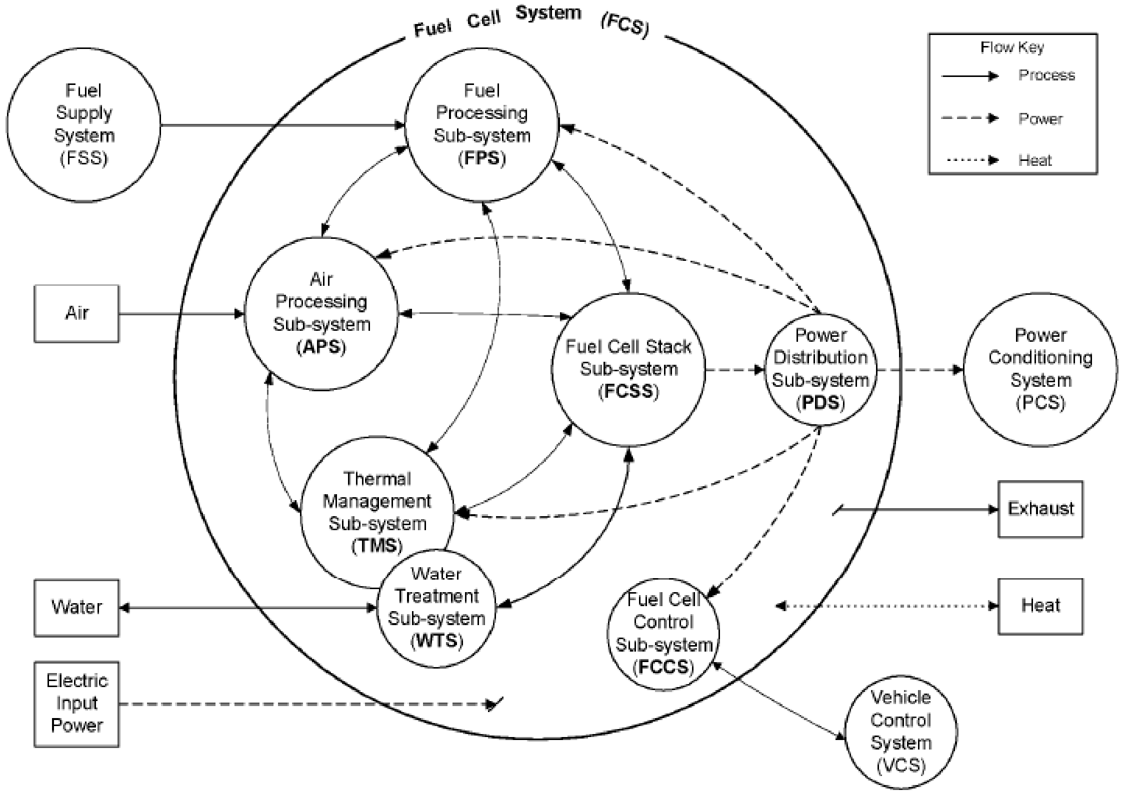
Individual cells do not produce sufficient power for most applications, including for vehicles, so several cells are combined into a stack. Hydrogen, air, and thermal management components, referred to as balance-of-plant, combined with one or several fuel cell stacks create a fuel cell system (FCS), and the generic components are illustrated in Figure 5-2. For heavy-duty vehicle applications, typical power output levels are 30kW, 50kW, 80kW, 100kW, and 200kW; if more power is required several FCS are combined. FCS efficiency curves as measured in on-road hydrogen fuel cell cars are provided in Figure 5-3. As can be seen the efficiency of FCS is higher than for a comparable diesel engine and some of the tested systems never drop below 50%. A further observation is that the highest efficiencies occur at partial load. The higher overall efficiency enables a reduction in energy consumption and allows less on-board energy storage for a comparable range to a gasoline or diesel vehicle. Lifetimes of heavy-duty FCS have exceeded 30,000 hours[12] and these are still in operation. Similar systems would be utilized in railway vehicle applications.

[10] Department of Energy. (2011). *Types of Fuel Cells*. Retrieved from http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html

[11] Schlapbach, L. (2009). Technology: Hydrogen-fuelled vehicles. *Nature, 460*(7257), 809-811.

[12] Technology Acceleration: Fuel Cell Bus Evaluations Leslie Eudy National Renewable Energy Laboratory May 1, 2019; Available at https://www.hydrogen.energy.gov/pdfs/review19/ta013_eudy_2019_o.pdf

Figure 5-2: General Schematic of a Fuel Cell System[13]



Hydrogen is typically stored at a pressure of 350bar or 700bar on-board of vehicles; the former often used in bus and truck applications while the latter is usually preferred in automotive applications. The higher pressure allows more hydrogen storage in a given volume, providing a longer range, and this is especially important in space constraint applications such as cars. A schematic of a compress gas tank is provided in Figure 5-4. Compressed gas tanks are the likely choice for a hydrogen-powered railway vehicle as they are commercially available and already used in other transportation applications, further, the Alstom Coradia iLINT train uses both compressed gas tanks and PEM fuel cells. Entities such as the American National Standards Institute, the U.S. Department of Transportation, and the Society of American Engineers have developed hydrogen codes and standards for vehicles. Current testing of compressed hydrogen tanks has been in the storage of hydrogen at high pressure in order to increase the driving range of hydrogen-fueled vehicles. In the next section, the results of single train performance simulation of a possible hydrogen and a hydrogen fuel cell hybrid, with batteries, are presented. The option was chosen as a comparison to diesel due to their zero-emission characteristics. The hybrid option enables utilization of regenerative braking, with potential for additional energy and subsequent emission reductions.

[13] SAE International. (2005). Testing Performance of the Fuel Processor Subsystem of an Automotive Fuel Cell System. https://www.sae.org/standards/content/j2616_200506/

Figure 5-3: Fuel Cell System Efficiency[14]

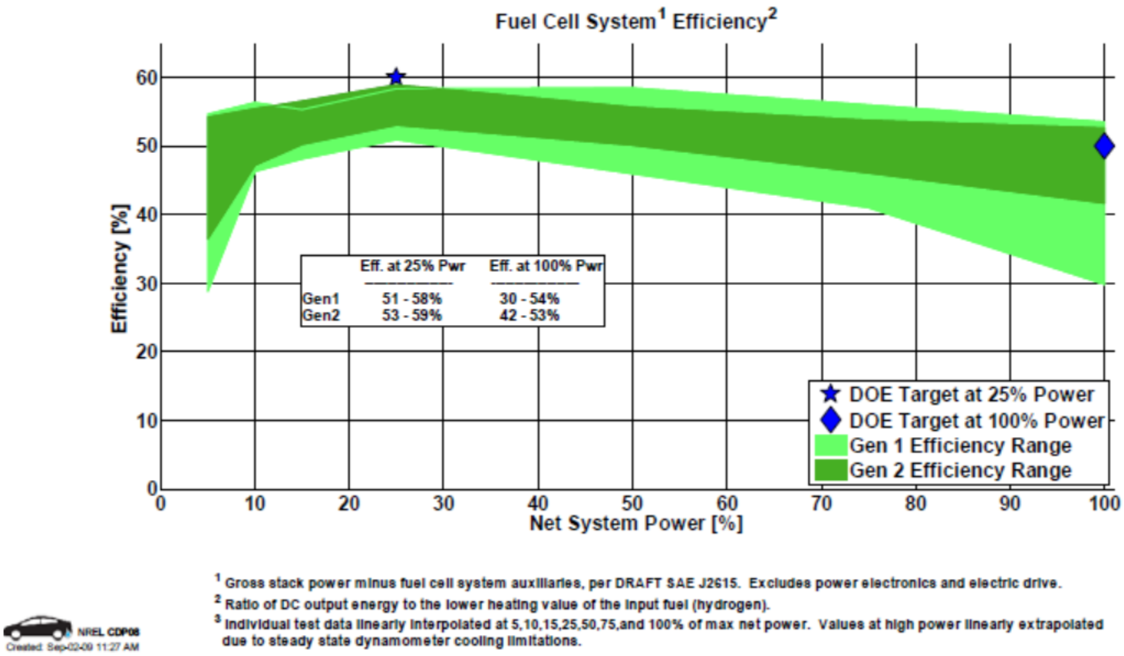
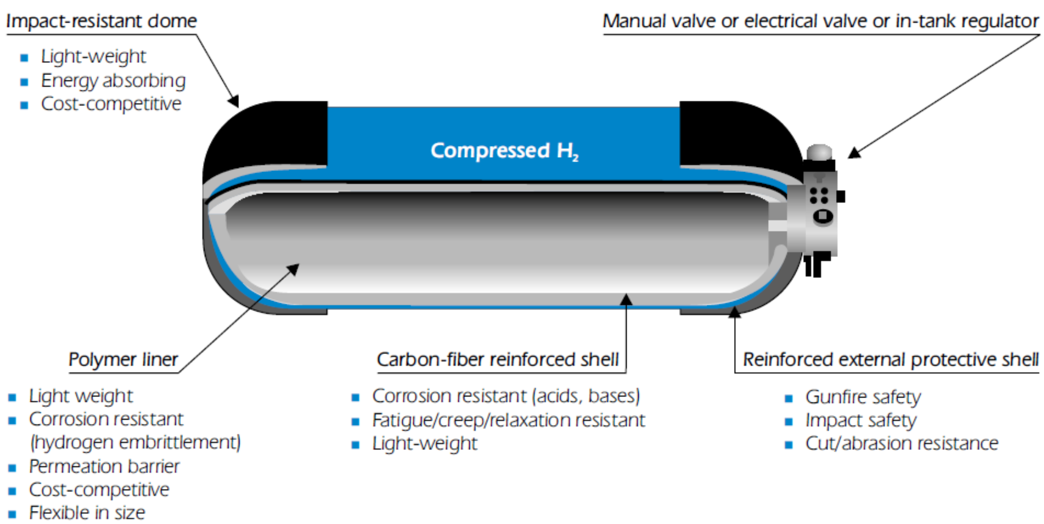


Figure 5-4: Schematic of a Compressed Hydrogen Tank Made from Composite Material[15]



[14] NREL (2012) National Fuel Cell Electric Vehicle Learning Demonstration Final Report. https://www.nrel.gov/docs/fy12osti/54860.pdf

Acronyms: Gen 1 = First Generation Fuel Cell Systems; Gen 2 = Second Generation Fuel Cell Systems; DOE = Department of Energy

[15] International Energy Agency [IEA]. (2006). *Hydrogen Production and Storage: R&D Priorities and Gaps*. Paris

5.2 Operational performance

Single train simulation has been performed to estimate the performance of the benchmark diesel-electric multiple unit (Diesel), diesel-electric multiple unit hybrid with an added on-board battery system (Diesel Hybrid), hydrogen fuel cell multiple unit (HFC), and a hydrogen fuel cell multiple unit hybrid with an on-board battery system (HFC Hybrid). A general description of the simulator is provided in Appendix G.

The route from SBTC to the University of Redlands is approximately 9 miles long and all modelled options can complete a roundtrip journey without refueling. General vehicle characteristics are provided in Table 5.1. A diesel powerplant consists of a diesel engine, generator, and power convertor while a fuel cell system powerplant consists of the fuel cell system and a power convertor. Estimated typical duty cycle powerplant efficiencies are presented in Table 5.1, the efficiencies of the diesel hybrid powertrain are higher than the conventional diesel and lower for the HFC due to the characteristics of the engine FCS. Diesel engines achieve higher efficiency closer to full load (typically around or above 50% load) while FCS achieve their highest efficiencies at partial load (typically 50% or lower load) as discussed in the previous section. Battery characteristics where based on an ABB lithium-titanate oxide (LTO) product and charging was assumed to be 86% efficient[16].

Table 5.1: 2-Car Multiple Unit Vehicle Characteristics

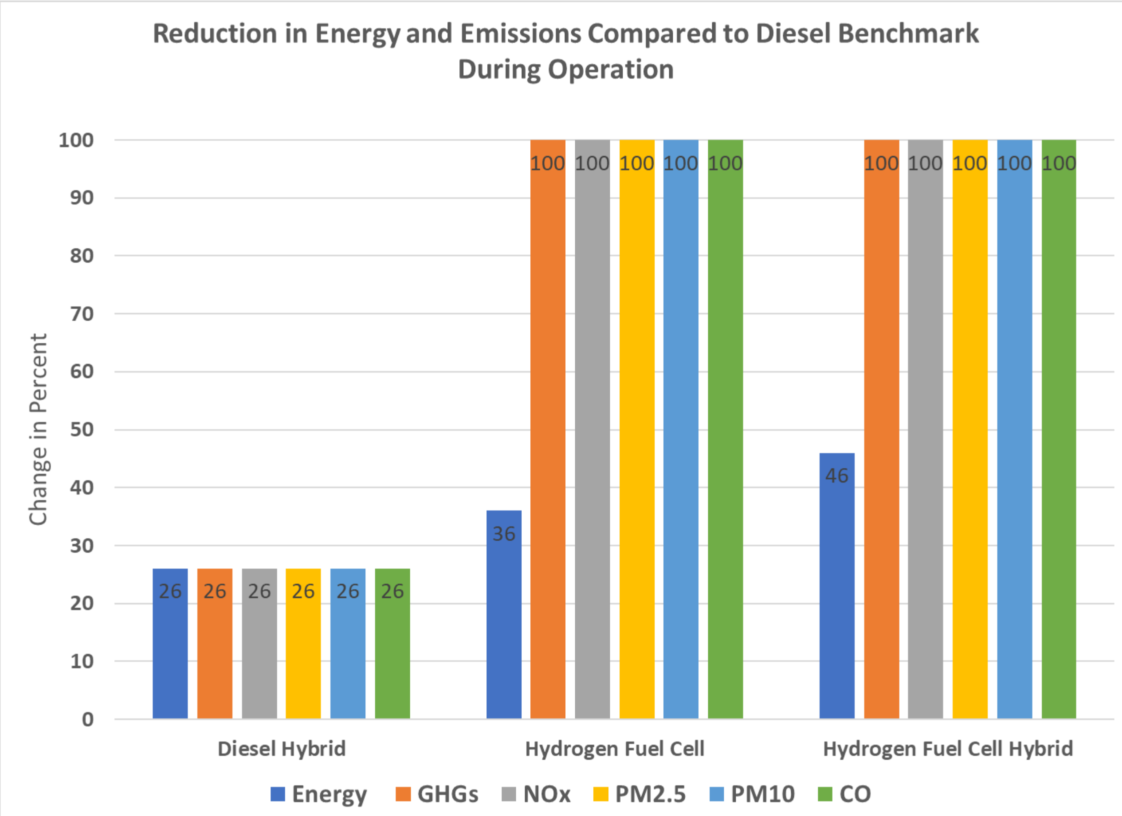
Powertrain Configuration	Diesel	Diesel Hybrid	HFC	HFC Hybrid
Mass (tonnes)	134	134	132.5	132
Max. Power at Wheels (kW)	700			
Powerplant Power (kW)	1016	520	1000	300
Average Duty Cycle Powerplant Efficiency (%)	30	33	51	49
Battery Power (kW)	-	828	-	828
Battery Capacity (kWh)	-	138	-	138
Battery Charging Efficiency (%)	-	86	-	86

All trains achieve a roundtrip journey time of approximately 40 minutes, including 1-minute dwell time at intermediate stations. This journey time would enable a 10-minute dwell at the terminals of SBTC and University of Redlands. An hourly service in off-peak times is therefore possible with a single train while a half-hourly service in peak periods can also be realized with the addition of a second train, therefore matching the benchmark DMU train.

Emissions that impact air quality are regulated by the Environmental Protection Agency and currently applicable standard is Tier 4 for railway vehicles. Figure 5-5 illustrates the energy, GHG, and regulated emission reductions of the three mentioned alternatives compared to the diesel benchmark during operation. Energy supply chain and associated emission impacts are considered in the infrastructure part below and further details are provided in Appendix H.

[16] ABB. (2016). Charged in a flash. AAB Review. https://library.e.abb.com/public/25aadd82a8f14d88b1813157db771d61/08-12%204m6069_EN_72dpi.pdf

Figure 5-5: Energy and Emission Reduction from Operation of 2-Car Train Options of the Redlands Route



All options show reduced energy and emissions compared to the diesel benchmark. The zero-emission operation of the two hydrogen trains can be identified and the progressive energy saving increases, from diesel hybrid via HFC to HFC hybrid, is also apparent from the illustration in Figure 5-5.

It is assumed that the diesel tank can be accommodated on the diesel hybrid vehicle, and that the batteries can be installed on the respective hybrid train as the overall powerplant provision is smaller (e.g., one instead of two diesel engines). The primary constraint for HFC and HFC hybrid vehicles is the space required for hydrogen storage tanks. For one roundtrip on the Arrow 9-mile route, the required on-board hydrogen storage for the different options is as follows: A 2-car train HFC requires 15kg and a 2-car HFC hybrid requires 13kg. More detailed modelling results including results for 4-car versions are presented in Appendix H.

Given a 16-hour service day with the premise of daily refueling, hydrogen storage requirements would be as follows: HFC 2-car requires 240kg of storage while a 2-car HFC hybrid requires 208kg. An additional hydrogen storage quantity to provide a safety buffer as well as range to reach the maintenance depot is suggested. Table 5.2 provides estimated data for the FCS, hydrogen tanks, and battery pack where applicable.

Table 5.2: Summary of Approximate Mass and Volume of FCS, Hydrogen Tanks, and Battery Pack for 16h Service Day Including Buffer on the Arrow Route for a 2-Car Train

Powertrain Type	HFC	HFC Hybrid
Fuel Cell System		
Power (kW)	1000	300
Mass (kg)	2,750	825
Volume (m^3)	5	1.5
Hydrogen Tanks		
Pressure (bar)	350	350
Hydrogen stored (kg)	270	220
Mass of tanks and hydrogen (kg)	3,900	3,150
Volume (m^3)	20	16.5
Battery System	-	
Power (kW)	-	828
Mass (kg)	-	4,000
Volume (m^3)	-	4
Total		
Mass (kg)	6,650	7,975
Volume (m^3)	25	22

A high-level preliminary analysis suggests that the required hydrogen storage and other powertrain components could be installed on a 2-car train. For example, the 2-car hydrogen-hybrid Alstom Coradia iLINT train stores 180kg of hydrogen at 350bar[17] which could probably be expanded with addition of tanks. Increased pressure to 700bar would reduce the volume requirement for the hydrogen tanks extending range. Further, if a power-module arrangement, such as in the Stadler FLIRT vehicles, is employed, additional volume for components is available compared to the Alstom arrangement, which does not utilize a power-module. Note however, that to date Stadler have not confirmed their expected hydrogen storage capacity for their 2-car or 4-car FLIRT vehicle designs.

Alternative service arrangements would reduce the on-board hydrogen requirements, for example, if a train is designed for a 12-hour shift or refueling of the train occurs for a second time during the operational day. To summarize, an HFC or HFC hybrid powertrain arrangement would be feasible for the Arrow route with the potential of daily refueling.

[17] EY. (2016). Ergebnisbericht Studie Wasserstoff-Infrastruktur für die Schiene. NOW GmbH Nationale Organisation Wasserstoff und Brennstoffzellentechnologie: Berlin. https://www.now-gmbh.de/content/1-aktuelles/1-presse/20160701-bmvi-studie-untersucht-wirtschaftliche-rechtliche-und-technische-voraussetzungen-fuer-den-einsatz-von-brennstoffzellentriebwagen-im-zugverkehr/h2-schiene_ergebnisbericht_online.pdf

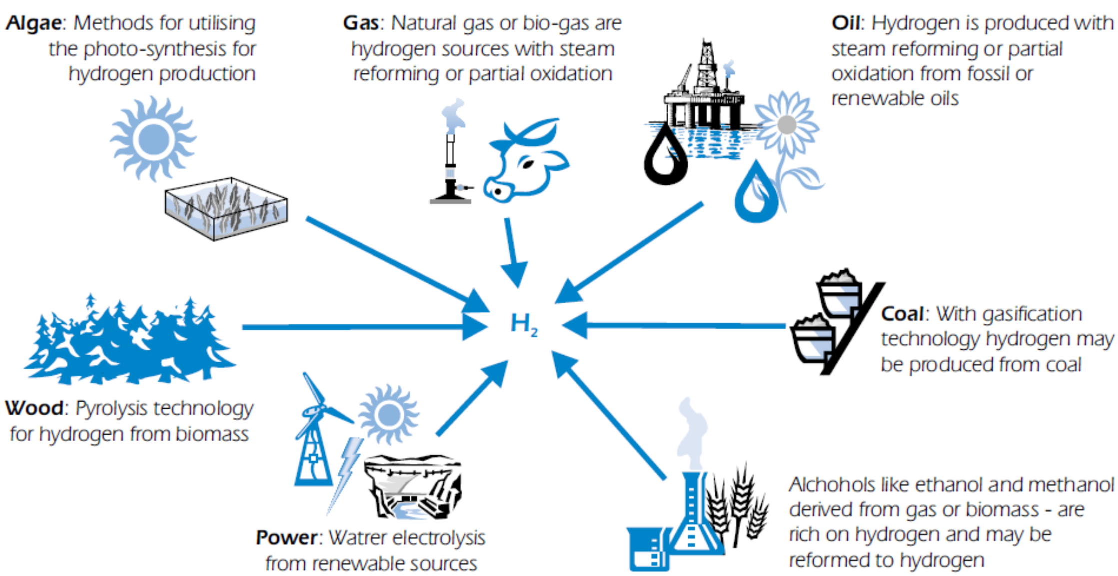
The LAUS to San Bernardino route and the LAUS to University of Redlands route can be realized with a hydrogen or hydrogen hybrid option. A 2-Car ZEMU it is expected to be capable of two round trips on these routes, roughly equivalent to 10 hours of service, however refueling would have to occur twice a day due to volume limitations on a 2-car train. It is possible that with additional cars, and therefore additional storage space, this fueling requirement may be reduced, however a detailed analysis of the vehicle design is required to determine this.

5.3 Infrastructure requirements

5.3.1 Production/transportation

There are several methods by which hydrogen can be produced and these are illustrated in Figure 5-6.

Figure 5-6: Selection of Hydrogen Feedstocks and Production Processes[18]



For the RPRP corridor application three hydrogen production methods have been investigated in more detail: on-site production via electrolysis, on-site production via steam methane reformation (SMR), and centralized production and delivery. These were selected based on an initial assessment of hydrogen availability in the region and emission reduction ambitions.

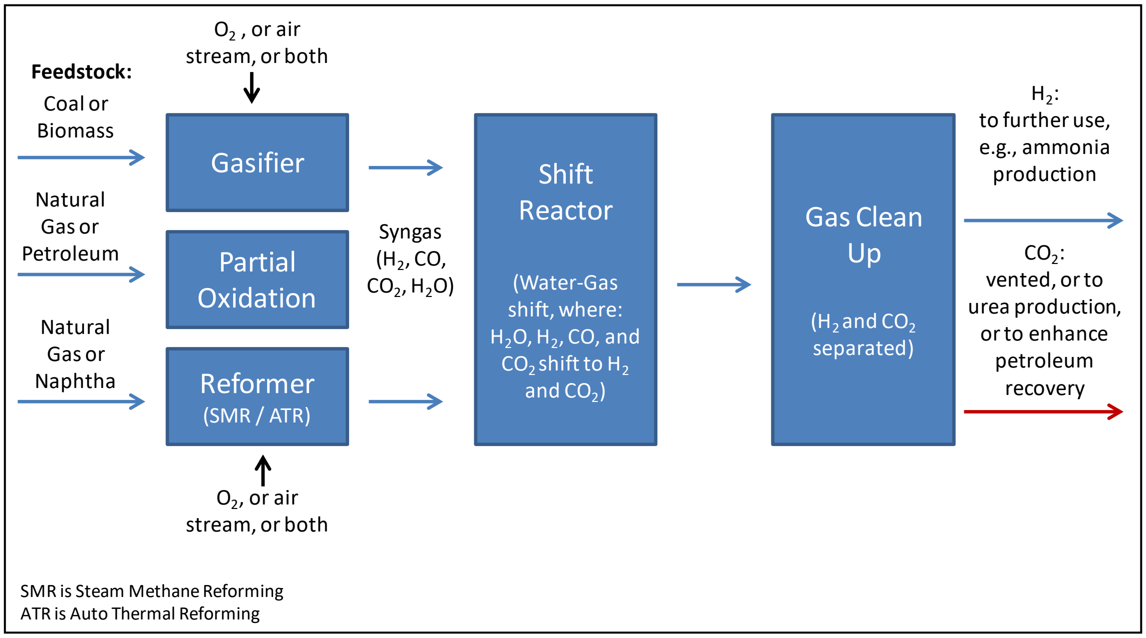
On-site hydrogen production would occur at a rail facility, e.g. a maintenance or refueling facility, which has the advantage of not relying on regular deliveries. On-site electrolysis refers to the production of hydrogen via electricity and water. Electrical charges in an electrolyzer separate H_2O (i.e. water) into hydrogen (H_2) and oxygen (O_2) gases; the reverse process of fuel cells. This can be an environmentally superior method of producing hydrogen, with the benefit depending on the specifics of the power grid. It offers the potential to be completely zero-emission, well-to-wheel, if renewable electricity sources are used. And it can assist in the management of the supply and demand of the electricity grid system (see the discussion on the duck curve in Section 3.3.3). It is, however, often a more expensive method to produce hydrogen than SMR, described below, due to the cost of electricity. A typical facility is illustrated in Figure 5-7.

[18] International Energy Agency. (2006). *Hydrogen Production and Storage: R&D Priorities and Gaps*. Paris.

Figure 5-7: Typical hydrogen production facility

Hydrogen can be produced from fossil fuels and the generalized process is illustrated Figure 5-8; production from the feedstock of natural gas is the most popular option currently. SMR is a process in which a gas, typically natural gas (i.e. mostly methane) is converted to hydrogen. Currently, SMR accounts for approximately 95% of hydrogen production in the US. It is the cheaper of the two main on-site production options at this point in time due to relatively low cost of natural gas. However, when natural gas is used, this process might not be as environmentally beneficial as electrolysis of water, depending on the electricity mix, as GHG emissions are a result of the production process. There is the possibility of utilizing renewable biogas or landfill gas, which can lead to a zero-emission option.

Figure 5-8: Generalized Hydrogen Production Process from Fossil Fuels



The third investigated option is delivery of hydrogen, which could address potential space or capital cost concerns. Hydrogen is produced at a central location (typically via SMR) and delivered to the refueling site. Often, the hydrogen is liquified for transportation in tanker trucks to minimize delivery frequency and cost. However, this leads to higher emissions and environmental impacts during the well-to-pump phase compared to on-site production due to emissions occurring during transportation and the significant energy requirement for hydrogen liquification. If relatively small quantities of hydrogen are required or a higher delivery frequency is possible, transportation as a gas with a tanker truck is an option.

5.3.2 Fueling

The fueling infrastructure for hydrogen is more complex than for diesel. While it is more similar to that required for CNG/LNG, there are a few significant differences. For example, there are significantly higher pressures involved, with hydrogen, due to the differing energy densities of the two fuels. As a result, more powerful compressors, stronger tanks, and even dispensers are required. This also typically implies different materials. Leak detection (e.g. from station storage tanks) of hydrogen is also a bit more technologically complex than it is with natural gas[19].

While the rate at which hydrogen enters the tank is significantly slower than diesel, similar refueling times can be achieved as less energy is stored on-board of a hydrogen train compared to a diesel variant. Estimated refueling times for the Arrow hydrogen-hybrid vehicle are 15 to 30 minutes. The Alstom Coradia iLINT hydrogen-hybrid has a refueling time of 15 minutes for 180kg, for example, and that train is relatively similar to the vehicle required on the Arrow route.

With two vehicles, it would probably make sense to refuel one vehicle in the morning and one at night. This would help balance the power demand and on-site hydrogen storage, impacting cost.

Re-fueling of the vehicle occurs in the gaseous state, both in the dispensing of the fuel as well as in its storage on the vehicle. Most likely the onboard storage would be at 350 bar pressure. 700 bar could also be accommodated, and would reduce the space required; however, it would

[19] Ogden et al., "Natural gas as a bridge to hydrogen transportation fuel: Insights from the Literature," Energy Policy, 2018

also result in greater cost. This is because higher pressure of the hydrogen requires further equipment to maintain the pressure and the storage tanks need to be of higher strength to accommodate the pressure.

5.3.3 Storage

To operate a passenger rail service with an HFC hybrid option, supporting infrastructure and services, including fuel storage and dispensing facilities will be required, even if hydrogen is not produced on-site, but delivered. This infrastructure is more complex than is the case with diesel, since hydrogen needs to be maintained at an appropriate pressure for storage and dispensing. The overall facilities sizes, including storage, have been estimated below:

- **On-site hydrogen via electrolysis** – this refueling facility would require ~1,300ft^2 (not including space for the vehicle), with a roof height of at least 20 feet (to enable stackable hydrogen storage). Such a facility would produce enough hydrogen to meet the Arrow system's daily needs.
- **On-site SMR** – the station size required is similar, at ~1,400ft^2 (again, not including space for the vehicle), with a height of approximately 13 feet.
- **Hydrogen delivery option** – assuming liquid storage, the area required would be around 1,600-1,700ft^2.

5.3.4 Utilities

For on-site production of hydrogen, regardless of the method, an electricity supply would be necessary, as would access to significant amounts of water. Production via steam methane reformation would, however, require five times the amount of water as electrolysis (~100,000 gallons per month for a non-hybrid service), and would also require a connection to the natural gas supply line.

Hydrogen has characteristics which make it a good choice for storing energy. This is due to its very significant energy density (i.e. energy within a given mass), but also due to its stability, and it is this characteristic which leads to its ability to provide storage for a longer time (on the scale of months[20]) than other currently existing storage alternatives[21].

Generally speaking, taking advantage of this potential role for hydrogen could serve as a way to address the substantial problem of mismatched supply and demand on the grid that results from the operating characteristics of renewable energy powerplants, solar, in particular, as discussed in Section 3.3.3.

5.3.5 Maintenance and Storage Facility Modifications

Based on the infrastructure assessment completed in Section 5.3, it is assumed that no additional infrastructure is required within the RPRP corridor to implement a hydrogen hybrid ZEMU. Any additions and modifications which are required, would be necessary for hydrogen storage and fueling and could be incorporated into the footprint of the current RPRP AMF. Should a hydrogen production facility also be constructed for opening day of the ZEMU project (or in the future) it could also be placed at the AMF.

[20] Hydrogen Energy Storage, The Linde Group. https://www.the-linde-group.com/en/clean_technology/clean_technology_portfolio/energy_storage/hydrogen_energy_storage/index.html

[21] Hydrogen Energy Storage: A New Solution to the Renewable Energy Intermittency Problem, Renewable Energy World, July 2014. https://www.renewableenergyworld.com/articles/2014/07/hydrogen-energy-storage-a-new-solution-to-the-renewable-energy-intermittency-problem.html

In addition to the new infrastructure listed above, the maintenance facility building itself would also require upgrades in order to safely maintain the hydrogen trains. This would include hydrogen leak detectors and ventilation equipment. Considerations regarding ventilation is discussed in further detail in the safety section of the hydrogen assessment. It was assumed that the necessary modifications and safety requirements could be retrofit into the existing building, and that a separate hydrogen maintenance facility would not be required.

5.4 Right of Way Impact Assessment

For the purposes of a right of way assessment, a conservatively sized hydrogen production facility was integrated into the existing AMF footprint. It was assumed that roughly 1,420 square feet would be required to accommodate all infrastructure, including the necessary storage and fueling equipment as described above. It was determined that no additional right of way or land acquisition would need to be acquired to accommodate this sized facility. The location of the production facility could be placed to the north-east of the maintenance building. It is assumed that any existing infrastructure in this location (indicated as a high hazard storage rooms which are modular building that are used to store oil, coolant, grease etc.) could be relocated, therefore creating sufficient space to accommodate for all necessary hydrogen infrastructure; and also allowing for refueling to occur at the storage track location to the north.

5.5 Market Availability

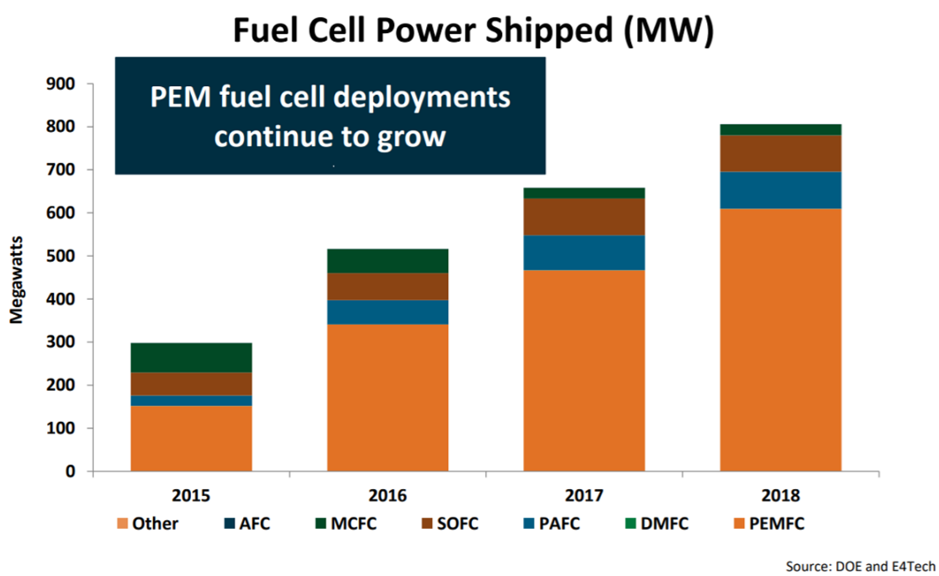
The necessary equipment for HFC trains and supporting infrastructure is available. However, the majority of commercially available equipment has been designed for non-rail applications, such as buses, but the equipment can be adapted for rail use. Ballard, Hydrogenics, and Plug Power, three possible suppliers of heavy-duty FCS are suppliers that would offer systems for trains. Air Liquide, Linde, and Trillium provide on-site SMR hydrogen production (and storage), while Trillium also provides on-site electrolysis production of hydrogen (along with storage). Millennium Reign, a firm in Ohio, also produces on-site electrolysis (and storage) systems, and its equipment has been utilized by TIG/m to supply its hydrogen-powered streetcars. Plug Power could provide refueling facilities where hydrogen is either delivered as a liquid or produced on-site through electrolysis. Air Products, Air Liquide, and Linde also provide centralized production of hydrogen, along with liquefaction (e.g. for distributed delivery of H2 as a liquid). In summary, refueling stations would be customized for the rail application but are relatively easily available. There are also several suppliers of high-pressure hydrogen tanks suitable for on-board storage, an example is Hexagon, Worthington Industries, and Fuel Solutions. Market availability of suitable batteries was discussed in the battery-train section. Currently, the most limiting part of the supply chain is the integration of all the necessary hydrogen-related components to produce a train. Only Alstom offers an off-the-shelf regional train that would be suitable for the Arrow application. However, several other manufacturers offer HFC railway vehicles, for example TIG/m and CRRC offer streetcars. In addition, regional HFC trains, similar to the vehicles required for the RPRP corridor are currently under development, most notably by Siemens and JREast/Toyota. Stadler is also currently developing five HFC trains for the Zillertal Railway in Austria, which is expected to use hydrogen that is produced locally with electrolyzers. An overview of other developments is provided in Appendix J.

5.5.1 Provider dependency

The hydrogen market is steadily growing. There are a few different locomotive manufacturers which have either already manufactured or are committed to manufacturing hydrogen railcars. Alstom’s hydrogen multiple unit cars, the first of their kind---i.e. in a regional passenger rail application---are operating in Germany, and that firm has also designed a vehicle that will operate on hydrogen in the United Kingdom[22]. Meanwhile, Stadler has committed to making rail equipment that would run along the "Zillertalbahn" route in Austria[23], with pilot operations to begin in 2020, while Siemens is working with Ballard to adapt its Mireo multiple unit vehicle to a hydrogen version[24]. Toyota and JR East, in Japan, have shown interest in this technology[25], as has South Korea[26]. *Tig/M,* a firm based in Southern California, has operated hydrogen trams for several years now[27], and CRRC has some hydrogen trams operating in China[28].

Hexagon Lincoln and Worthington Industries are two major manufacturers of hydrogen tanks, and it is quite likely that there will soon be additional competitors to these, given the growth in fuel cell deployment seen in recent years (as seen in Figure 5-9)[29].

Figure 5-9: Growth in Full Cell Deployment



Source: From Satyapal, Sunita, U.S. DOE, "Hydrogen and Fuel Cell Program Overview," 2019 Annual Merit Review, April 29, 2019

The remaining accessories can be sourced from a variety of manufacturers, as such equipment is common to most hydrogen fuel cell operations and even some other power applications. Hydrogen as a gas and/or the infrastructure necessary to produce it onsite is available from several suppliers (e.g. Air Liquide, Air Products, Trillium, and Linde, as noted earlier; also Millennium Reign Energy, for onsite electrolysis equipment). Hydrogen is already used in large

[22] Alstom and Eversholt Rail unveil a new hydrogen train design for the UK, Alstom, January 2019 https://www.alstom.com/press-releases-news/2019/1/alstom-and-eversholt-rail-unveil-new-hydrogen-train-design-uk

[23] Zillertalbahn selects hydrogen train supplier, Railway Gazette, May 2018 https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/zillertalbahn-selects-hydrogen-train-supplier.html

[24] Siemens wins BMVI funding to develop fuel cell train with Ballard, Fuel Cells Bulletin, March 2018 https://www.sciencedirect.com/science/article/pii/S1464285918300762

[25] Toyota, JR East to partner on hydrogen-based mobility; automotive and rail, Green Car Congress, September 2018 https://www.greencarcongress.com/2018/09/toyota-jr-east-to-partner-on-hydrogen-based-mobility-automotive-and-rail.html

[26] Hydrogen Fuel Cell Powered Train Project, Korea Railroad Research Institute, H2@Rail 2019 Conference https://www.energy.gov/sites/prod/files/2019/04/f62/fcto-h2-at-rail-workshop-2019-chang_1.pdf

[27] Tig/M https://www.tig-m.com/

[28] CRRC Tangshan trials new hydrogen-fueled tram, International Railway Journal, October 2017 https://www.railjournal.com/passenger/light-rail/crrc-tangshan-trials-new-hydrogen-fuelled-tram/

amounts by the oil refining sector and the agricultural sector (specifically in making ammonia for fertilizer), so the market for supply and production of the gas is rather mature, at this point.

5.5.2 Technology Obsolescence

Hydrogen is a fundamental building block of the universe, and the source of the sun's energy. It is also the most abundant element in the universe and plentiful on earth. As such, there will be no shortage of hydrogen, which sets it apart from the fossil fuels and rare earth-based materials, the latter often serving as key components in battery production. While using hydrogen as a fuel has historically proven to present some challenges, there has been significant past research and development (R&D) that has enabled us to get to a point where it is now viable in road, rail, and even stationary applications. More of the remaining challenges are likely to be overcome as the U.S. government and commercial entities invest further into R&D, and this will only serve to increase its attractiveness as an energy carrier. In recent conversations with private utility companies like SoCalGas (Sempra Energy) are look seriously at harnessing hydrogen technologies to capture surplus renewable electricity into hydrogen and then later used during peak periods. This method would thus improve the supply chain for renewable hydrogen.

While fossil fuels are also, by their very nature, solid fuel sources, their combustion is inherently polluting, which has negative implications for the earth's climate balance and for human health.

As noted above, California recently implemented the "Innovative Clean Transit" rule. Regulations such as these, in addition to helping to spur continued innovation within industry, will also serve to make fossil fuel-based technologies less and less advantageous as compared to alternatives such as hydrogen, which have not traditionally enjoyed the kinds of structural support and economic incentives that fossil fuels have received.

Natural gas has some benefit over diesel fuel in terms of its environmental effects; however, the benefits are likely not enough to compensate for the efforts that would be undertaken to change the vehicle and related refueling infrastructure. Moreover, with significant R&D focus on hydrogen and other technologies, as noted above, this technology, at least in a rail context, is also likely bound to become obsolete in the coming years.

Of course, any technology evolves over time, and the pace of technology change in this century is especially rapid. Areas such as fuel cell design and method of and materials used for hydrogen storage are likely to change, changes that will enhance hydrogen's viability and overcome the previously alluded to challenges. Examples of potential changes include a transition away from platinum-based catalysts, which are typically rather expensive, to materials that are cheaper. Similarly, storage may eventually evolve towards either a liquid organic-type carrier or otherwise a solid carrier, such as a metal hydride or metal organic framework, technologies which could potentially reduce the footprint for a given amount of hydrogen energy storage. Incorporating such future developments and/or others into vehicles whose components are reflective of the present technology should not be difficult, but rather require simply a period of vehicle refurbishment.

5.6 Safety

Hydrogen has a different chemical make-up than diesel fuel, which is a complex molecule made up of a variety of hydrocarbons. In many applications, including in railway vehicles, hydrogen is typically stored as a gas instead of a liquid. As such, hydrogen fuel's properties and resulting safety risks are rather different compared to diesel.

Hydrogen requires a much higher temperature before autoignition occurs, as compared to diesel fuel[30]/[31]. On the other hand, hydrogen requires a lower energy of ignition than does diesel fuel.

Due to the public's relatively limited experience with hydrogen as a fuel, along with an oversimplified understanding of its role in the Hindenburg disaster in the popular imagination, hydrogen fuel's public acceptance has been challenging, with concerns that the fuel is more dangerous than the widely used fuel sources. But different risks are not necessarily greater risks. In many cases, new methods of infrastructure protection will need to be employed, but these are not likely to be particularly costly nor are they technologically new; for example, pressure sensors and leak detectors, along with related warning systems, will be necessary since hydrogen is an odorless and colorless gas.

Due to it buoyancy, hydrogen tend to burn straight upwards if the leak has little pressure, otherwise, in the direction of the occurring leak. This characteristic can be used in risk mitigation, for example, through installation of tanks in designated areas that are well-ventilated in the upward direction and flame detectors.

In both production and storage, proper ventilation will support in mitigating hydrogen safety risks. This is particularly true due to the fact that hydrogen can permeate some of the materials that it may be stored in, for example, high-strength steel is subject to embrittlement. However, many other forms of steel and aluminum are unlikely to be affected given typical operating conditions, therefore appropriate material selection is essential. Embrittlement can lead to hydrogen escaping its container, and this means mixing with air. Limiting the rates and amounts of escape is a priority so as to keep the gaseous mixture nearby below the flammability limits (i.e. the air-hydrogen mixture at which a flame can result)[32]. Once a significant release occurs, avoiding sources of ignition will also become key, as any explosion that could result is more dangerous than the more straightforward release of a hydrogen flame. (More information on the optical and thermal sensors involved in flame detection can be found on this website.)

As with any fuel, periodic inspection and leak testing, will also be necessary. Leak testing is a bit more complicated for a gaseous fuel than a liquid fuel. In addition, ensuring that venting is both large enough to relieve pressure yet small enough to limit size of any resulting hydrogen "cloud" is also crucial in design risk mitigation.

Dispensing of the fuel involves most of the same risks as the other aspects of hydrogen fuel handing, while also requiring regular inspection of the component parts, emergency off switches, and leak checks immediately prior to refueling. Leak check detection is often automated as part of the standard installation of hydrogen sensors at refueling equipment.

Currently, hydrogen is safely used as a transportation fuel in several different applications, for example, cars and forklifts. In the forklift case, operation is usually in enclosed facilities and the associated risk are managed. Further improving the safe use of hydrogen in partially enclosed and indoor facilities is subject of ongoing research. Initial findings by a group at the Sandia National Lab suggest that aiming some air flow at the vehicle while under repair (though this could also apply to refueling), even if the facility is fully enclosed, would greatly reduce the risk of flame occurrence. That said, a fully enclosed area is likely not ideal for hydrogen refueling and maintenance work, while a partially enclosed area would be adequate. Such a partially enclosed solution has, in fact, been implemented in the case of a facility that is located in

[30] Chevrolet Equinox Fuel Cell Emergency Response Guide https://h2tools.org/sites/default/files/EqFuelCellRResponseGuide.pdf

[31] Ignition Temperature, Science Direct https://www.sciencedirect.com/topics/physics-and-astronomy/ignition-temperature

[32] "Regional Express Rail Program Hydrail Feasibility Study Report," CH2M Hill, February, 2018

Orange County, where a new hydrogen fuel cell bus fleet has recently begun operations[33]. If possible, a similar arrangement of a partially enclosed maintenance facility for the RPRP corridor is suggested, while locating hydrogen refueling and dispensing equipment outside is the suggested approach.

During the refueling station implementation process, it is suggested to incorporate national standards developed by the National Fire Protection Association (NFPA). The NFPA 2 provides information relating to hydrogen installation and handling. Information on this section of code can be accessed on the NFPA website via this link.

In total, there are now 40 public hydrogen refueling stations located in the U.S., with 39 of them located in California (and the remaining one located in Hawaii)[34] [35]. With all of these stations in place, the industry and researchers will continue to learn more about hydrogen safety. In the meantime, in order to ensure that helpful information on hydrogen safety is readily available, the Department of Energy has set up this website. The website includes a link to a hydrogen incident database, which can also be found at this link. The site also provides information regarding safe hydrogen handling and equipment implementation.

For a more technical appraisal of the risks associated with hydrogen for a given production and refueling site, the Department of Energy has also set up a risk assessment model. More information on the model, including instructions on how to access it, can be found here. Information from this tool can be incorporated in a detailed risk and mitigation design analysis. If hydrogen would be implemented as a solution, more detailed work would be required.

5.7 Cost

In this section, the estimated capital cost for a 2-car HFC hybrid vehicle and three hydrogen provision options are presented. Estimate operational cost, including expenses for fuel and major component overhaul for the vehicle powertrains and hydrogen provision infrastructure are also shown over a 30-year anticipated vehicle life.

5.7.1 Capital Costs

The up-front capital costs associated with implementing a 2-car HFC hybrid vehicle for a ZEMU service are summarized in Table 5.3 to Table 5.5. Costs are broken down by major components and estimated values are presented. Further detail on the items are provided in Appendix I.

Table 5.3: Capital Cost for Hydrogen Fuel Cell Hybrid ZEMU with On-Site Electrolysis

Item	Cost
HFC hybrid ZEMU vehicle, including: - Modified base vehicle designed to accept and integrate a HFC hybrid powertrain - PEM FCS power assumed 400 kW - Hydrogen storage assumed 220 kg - LTO battery system assumed 140 kWh	$11,200,000
ZEMU vehicle non-recurring costs, including: - Project and engineering management / overhead - Engineering and design - Testing and commissioning	$10,000,000

[33] New Flyer's Xcelsior CHARGE H2 fuel cell bus achieves 350 miles of zero-emission range in a test demonstration for OCTA, Green Car Congress, April 2019 https://www.greencarcongress.com/2019/04/20190426-nfi.html

[34] Alternative Fuels Data Center, Department of Energy. https://afdc.energy.gov/fuels/hydrogen_locations.html#/find/nearest?fuel=HY&country=US

[35] California Fuel Cell Partnership https://cafcp.org/sites/default/files/h2_station_list.pdf

- FRA process approval	
HFC hybrid ZEMU specific capital spares	$1,000,000
Hydrogen production, storage and dispensing infrastructure, including: - Electrolyzer - Fuel storage & dispenser - Utility connections - AMF Retrofit	$3,300,000
General costs, including: - Environment and permitting - Project and construction management - Public outreach campaign	$3,300,000
Unallocated contingencies (20% of total)	$5,800,000
TOTAL – HFC hybrid and electrolysis option	**$34,600,000**

Table 5.4: Capital Cost for Hydrogen Fuel Cell Hybrid ZEMU with On-Site Steam Methane Reforming

Item	Cost
HFC hybrid ZEMU vehicle, including: - Modified base vehicle designed to accept and integrate a HFC hybrid powertrain - PEM FCS power assumed 400 kW - Hydrogen storage assumed 220 kg - LTO battery system assumed 140 kWh	$11,200,000
ZEMU vehicle non-recurring costs, including: - Project and engineering management / overhead - Engineering and design - Testing and commissioning - FRA process approval	$10,000,000
HFC hybrid ZEMU specific capital spares	$1,000,000
Hydrogen production, storage and dispensing infrastructure, including: - Steam Methane Reformer - Fuel storage & dispenser - Utility connections - AMF Retrofit	$2,800,000
General costs, including: - Environment and permitting - Project and construction management - Public outreach campaign	$3,200,000
Unallocated contingencies (20% of total)	$5,600,000
TOTAL – HFC hybrid and steam methane reforming option	**$33,800,000**

Table 5.5: Capital Cost for Hydrogen Fuel Cell Hybrid ZEMU with Hydrogen Delivery

Item	Cost
HFC hybrid ZEMU vehicle, including: - Modified base vehicle designed to accept and integrate a HFC hybrid powertrain - PEM FCS power assumed 400 kW - Hydrogen storage assumed 220 kg - LTO battery system assumed 140 kWh	$11,200,000
ZEMU vehicle non-recurring costs, including: - Project and engineering management / overhead	$10,000,000

- Engineering and design - Testing and commissioning - FRA process approval	
HFC hybrid ZEMU specific capital spares	$1,000,000
Hydrogen storage and dispensing infrastructure, including: - Fuel storage & dispenser - Utility connections - AMF Retrofit	$2,300,000
General costs, including: - Environment and permitting - Project and construction management - Public outreach campaign	$3,000,000
Unallocated contingencies (20% of total)	$5,500,000
TOTAL – HFC hybrid and hydrogen delivery option	**$33,000,000**

Cost for a 2-car HFC hybrid vehicle is $22.2 million and this cost does not change regardless of the hydrogen provision option. Overall, the highest capital cost is occurred with the on-site electrolysis option followed by on-site steam methane reforming while the cheapest is hydrogen delivery as a liquid.

5.7.2 Operational and Maintenance Cost

The on-going operations and maintenances costs associated with implementing a 2-car HFC hybrid ZEMU service are summarized in Table 5.6 to Table 5.8. These calculations assume that two 2-car trains are necessary for the proposed Arrow service. Operation costs are broken down by major components and estimated values are shown. As a point of comparison, the total annual estimated equivalent DMU vehicle for fuel, service and engine overhaul is $750,000 per year. Further details on these items are provided in Appendix I.

Table 5.6: HFC Hybrid ZEMU Operating and Maintenance Costs for On-Site Electrolysis

Item	Quantity	Frequency	Unit Price	Equivalent Annual Cost
Hydrogen fuel costs, including: - Electricity and water supply (~$4.30 per kg) - Compression costs - Dispensing costs	1	Annual	$520,000	$520,000
FCS and battery replacement / overhaul – ZEMU	2 ZEMUs	7.5 years	$980,000	$196,000
Hydrogen tank replacement – ZEMU	2 ZEMUs	15 years	$180,000	$12,000
Infrastructure maintenance, including: - Production equipment - Storage equipment - AMF equipment	1	Annual	$60,000	$60,000
Hydrogen production and storage facility overhaul	1	15 years	$2,000,000	$68,000
TOTAL ANNUAL ex contingency – Electrolysis Option				**$856,000**

Table 5.7: HFC Hybrid ZEMU Operating and Maintenance Cost for On-Site Steam Methane Reforming

Item	Quantity	Frequency	Unit Price	Equivalent Annual Cost
Hydrogen fuel costs, including: - Natural Gas, electricity and water supply (~$1.77 per kg) - Compression costs - Dispensing costs	1	Annual	$220,000	$220,000
FCS and battery replacement / overhaul – ZEMU	2 ZEMUs	7.5 years	$980,000	$196,000
Hydrogen tank replacement – ZEMU	2 ZEMUs	15 years	$180,000	$12,000
Infrastructure maintenance, including: - Production equipment - Storage equipment - AMF equipment	1	Annual	$60,000	$60,000
Hydrogen production and storage facility overhaul	1	20 years	$1,500,000	$52,000
TOTAL ANNUAL ex contingency – Steam Methane Reforming Option				**$540,000**

Table 5.8: HFC Hybrid ZEMU Operating and Maintenance Costs for Hydrogen Delivery

Item	Quantity	Frequency	Unit Price	Equivalent Annual Cost
Hydrogen fuel costs, including: - Hydrogen supply (~$7.50 per kg) - On-site liquid and compressed storage - Compression costs - Dispensing costs	1	Annual	$890,000	$890,000
FCS and battery replacement / overhaul – ZEMU	2 ZEMUs	7.5 years	$980,000	$196,000
Hydrogen tank replacement – ZEMU	2 ZEMUs	15 years	$180,000	$12,000
Infrastructure maintenance, including: - Storage equipment - AMF equipment	1	Annual	$29,000	$29,000
Hydrogen storage facility overhaul	1	15 years	$810,000	$27,000
TOTAL ANNUAL ex contingency – Hydrogen Delivery Option				**$1,154,000**

The lowest cost is realized with on-site SMR, which is primarily due to the relatively low cost of natural gas. Electrolysis offers the cost in the middle, similar to the diesel option, while hydrogen delivery is the most expensive option, due to the high cost of hydrogen. Cost with electrolysis can potentially be reduced if an agreement with the electricity supplier can be reached though assistance with the management of the duck curve challenge.

SBCTA is eligible to receive LCFS credits by either owning the finished hydrogen fuel at the time the finished fuel is created or acquiring ownership of the finished hydrogen fuel if a contract is agreed upon between transferor and recipient.[36] The credits will be generated for each metric

[36] California Air Resources Board. (2016). LCFS Hydrogen Programs Regulatory Guidance.

ton of CO2 emissions reduced through the use of hydrogen, which can be sold for monetary value through CARB's credit Report and Credit Bank & Transfer System.

5.8 Feasibility of application for RPRP Corridor

A hydrogen solution is feasible for the corridor. A 2-car hydrogen hybrid option with sufficient hydrogen storage to allow daily refueling (~220kg on-board hydrogen storage) is recommended to most closely match the operation of the conventional diesel trains.

From a hydrogen supply perspective, electrolysis offers the highest emission reduction potential through utilization of renewable electricity generation. However, currently this is a costlier alternative but has the potential for significantly reduced hydrogen cost if an agreement with the local utility can be arranged, through assistance of managing the duck curve effect. In addition, operational cost for the HFC hybrid option with electrolysis are similar to the conventional diesel. On-site SMR offers attractive regulated emission, GHG, and energy reductions while also being a commercially attractive option due to the low natural gas prices, and in the HFC hybrid option reduced operating cost significantly compared to the conventional diesel. In the future, emission could be further reduced through utilization of renewable gas. Hydrogen delivery as a liquid is an option with slightly reduced capital expenditure compared to SMR but significantly higher operating cost, which are due to the higher cost of hydrogen. This option offers the flexibility of hydrogen provider choice and 100% renewable hydrogen is likely to be available in the 2020 to 2025 timeframe at similar cost to centrally produced SMR hydrogen.

All options require construction of facilities, most likely located close to the maintenance facility. The choice of hydrogen production will primarily depend on the objectives of SBCTA and associated ability to cover capital and operating expenses. Electrolysis is the option for the highest emission reduction, while on-site SMR offers attractive operating costs and significant emission reductions, delivery would be the most flexible and least supplier dependent choice but has the highest hydrogen cost. To initially implement the technology, hydrogen delivery to a mobile refueling station would be an attractive option, due to the avoidance of significant infrastructure capital expenditure but this will be offset by a higher hydrogen cost, estimated at ~$10 to ~$20 per kilogram.

5.9 System Expansion to LA Union Station

One of the primary advantages of a hydrogen solution is the comparatively easy expansion of the service onto other routes as no ROW infrastructure for energy supply is required, as long as the train operates within the on-board energy storage range, which is substantial. Extension of the service to LA Union Station is possible with hydrogen options. The recommended 2-car hydrogen-hybrid train would be able to complete two roundtrips on the Redlands – LA Union Station route, approximately a 10-hour shift before requiring refueling. More detailed simulation results including for a 4-car train are presented in Appendix H. Expansion of service would require additional hydrogen delivery and production and all investigated options can technically be scaled to increase provision. The easiest option is with hydrogen delivery as the only required adjustment would be an increase in the frequency of hydrogen delivery. The on-site production methods would require additional capital investment to increase production rates.

6 Environmental Impacts

It is expected that the ZEMU and its supporting infrastructure will need to undergo environmental review with either the National Environmental Policy Act (NEPA) and/or the California Environmental Quality Act (CEQA). Generally, the key environmental impacts the ZEMU and its supporting infrastructure could potentially have are:

- Visual Quality and Aesthetics
- Noise
- Air Quality and GHGs
- Hazardous Waste and Materials
- Energy
- Socio-economic / Environmental Justice impacts

The operation of the ZEMU vehicle is anticipated to provide positive effects by reducing air pollutants at the site of operation. The potential conversion of the rest of the Arrow service fleet to a low/zero emissions rail vehicle type could further improve air quality. A high-level environmental assessment was conducted as part of the study to identify the feasible technologies for the Arrow service. However, a complete environmental assessment will be needed to determine the environmental effects of the chosen technology.

7 Risk Analyses

7.1 Overview

A qualitative risk analysis has been completed to identify and compare the risks of implementing a battery ZEMU and hydrogen ZEMU in the RPRP Corridor. The risks were identified at a high level in two risk registers (See Appendix L) for both a battery and hydrogen hybrid option. Risks in the registers have been categorized as follows:

- Regulatory
- Technical – Vehicle
- Technical – Infrastructure
- Implementation Cost
- Market Availability
- Socio-Economic and Environmental

The intent of the risk analyses is to highlight critical aspects of the project which have the most uncertainty and then determine how the project will manage the risk moving forward. In most instances, the risk can be further mitigated through engineering design, engagement with appropriate agencies and planning in future phases of the project. Given the ZEMU project is in the planning phase, significant risks have been identified as needing further analysis in Phase 2 to complete engineering design and engage with 3rd parties such as the FRA, Metrolink, Omnitrans and utility providers.

As a part of the overall analyses and evaluation of the two technologies, the risks have been evaluated relative to the overall capital and operating costs and will be incorporated into the overall cost estimate as contingencies. SBCTA should closely consider the risks associated with both technologies in their assessment and selection of a preferred technology.

7.2 Battery Risk Assessment

A summary matrix documenting the risks identified for a battery ZEMU can be found in Appendix L.

Key risks identified for a battery ZEMU are related to the uncertainty of the performance of battery technology in rail applications, engagement with the FRA and power supply. While batteries are starting to be more widely used in transportation, there is limited information available on the performance and lifespan of batteries when used to propel rail vehicles. SBCTA should consider the risk associated with procuring batteries and maintaining those batteries to achieve the maximum lifespan during operations. In addition, Stadler has not indicated their battery supplier or provided information pertaining to their final design for a battery powered ZEMU. Replacement battery life is not well known and given the advancements of battery technology, could also present a risk for future procurement of replacement batteries should SBCTA be required to work with a single supplier. There is also uncertainty associated with the approval process for a battery ZEMU given the FRA have not yet provided feedback on whether a waiver or letter of concurrence will be required. While they have indicated the process for approval will be similar to CNG for Hydrogen, it might be less onerous for batteries. These are risks which will hopefully be mitigated in Phase 2, when Stadler provides a proposal to develop the technology, engage with the FRA to determine the process for approval and partner with a battery supplier.

The longer-term risks are associated with the power supply. Regardless of whether TPSS or WESS is used in the corridor to provide power to the vehicles, the operating costs will be tied to availability and prices for electricity from the local supplier SCE.

With regards to potential opportunities, it was also identified that battery technology could continue to improve over time and become cheaper to procure. This could result in an overall decrease in operating costs to the project if replacement of the batteries becomes cheaper.

7.3 Hydrogen Risk Assessment

A summary matrix documenting the risks identified for a Hydrogen ZEMU can be found in Appendix K.

Key risks identified for a hydrogen-hybrid ZEMU are related to the technology being relatively new in railway applications, hydrogen cost, and engagement with the FRA. While hydrogen fuel cell hybrid vehicles are starting to be more widely used, such as in cars, busses, and trucks, there are currently limited applications to rail operating in Europe, and no hydrogen train is commercially operating in the US. This situation leads to the requirement to work closely with the regulator to develop appropriate provisions and regulations, which has an impact on project timelines. The FRA has indicated that the process for approval will be similar to CNG, which is useful as documents and testing requirements for hydrogen could emulate the process. Mitigation of the uncertainty around approval, will hopefully be reduced in Phase 2, when Stadler would provide a proposal to develop the technology and engage with the FRA to determine the process for approval and probably partner with key component suppliers.

Only a single vehicle supplier has a produced a regional passenger train which is in commercial operation in Germany, and such a train is similar to what would be required for the Arrow service. Other manufacturers, including Stadler, would have to develop a new train but some effort could be shared with their existing hydrogen-hybrid project in Austria as many technology parts, processes, and design concepts could be transferred. Development of the technology for the North American rail market and SBCTA will have a capital cost implication but the difference to a battery solution is relatively small.

Currently, hydrogen is expensive if not purchased in large quantities or produced on-site. No large-scale hydrogen production facility is in the immediate surroundings of San Bernardino, but significant production takes place in the Wilmington and Carson areas, which are linked with a hydrogen pipeline. It is likely that hydrogen can be delivered from these areas but at relatively high cost. On-site production through steam methane reforming offers a commercially attractive option with anticipated lower operational cost than diesel and it is well-established technology, however, it would result in emissions at the hydrogen production site, but these would be lower than diesel train operation. On-site electrolysis utilizing 100% renewable electricity is the option that reduced emissions most but dependence on the local electricity supplier SCE would be a result. If current electricity and water prices are applied to electrolysis, fuel cost would be similar to diesel operation.

Compared to batteries, it is very likely that additional public outreach regarding hydrogen for transportation use is required. This is due to the perception of hydrogen being a dangerous product by the general public. However, hydrogen is already being used safely in many applications, including transportation and knowledge transfer from hydrogen bus operators, such as Sunline, would be a way to respond to this possible challenge.

8 Conclusions and Recommendations

This report provided a detailed evaluation of battery and hydrogen hybrid technologies for the Arrow service utilizing evaluation criteria and analysis for key issues such as operational viability, costs, implementation risks and environmental impacts. This analysis has concluded that both options are viable but there are specific tradeoffs that need to be considered prior to making a choice about a preferred technology and supporting infrastructure. Two primary technologies where identified: A lithium titanate battery train and a hydrogen fuel cell hybrid train. These options where chosen due to their environmental performance and possibility to reduce energy and operating costs.

8.1 Capital Cost, Operating Cost and Emission Reductions

Figure 8-1 provides a summary of the relative costs and emissions for the two key technology options, as well as for each of the viable supporting infrastructure alternatives. This is critical to consider in the overall evaluation as the supporting infrastructure has a large impact to the operation and maintenance costs but can vary in terms of the overall GHG emission reduction.

Figure 8-1: Cost and Emissions Reduction Summary Table

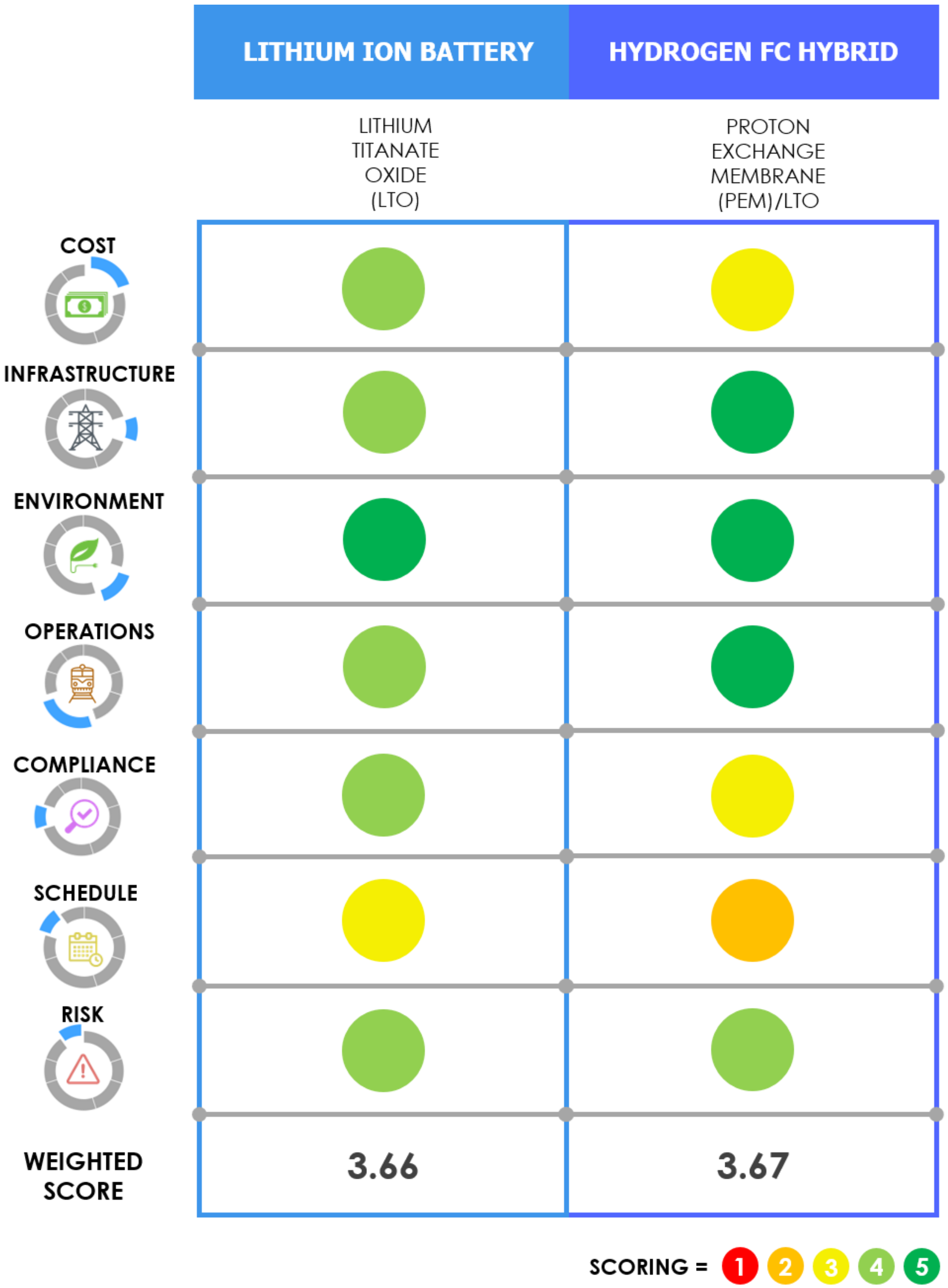
	BATTERY		HYDROGEN FUEL CELL HYBRID			
	TRACTION POWER SUBSTATION (TPSS)	WAYSIDE ENERGY STORAGE SYSTEM (WESS)	HYDROGEN DELIVERY	ON-SITE STEAM METHANE REFORMING	ON-SITE ELECTROLYSIS	
CAPITAL COST (TO PURCHASE ONE NEW ZEMU VEHICLE)	$29 M	$31 M	$33 M	$33.8 M	$34.6 M	
ANNUAL O&M COST (TO OPERATE FULL ZEMU ARROW SERVICE 2 VEHICLES)	$769 K	$690 K	$1.2 M	$540 K	$856 K	
EMISSIONS REDUCTION (PERCENTAGE IN COMPARISON TO DIESEL BENCHMARK ON A WELL-TO-WHEEL BASIS)* — Energy	60% ↓	68% ↓	.45% ↓	21% ↓	-24% ↑	24% ↓
GHGs	75% ↓	100% ↓	25% ↓	37% ↓	25% ↓	100% ↓
NOx	98% ↓	100% ↓	96% ↓	96% ↓	95% ↓	100% ↓
PM2.5	97% ↓	100% ↓	93% ↓	95% ↓	89% ↓	100% ↓
PM10	93% ↓	100% ↓	90% ↓	95% ↓	79% ↓	100% ↓
CO	90% ↓	100% ↓	82% ↓	79% ↓	71% ↓	100% ↓
	CA GRID MIX	IF 100% RENEWABLE			CA GRID MIX	IF 100% RENEWABLE

*EMISSIONS LEGEND
■ Energy ■ GHGs ■ NOx ■ PM2.5 ■ PM10 ■ CO

8.2 Technology Evaluation Matrix

The simplified matrix shown in Figure 8-2 provides a summary of how the preferred technology options were evaluated relative to the criteria and conceptual studies completed. The results in this matrix provide support to the recommendations provided in sections 8.3 and 8.4 below. For additional details on the weighting, scores and technical content; including more details on the evaluation of the supporting infrastructure, refer to the detailed technology evaluation matrix in Appendix L.

Figure 8-2: Technology Evaluation Matrix Summary



8.3 Battery

Both the WESS and TPSS provide a good option to implement ZEMU service on the 9-mile Arrow service corridor. Battery technologies have not yet been used as the primary propulsion technology on regional trains in the United States, but batteries are widely used in the passenger rail industry for vehicle auxiliary functions. This may allow for more design options and streamlining the regulatory process.

Between the WESS and TPSS there is an overall tradeoff between upfront capital cost and long-term operational cost. The WESS has a higher upfront cost but lower operating cost, while TPSS is the opposite. It is the recommendation of this analysis that if batteries are selected as the preferred propulsion technology that WESS be utilized such that the higher capital cost will be offset by long-term operational cost savings. The WESS also provides flexibility when power is drawn from the California power grid, easing the demand during peak hours, allowing for power to be drawn when only 100% renewable power is generated thus helping to manage the socio-economics impact on the local area. This benefit is captured in Figure 8-1 above, which shows the potential for 100% emission reduction (when compared to a DMU) when implementing a battery ZEMU with a WESS as the supporting infrastructure.

It was found that the primary constraint with current battery technology is that it does not perform well outside of the 9-mile Arrow service corridor. While it is still feasible to use batteries to extend the corridor, additional charging points will be required, likely for each station and dwell times may need to increase (90 seconds) at each charge point to allow for sufficient charging time for the batteries. Should the dwell times need to be maintained, the charging infrastructure size and scale, and the demand on the local grid, would be significant in terms of costs and likely not within a reasonable cost-benefit range. Additionally, traveling longer distances would increase the number of charge and discharge cycles per day, directly decreasing the service life of the batteries and requiring more replacements, which negatively impacts operating cost. Therefore, if there is a desire to expand beyond the RPRP corridor in the lifespan of the vehicle (30 years) consideration should be given to the impact to operations and high capital costs for such an expansion.

A key consideration for the assessment of batteries is the general acceptance of batteries onboard rail vehicles. It is likely that the approval and regulatory process for a battery powered ZEMU will be less onerous than that of a hydrogen powered ZEMU and could result in a shorter implementation schedule for both the pilot project as well as a ZEMU passenger service. In addition, given battery technology for rail applications has been more widely applied to date than hydrogen, it is possible that the reliability of a battery ZEMU could be better than that of a hydrogen ZEMU during the initial testing phases.

In conclusion, battery propulsion with a WESS is the preferred option if there is not a strong desire to expand outside of 9-mile Arrow corridor. If there is a desire to expand beyond the existing corridor in the lifespan of the vehicle (30 years) it is not recommended to move forward with battery propulsion technology.

8.4 Hydrogen Hybrid

While hydrogen technologies are not new to the transportation industry, it is relatively new to passenger rail. There is only one example of a regional train, similar to what would be required for the Arrow service, in revenue operation today (Coradia iLint in Germany), but there are several other projects under development in North America and Europe, and light rail/streetcar trains operate in China[37]. This report found that a hydrogen-hybrid would be a viable option for both the initial 9-mile Arrow service while having the capability to expand to LAUS if desired with less significant additional investment. The tradeoffs with the hydrogen hybrid propulsion option is that it carries additional upfront capital cost and has uncertainties and risks around the technology. While the upfront vehicle costs, when compared to a battery ZEMU are not significant, relative to the overall cost for the project, the initial operating costs will likely be more expensive than batteries, depending on the method by which SBCTA obtains its hydrogen. A commercially attractive option that would have lower operating cost than diesel is on-site SMR; it also offers substantial reductions in emissions, but this option does not allow for zero-emission well-to-wheel operation due to the utilization of low-cost natural gas. On-site electrolysis has similar operational cost to diesel, but more than SMR, while offering significant emission reductions with the possibility of a 100% zero-emission option well-to-wheel. SMR is better regarding cost while electrolysis has the potential to be much better from an environmental perspective.

Hydrogen fuel is currently not readily available near the Arrow service. While there are plans to develop hydrogen production facilities by private companies, unless a new hydrogen production plant is included in the project, there is no certainty that the fuel will be available at a reasonable price. As with all alternative fuels, there is a risk that the price to purchase hydrogen will remain expensive, ultimately resulting in significant operating cost to SBCTA for the life of the Arrow Service operations. Based on the evaluation completed in this report, and should a hydrogen ZEMU vehicle be procured, it is likely recommended to operate the pilot project with a temporary hydrogen fueling station which would receive deliveries of hydrogen from an offsite production facility (there are a few in Southern California) with the intent to eventually construct a hydrogen production facility once the vehicle is approved to go into full passenger service operations (this temporary option to obtain approval is not a possibility with a battery train as the charging infrastructure has to be constructed for operation). Should a production facility not be able to be constructed, SBCTA should consider partnerships with 3rd party agencies who are producing or supplying hydrogen in the area in order to mitigate the risk of elevating hydrogen prices.

Another important risk to consider in the evaluation of this technology is the fact that few hydrogen railway vehicles are in operation and these projects are not within the United States. It is likely that the approval process for a hydrogen hybrid ZEMU will be more onerous as both the hydrogen propulsion system and the use of batteries onboard a passenger vehicle will need to be assessed. With that in mind, the FRA has been engaged to date on the advancement of this technology and has indicated that the approval process may be similar to that of natural gas.

The final consideration for SBCTA will be the reliability of the technology. Given there is limited data available on the operation of a hydrogen rail vehicle, the analyses completed in this report has had to rely on the assessment of the few vehicles as mentioned above, with the primary focus on the Alstom train as it most closely matches the requirements of the Arrow service. The ZEMU project has entered into a partnership with Stadler to procure the ZEMU vehicle, and therefore some uncertainty exists surrounding the timeline for the development of a hydrogen hybrid ZEMU, ability to convert the existing fleet to match this design and the reliability of this technology when placed into testing & operations.

One of the primary advantages of a hydrogen-hybrid solution is that the service can be expanded easily. The vehicles do not rely on frequent wayside infrastructure to recharge and

[37] CRRC Tangshan trials new hydrogen-fuelled tram. International Railway Journal, October 2017. https://www.railjournal.com/passenger/light-rail/crrc-tangshan-trials-new-hydrogen-fuelled-tram/

could also provide service extension to LA Union Station. The primary required change would be additional hydrogen production to refuel more trains.

In conclusion, if there is a desire to extend the Arrow service beyond the planned 9-mile corridor, capital funding is available, and the additional risks as described above are acceptable, then the recommendation is to move forward with the hydrogen hybrid propulsion option.

9 Next Steps

9.1 Further Engagement with Stadler

As it is anticipated that the ZEMU vehicle will be a Stadler FLIRT vehicle, once the propulsion technology has been selected, further engagement with Stadler will be required to ensure that the propulsion system can interface with existing systems on the Stadler vehicle appropriately.

As the propulsion system needs to fit within an existing rail vehicle design, understanding of the available space and identification of the systems which will be impacted by the changes will be the first step in the design process.

9.2 Development of Technical Specifications for Stadler

The project team will develop specifications for Stadler so that the selected propulsion technology can be procured. As the original equipment manufacturer (OEM), it is anticipated that Stadler will procure the propulsion system to be designed and installed. The likely aspects that the specifications will cover include:

- Expected performance of the propulsion system in terms of power output and range
- Capacity of backup power source(s)
- Operations & Maintenance regime

9.3 Vehicle Design

Following on from the selection of the propulsion technology, design of the system will take place. Tasks for the next phase are anticipated to be design-based with frequent interfacing between SBCTA, Stadler and FRA. Some of the anticipated tasks include:

- Liaison with FRA throughout design process and reviews
- Review of rail vehicle design criteria to identify where standards/codes and regulatory requirements may need to be established
- Design of propulsion system and interfaces with Stadler vehicle
- Design of supporting infrastructure

The overall timeline for design and development is anticipated to be three and a half years, with a year and a half of acceptance and testing and FRA concurrence. However, the overall schedule is dependent on when the FRA concurrence is achieved.

Appendices

A. Battery Chemistries Evaluation Matrix

						On-board Energy Storage System (OESS)
Technology Alternatives for Vehicle Power				**Lithium Ion Battery (LIB)**		
General Description of Technology				**A battery is a device that converts chemical energy into electrical energy to provide onboard power. In Lithium Ion type configurations, lithium ions move from the negative electrode (anode) to the positive electrode (cathode) during discharge and in the opposite direction during charging. Different chemistries are combined to form the cathode and anode of a LIB, which result in many different specific configurations of LIBs.**		
Specific Types				**Lithium Iron Phosphate (LFP)**	**Lithium Nickel Maganese Cobalt Oxide (NMC)**	**Lithium Titanate (LTO)**
Description				LIB which utilizes lithium iron phosphate ($LiFePO_4$) for the cathode and graphite/carbon for the anode	LIB which utilizes Nickel Manganese Cobalt Oxide for the cathode.	Modified LIB which utilizes lithum titanate nano-crystals for the anode.
Suppliers (Vehicle or *Technology Specific)				Carbuilders with service proven experience: Stadler, Siemens, Alstom, CAF, Bombardier (Talent 3), Kawasaki, Kinki Sharyo, & others, *SAFT, *Akasol, *Centum Adetel, *ABB	CAF, *SAFT,* Akasol	*Centum Adetel, *ABB
Evaluation Criteria						
	Weighting		*Weighting*			
Cost	**0.20**	Cost - Capital	0.08	Total capital cost depends on fleet size. Per vehicle may be approximately 20-30% extra on top of an equivalent DMU cost. Requires capital for charging stations which for longer network mileage could be significant. Research shows that LFPs cost $580/kWh	Total capital cost depends on fleet size. Per vehicle may be approximately 20-30% extra on top of an equivalent DMU cost. Requires capital for charging stations, which for longer network mileage could be significant. Research shows that NMCs on average cost $420 /kWh	Total capital cost depends on fleet size. Per vehicle may be approximately 20-30% extra on top of an equivalent DMU cost. Requires capital for charging stations which for longer network mileage could be significant. However, research shows LTOs to cost the most of LIB at an average $1000/kWh
		Cost - Operations (fuel cost / energy efficiency)	0.06	Electricity supplied by grid. Slightly worse efficiency than OSC due to losses in charging cycles, however can store regenerated power from braking.	Electricity supplied by grid. Slightly worse efficiency than OSC due to losses in charging cycles, however can store regenerated power from braking.	Electricity supplied by grid. Slightly worse efficiency than OSC due to losses in charging cycles, however can store regenerated power from braking. LTO has the highest charging efficiency of the LIB chemistries.
		Cost - Life Cycle (maintenance)	0.06	Replace batteries after approximately 7 years, however they may have residual re-sale value. Minimal preventative maintenance required (less than diesel engine).	Replace batteries after approximately 7 years, however they may have residual re-sale value. Minimal preventative maintenance required (less than diesel engine).	Replace batteries after approximately 7 years, however they may have residual re-sale value. Minimal preventative maintenance required (less than diesel engine).

Specific Types				Lithium Iron Phosphate (LFP)	Lithium Nickel Maganese Cobalt Oxide (NMC)	Lithium Titanate (LTO)
Infrastructure	**0.10**	Additional ROW or land acquisition required	0.02	Potentially needed for multiple substations	Potentially needed for multiple substations	Potentially needed for multiple substations
		Catenary Free (When vehicle is in movement)	0.04	Yes	Yes	Yes
		Charging/Fueling Infrastructure Required	0.03	Overhead or under vehicle charging. Can be contact or wireless (inductive) system. Either requires substation(s) to step up/stepdown voltages/currents or wayside energy storage. Generally, voltages at utility distribution level (13kV or 4kV AC, 3 phase) would be stepped down to 600V-1500V AC then rectified to 600V-1500V DC for charging.	Overhead or under vehicle charging. Can be contact or wireless (inductive) system. Either requires substation(s) to step up/stepdown voltages/currents or wayside energy storage. Generally, voltages at utility distrubution level (13kV or 4kV AC, 3 phase) would be stepped down to 600V-1500V AC then rectified to 600V-1500V DC for charging.	Overhead or under vehicle charging. Can be contact or wireless (inductive) system. Either requires substation(s) to step up/stepdown voltages/currents or wayside energy storage. Generally, voltages at utility distrubution level (13kV or 4kV AC, 3 phase) would be stepped down to 600V-1500V AC then rectified to 600V-1500V DC for charging.
		Utility/Fuel Availability	0.02	Can be supplied from electrical grid, or is possible to have completely independent solar/wind generation.	Supplied from electrical grid, requires substation to step up voltages/currents or wayside energy storage.	Supplied from electrical grid, requires substation to step up voltages/currents or wayside energy storage.
Environmental Considerations	**0.15**	Land use compatibility	0.01	No emissions are expected during operations, therefore have no impact on sensitive land use receptors in the area. Charging infrastructure may add additional structures within ROW/station area which is also zoned for transportation purposes.	No emissions are expected during operations, therefore have no impact on sensitive land use receptors in the area. Charging infrastructure may add additional structures within ROW/station area which is also zoned for transportation purposes.	No emissions are expected during operations, therefore have no impact on sensitive land use receptors in the area. Charging infrastructure may add additional structures within ROW/station area which is also zoned for transportation purposes.
		Potential Greenhouse Gas Reductions (at Vehicle)	0.06	Zero Emissions	Zero Emissions	Zero Emissions
		Recyclability of components	0.03	The battery cells can be recycled to retreive certain metals, however the applications and commercial viability can be limited. There may be options to on-sell batteries as LIB's do not suffer 'sudden death' failure but rather gradual reduced performance, typically a reduction in capacity of 20-30%. This state is too low for rail vehicle application but could be utilized for other applications, e.g. stationary storage.	The battery cells can be recycled to retreive certain metals, however the applications and commercial viability can be limited. There may be options to on-sell batteries as LIB's do not suffer 'sudden death' failure but rather gradual reduced performance, typically a reduction in capacity of 20-30%. This state is too low for rail vehicle application but could be utilized for other applications, e.g. stationary storage.	The battery cells can be recycled to retreive certain metals, however the applications and commercial viability can be limited. There may be options to on-sell batteries as LIB's do not suffer 'sudden death' failure but rather gradual reduced performance, typically a reduction in capacity of 20-30%. This state is too low for rail vehicle application but could be utilised for other applications, e.g. stationary storage.
		High voltage clearance requirements	0.01	Only at charging points	Only at charging points	Only at charging points

Specific Types				**Lithium Iron Phosphate (LFP)**	**Lithium Nickel Maganese Cobalt Oxide (NMC)**	**Lithium Titanate (LTO)**
		Socio-economic impacts of ZEMU vehicles and infrastructure	0.02	Technology anticipated to be zero emissions which will alleviate some of the pollution as experienced by disadvantaged communities as defined by SB 535. New propulsion technology has potential to create new supporting job opportunities for the local community.	Technology anticipated to be zero emissions which will alleviate some of the pollution as experienced by disadvantaged communities as defined by SB 535. New propulsion technology has potential to create new supporting job opportunities for the local community.	Technology anticipated to be zero emissions which will alleviate some of the pollution as experienced by disadvantaged communities as defined by SB 535. New propulsion technology has potential to create new supporting job opportunities for the local community.
		Aesthetics	0.02	Good	Good	Good
		Noise	0.02	Some noise will be emitted from cooling system fans but expect the system will be quieter than the equivalent DMU.	Some noise will be emitted from cooling system fans, but expect the system will be quieter than the equivalent DMU.	Some noise will be emitted from cooling system fans, but expect the system will be quieter than the equivalent DMU.
		Range	0.08	Longer range travel will require larger battery pack or more charging points. However, if maintained properly, batteries with greater energy density will allow for longer range.	Longer range travel will require larger battery pack or more charging points. However, NMC LIB do have the highest energy densities in the LIB family today.	Longer range travel will require larger battery pack or more charging points. Note, on average the energy density of LTO batteries is lower than most LIB due to smaller cell voltages.
		Energy Density (Wh/L)	0.00	190 - 300 Wh/L @ Cell Level	260-400 Wh/L @ Cell Level	170 - 230 Wh/L @ Cell Level
		Specific Energy (Wh/kg)	0.00	90-150 Wh/kg @ Cell Level	100 - 200 Wh/kg @ Cell Level	90 - 130 Wh/kg @ Cell Level
		Performance (acceleration / top speed)	0.05	Battery configuration must be large enough to deliver above the max vehicle power required. Maximum C-Rate is also important to consider, ensuring the battery can supply the rated motor current without being damaged. LFP's have a high power density, which would yield a smaller battery configuration that could discharge the power to achieve nominal train performance. LFP C-Rates: 5C Continuous, 10C Pulse	NMCs have lower power densitity and lower C-Rates, which would lead to a larger battery pack in comparison to LFP or LTO configuration. NMC C-Rates: 3C Continuous, 6C Pulse	Utilizing LTOs would likely require a larger battery configuration to achieve the requireed power for train performance due to lower power density than LFPs. However, they are also an optimal choice due to higher achievable C-rates. LTO C-Rates: 10C Continuous, 60C Pulse
		Power Density (W/L)	0.00	≈ 400 W/L @ at nominal C-Rate	< 400 W/L @ at nominal C-Rate	< 400 W/L @ at nominal C-Rate, but can operate safely at much higher C-Rates

Specific Types				Lithium Iron Phosphate (LFP)	Lithium Nickel Maganese Cobalt Oxide (NMC)	Lithium Titanate (LTO)
Operations	**0.25**	Specific Power (W/kg)	0.00	≈ 200 W/kg @ at nominal C-Rate	< 200 W/kg @ at nominal C-Rate	< 200 W/kg @ at nominal C-Rate, but can operate safely at much higher C-Rates
		Energy Recovery from Regenerative Braking	0.03	Higher C-Rates allow battery configurations to be charged with higher power and therefore more quickly. LFPs would accept more of the power regenerated until near full than compared to an NMC.	Lower C-Rates and higher internal resistance limit the amount of power that can be accepted from NMCs.	LTOs have highest C-rates available today, making them the most optimum to accept high amounts of regenerated power. For this ZEMU application, they are considered equivalent in performance to supercapacitors.
		Operational Compatibility	0.01	A battery ZEMU will require operational management of charge levels, while charging infrastructure needs to be designed for compatibility with other network users (i.e. freight and locomotive hauled coaches).	A battery ZEMU will require operational management of charge levels, while charging infrastructure needs to be designed for compatibility with other network users (i.e. freight and locomotive hauled coaches).	A battery ZEMU will require operational management of charge levels, while charging infrastructure needs to be designed for compatibility with other network users (i.e. freight and locomotive hauled coaches).
		Life span (before replacement)	0.03	2000-3000 charge/discharge cycles	2000-3000 charge/discharge cycles	3000-8000 charge/discharge cycles
		Frequency of Major Overhauls	0.01	Replace after approximately 5-7 years if managed properly.	Replace after approximately 5-7 years if managed properly.	Replace after approximately 7-10 years if managed properly.
		Reliability	0.01	A complicated battery and thermal management system is required to achieve reliability.	A complicated battery and thermal management system is required to achieve reliability.	A complicated battery and thermal management system is required to achieve reliability. LTO is the most robust and stable chemistry for high charging rates and cycles, and thermal loads.
		Scalability	0.04	The limitation to scalability is primarily the charging infrastructure required at terminals and en-route for mid-to-long routes.	The limitation to scalability is primarily the charging infrastructure required at terminals and en-route for mid-to-long routes.	The limitation to scalability is primarily the charging infrastructure required at terminals and en-route for mid-to-long routes.
Regulatory Compliance	**0.10**	FRA, NFPA, Electrical Codes etc.	0.10	Currently, no specific power source standards for rail industry. However, some direction is provided by examples of regulator approval in Europe and the UK.	Currently, no specific power source standards for rail industry. However, some direction is provided by examples of regulator approval in Europe and the UK.	Currently, no specific power source standards for rail industry. However, some direction is provided by examples of regulator approval in Europe and the UK. Of the LIB family, the LTO is best placed to pass approvals based on its specific thermal safety characteristics and redunancy of energy capacity.

Specific Types				Lithium Iron Phosphate (LFP)	Lithium Nickel Maganese Cobalt Oxide (NMC)	Lithium Titanate (LTO)
Implementaion Schedule	**0.10**	Time for Planning, Design, Construction Phases	0.10	3 - 4 years for development and delivery of the first vehicle.	3 - 4 years for development and delivery of the first vehicle.	3 - 4 years for development and delivery of the first vehicle.
Risk Analysis	**0.10**	Availability of Warranty	0.03	Typical warranty would be 2 years leaving a significant risk with SBCTA regarding battery life. Suppliers may be open to extended warranties, however there will be costs involved. SBCTA should discuss with supplier the optimum operating conditions to maintain battery life and warranty.	Typical warranty would be 2 years leaving a significant risk with SBCTA regarding battery life. Suppliers may be open to extended warranties, however there will be costs involved. SBCTA should discuss with supplier the optimum operating conditions to maintain battery life and warranty.	Typical warranty would be 2 years leaving a significant risk with SBCTA regarding battery life. Suppliers may be open to extended warranties, however there will be costs involved. SBCTA should discuss with supplier the optimum operating conditions to maintain battery life and warranty.
		Maturity of technology	0.03	First introduced to market in 1996, introduced to rail vehicles in last decade.	First introducted to market in 2008. Most utilized battery in automotive electric vehicle industry for propulsion and is fastest growing.	First introducted to market in 2008, but not as prevalent as NMC or LFP. Development/implementation is growing and is most suited to rail vehicle applications.
		Technology related health, safety & environment risk	0.05	Batteries cannot be completely discharged and therefore remain an inherent hazard that needs to be managed for maintenance and storage. LFP specifically carry overcharge and thermal runaway risks.	Batteries cannot be completely discharged and therefore remain an inherent hazard that needs to be managed for maintenance and storage. NMC specifically carry overcharge and thermal runaway risks.	Batteries cannot be completely discharged and therefore remain an inherent hazard that needs to be managed for maintenance and storage. LTO specifically are designed to mitigate overcharge and thermal runaway risks.
Total Weighted Scores	**1.00**		**1.00**	**3.24**	**3.24**	**3.52**

B. Power Demand Modeling

Technical Note

Project:	SBCTA: Zero Emission Multiple Unit		
Our reference:	309710-MMD-05-MO-RS-0001	**Your reference:**	CTO-64
Prepared by:	Z White	**Date:**	March 6, 2019
Approved by:	M Terry	**Checked by:**	N Laverick
Subject:	ZEMU Performance and Energy Simulations		

1 Introduction

This technical memo presents preliminary simulation results regarding the performance of a Zero Emissions Multiple Unit (ZEMU) rail vehicle to be implemented on the Redlands Passenger Rail Project (RPRP) mainline track in the San Bernardino County corridor. Stadler, the proposed vehicle provider, had produced estimated trip times and acceleration rates along the RPRP corridor, but no data concerning the energy and power consumption over time was disclosed. Due to this, Mott MacDonald has performed vehicle simulations to quantify these energy and power requirements to provide potential On-board Energy Storage System (OESS) suppliers with realistic information and to further provide valuable data to the San Bernardino County Transit Authority (SBCTA) that will help them in selecting and planning for their preferred technology alternative for the ZEMU. Results have been obtained for the RPRP track (9 miles) as well as for the San Bernardino Line extending from San Bernardino Transit Center (SBTC) to Los Angeles Union Station (LAUS) (57.6 miles).

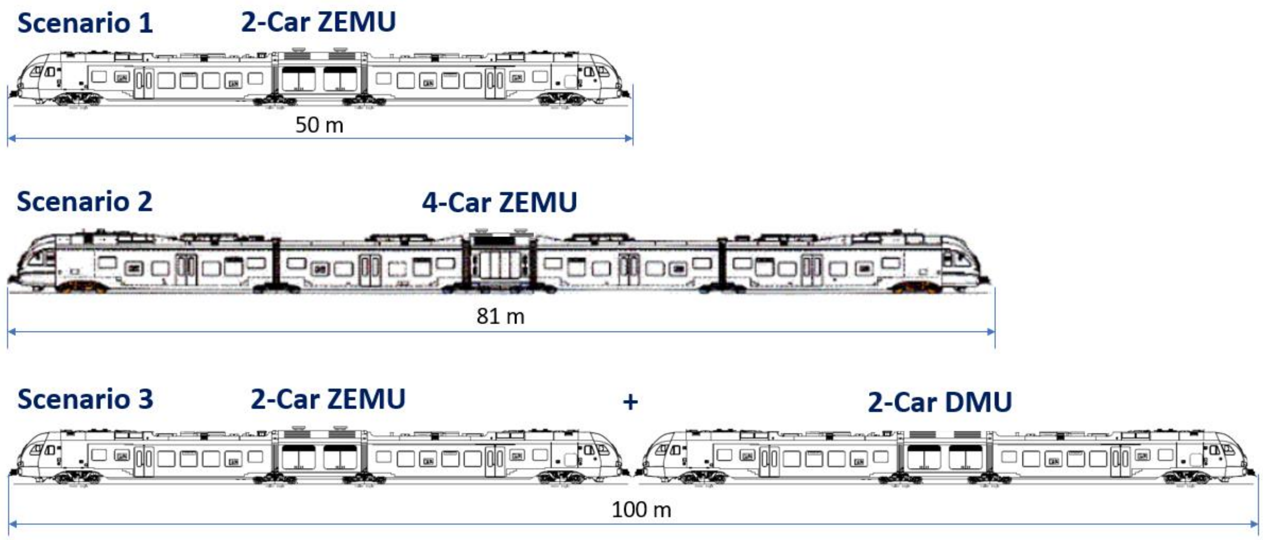
2 Simulation Overview & Inputs

The simulation computes the energy and power demands by calculating the forces, accelerations, and velocities at each instant in time during simulated service runs of the ZEMU. It contains highly detailed track data and factors in any change in gradient and horizontal curvature throughout the RPRP track as well as for the San Bernardino Line and enforces all documented speed restrictions including stopping at all stations. Simulations have been run for the following vehicle configuration scenarios:

- Scenario 1 - a 2-car plus one power module ZEMU (similar in configuration to the Arrow DMU currently being procured), this is denoted a 2-Car ZEMU.
- Scenario 2 - a 4-Car ZEMU (similar to the TexRail vehicle); and
- Scenario 3 - a consist of a 2-Car ZEMU and a second inoperable (for traction) 2-Car DMU.

Each of these scenarios are illustrated in Figure 1 below.

Figure 1: Vehicle configurations considered for simulations



The parameters that are common for all of the various simulation scenarios are as follows:

- Electric traction and braking performance curves provided by vehicle supplier, all simulations are based on only one operable power module and corresponding propulsion system i.e. 4 driven axles;
- 3-phase induction motor and drive train efficiency of 85%;
- The initial simulations will assume a combination of friction braking and dynamic braking from the traction motors, but with no regenerative braking as the energy created during dynamic braking is dissipated through on-board resistors (rheostatic) rather than being used to recharge the OESS, as well friction brakes offer no possibility of energy recovery. This is necessary in order to quantify the total energy consumption for each trip. Additional simulations in this memo assume dynamic braking using regenerative braking (i.e. best case) at a 67% regenerative braking and drive train efficiency (typical of 3 phase induction motors). Note that regenerative braking is blended with friction braking at moderate and higher speeds (greater than 23 mph) in order to achieve effective deceleration levels;
- Nominal maximum power at the wheels of 700 Kilowatt (kW) for traction and 1800 kW for braking;
- One-minute dwell times at intermediate stations;
- Additional dwell times for static charging at terminal stations have not been considered;
- No allowance yet made for constraints of Positive Train Control (PTC) system braking curves, i.e. locomotive hauled coach braking curves causes longer braking distances and therefore longer run times (minor impact on energy consumption); and
- No allowance for potential delays due to waiting for single line sections to be cleared or other unforeseen circumstances.

3 Scenario 1 – 2-Car ZEMU Simulations

The 2-Car ZEMU simulations were run with the following vehicle parameters in addition to the general conditions noted in Section 2:

- 2-Car ZEMU vehicle weight with one power module, AW3 loading condition (6 standees per square meter as defined in SBCTA's DMU specifications) + 20 % contingency (170 metric tons total);
- 2-Car ZEMU with 8 axles, including 4 driven and 4 trailer axles; and
- Constant 132 kVA auxiliary power load at a power factor of 0.89, resulting in 117.5 kW of real load. This represents a worst case with Heating, Ventilation, and Air Conditioning (HVAC) in full operation.

3.1 RPRP Corridor Simulations

Figure 2 and Figure 3 below illustrate the potential ZEMU's performance, energy, and power demands for the RPRP Corridor. From left to right, the plots represent a full journey from the SBTC to University of Redlands Station, which is the central point of the graph and the return of journey represents a mirrored version of the track data. Speed limits are based on design limits for each route and points of zero velocity represent stopping at stations. Terminals stations are labeled accordingly on the plots.

Figure 2: RPRP Corridor – ZEMU Speed, Track Elevation, & Horizontal Curvature vs. ZEMU Position

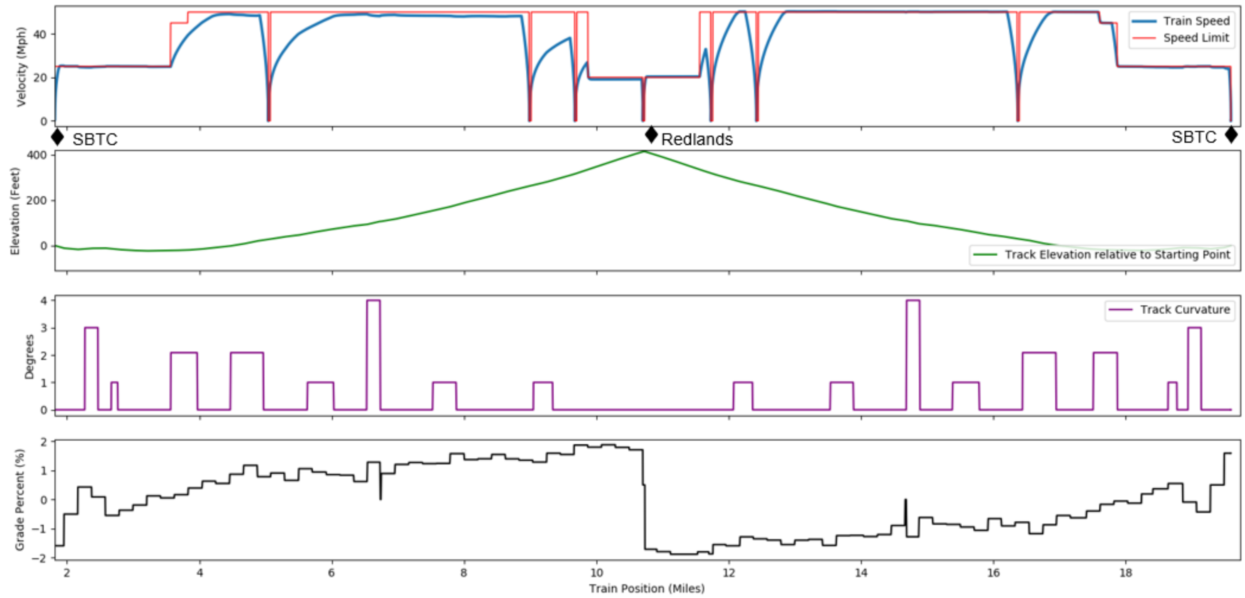
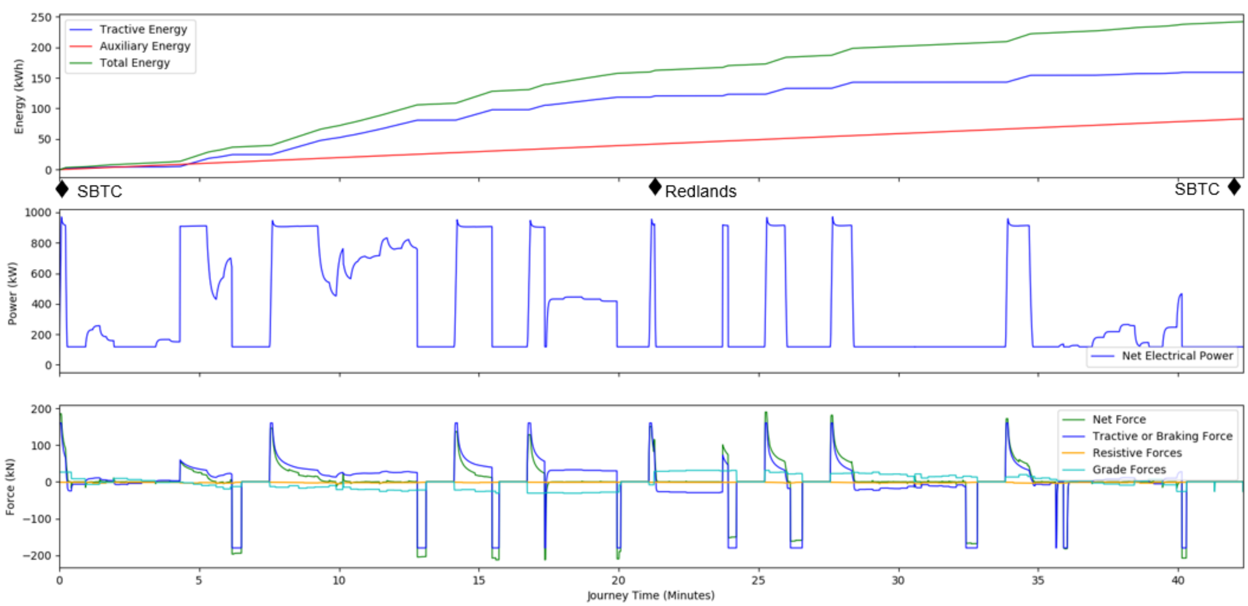


Figure 3: RPRP Corridor – ZEMU Energy, Power and Horizontal Forces vs. Journey Time



The tractive, auxiliary, and total energy consumed between stations on the RPRP alignment is shown below in Table 1:

Table 1: RPRP Corridor – Energy Required Between Stations

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
SBTC	Tippecanoe	3.23	24.50	12.74	37.24	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Tippecanoe	New York	3.95	56.28	10.95	67.22	-
Dwell	1 minute	-	0.00	1.97	1.97	-
New York	Downtown Redlands	0.69	17.06	3.13	20.19	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Downtown Redlands	University Redlands	1.03	20.46	6.54	27.00	-
Sub Total		**8.89**	**118**	**39**	**158**	**-**
University Redlands	Downtown Redlands	1.03	4.96	6.14	11.09	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Downtown Redlands	New York	0.69	9.58	2.63	12.21	-
Dwell	1 minute	-	0.00	1.97	1.97	-
New York	Tippecanoe	3.95	10.03	10.28	20.31	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Tippecanoe	SBTC	3.22	16.17	12.66	28.83	-
Sub Total		**8.89**	**41**	**38**	**78**	**-**
Total Round Trip		**17.78**	**159**	**77**	**236**	**-**

3.2 San Bernardino Line Simulations

Figure 4 and Figure 5 below illustrate the potential ZEMU's performance, energy, and power demands for the Metrolink alignment along the San Bernardino Line. From left to right, the graphs represent a full journey from Los Angeles Union Station to SBTC, which is the central point of the graph and the return journey represents a mirrored version of the track data.

Figure 4: San Bernardino Line – ZEMU Speed, Track Elevation, & Horizontal Curvature vs. ZEMU Position

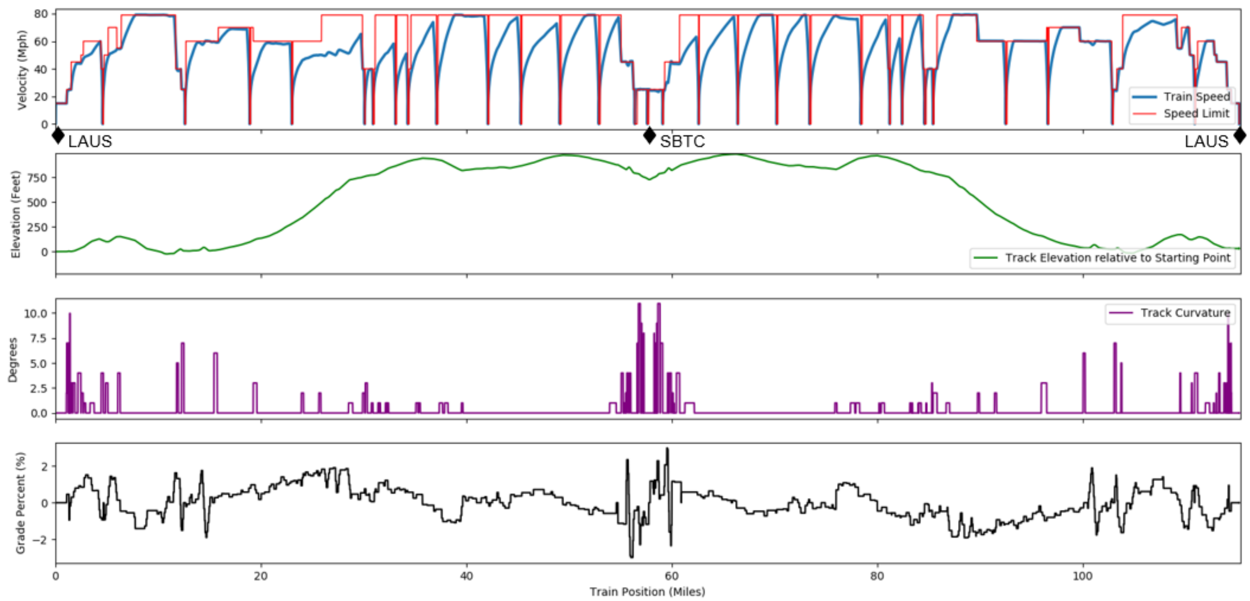
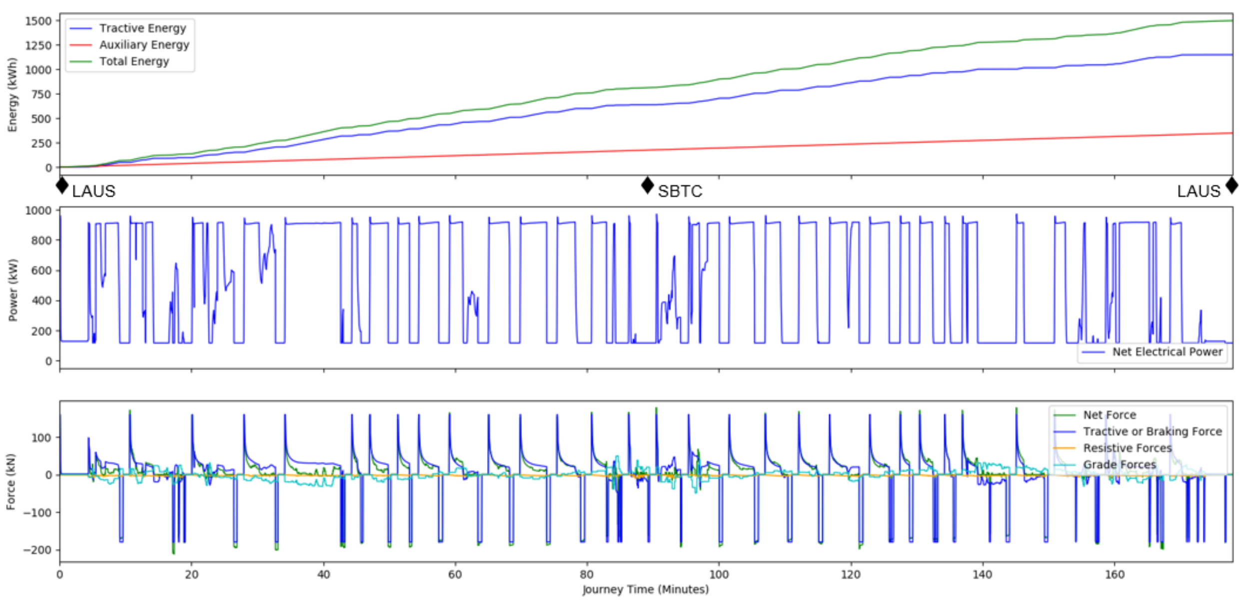


Figure 5: San Bernardino Line – ZEMU Energy, Power, & Horizontal Forces vs. Journey Time



As done for the RPRP Simulations, data for the energy consumed between each stop on Metrolink track is tabulated below in Table 2:

Table 2: San Bernardino Line – Energy Required Between Stations

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
LA Union	Cal State LA	4.60	48.80	18.83	67.63	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Cal State LA	El Monte	8.01	47.99	16.51	64.50	-
Dwell	1 minute	-	0.00	1.97	1.97	-
El Monte	Baldwin Park	6.31	55.24	13.43	68.67	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Baldwin Park	Covina	4.10	54.55	10.18	64.73	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Covina	Fairplex	7.10	112.05	17.90	129.95	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fairplex	Pomona	0.81	12.66	3.34	16.00	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Pomona	Claremont	2.19	36.89	6.35	43.23	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Claremont	Montclair	1.20	23.24	4.24	27.48	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Montclair	Upland	2.80	40.25	7.15	47.40	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Upland	Rancho Cucamonga	5.01	34.31	9.66	43.97	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rancho Cucamonga	Speedway	3.20	42.10	7.41	49.51	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Speedway	Fontana	3.80	53.21	8.97	62.19	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fontana	Rialto	3.80	37.69	8.29	45.98	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rialto	SB Depot	3.50	34.05	9.04	43.09	-
Dwell	1 minute	-	0.00	1.97	1.97	-
SB Depot	SBTC	1.23	3.56	6.23	9.79	-
Sub Total		**57.63**	**637**	**175**	**812**	**-**
SBTC	SB Depot	1.49	16.37	7.59	23.96	-
Dwell	1 minute	-	0.00	1.97	1.97	-

SB Depot	Rialto	3.50	51.03	10.08	61.11	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rialto	Fontana	3.80	50.48	8.75	59.23	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fontana	Speedway	3.79	31.56	7.98	39.54	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Speedway	Rancho Cucamonga	3.22	36.51	7.16	43.67	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rancho Cucamonga	Upland	4.98	55.89	9.95	65.84	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Upland	Montclair	2.81	39.07	7.10	46.17	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Montclair	Claremont	1.20	18.71	3.80	22.51	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Claremont	Pomona	2.20	26.21	5.45	31.66	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Pomona	Fairplex	0.82	9.64	3.28	12.92	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fairplex	Covina	7.08	27.96	14.06	42.03	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Covina	Baldwin Park	4.10	14.92	9.37	24.28	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Baldwin Park	El Monte	6.30	28.94	13.23	42.17	-
Dwell	1 minute	-	0.00	1.97	1.97	-
El Monte	Cal State LA	8.00	79.87	17.13	97.00	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Cal State LA	LA Union	4.34	24.21	16.61	40.82	-
Sub Total		**57.63**	**511**	**169**	**681**	**-**
Total Round Trip		**115.26**	**1148**	**344**	**1492**	**-**

3.3 Scenario 1 - Summary of Results

Based on the results provided in sections 3.1 and 3.2 above, Table 3

Table 3 below summarizes the amount of energy utilized for a trip from one terminal station to another and gives a total summation of the energy required to travel from Redlands to Los Angeles Union Station and back.

Table 3: Energy between Terminal Stations and Total Sum

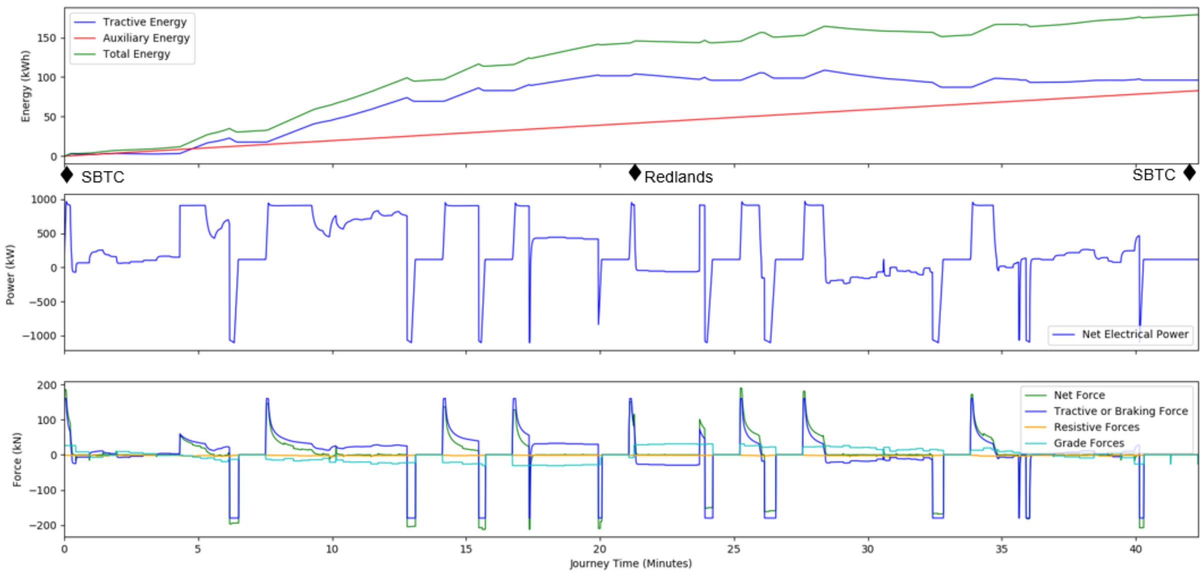
Journey		Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Total Energy (kWh)
SBTC	Redlands	8.89	118	39	158
Redlands	SBTC	8.89	41	38	78
LA	SBTC	57.63	637	175	812
SBTC	LA	57.63	511	169	681
Total		**133.04**	**1307**	**421**	**1728**

3.4 Regenerative Braking

In addition to the above results, simulations were conducted with regenerative (dynamic) braking. During dynamic braking, the magnetic fields of the motors’ reverse directions, and the kinetic energy of the vehicle drives the motors against the magnetic fields causing them to act as electrical generators while at the same time also slowing the vehicle. If facility exists to re-use or store the power that is generated, it is known as regenerative braking. However, should the OESS be non-receptive (i.e. nearing full charge or limited by heat build-up etc.) the traction/braking control systems will automatically revert to rheostatic braking which diverts the energy being created to the braking resistors which is where the energy is dissipated through heat. It should be noted that by design, three phase induction motors are not as efficient when utilized as generators when compared to being used for motoring. Nonetheless, the dynamic braking effort from the motors whether in regenerative or rheostatic mode provides a very effective means of braking as it reduces the wear and tear of the friction braking system.

The Figure 5 below shows the energy and power demands of the ZEMU vehicle for the RPRP corridor. The effect of regenerative braking can be seen in the negative values for net power (middle plot) and the reduction in energy used is illustrated in the negative slope of the tractive energy curve at times of regenerative braking. This figure can directly be compared to Figure 2, where no regenerative braking is used.

Figure 5: RPRP – ZEMU Energy, Power, Forces with regenerative braking



The table below summarizes the results for same scenarios as assessed in Section 3 above, but includes the use of entirely regenerative braking (best case) rather than entirely rheostatic braking and/or friction braking as simulated in Section 3.3 (worst case). It is assumed that all the energy regenerated by the motors can be accepted (stored) and reutilized. However, in practice the OESS will at times become non-receptive due to it being fully charged resulting energy being diverted to the braking resistors until the OESS becomes receptive again.

Table 4: Total Energy between Terminal Stations with Regenerative Braking

Journey		Section Length (Miles)	Total Energy - No Regen Braking (kWh)	Total Energy - With Regen Braking (kWh)	Net Decrease in Energy (%)
SBTC	Redlands	8.89	158	141	11%
Redlands	SBTC	8.89	78	32	59%
LA	SBTC	57.63	812	672	17%
SBTC	LA	57.63	681	497	27%
Total		**133.04**	**1728**	**1342**	**22%**

4 Scenario 2 – 4-Car ZEMU Simulations

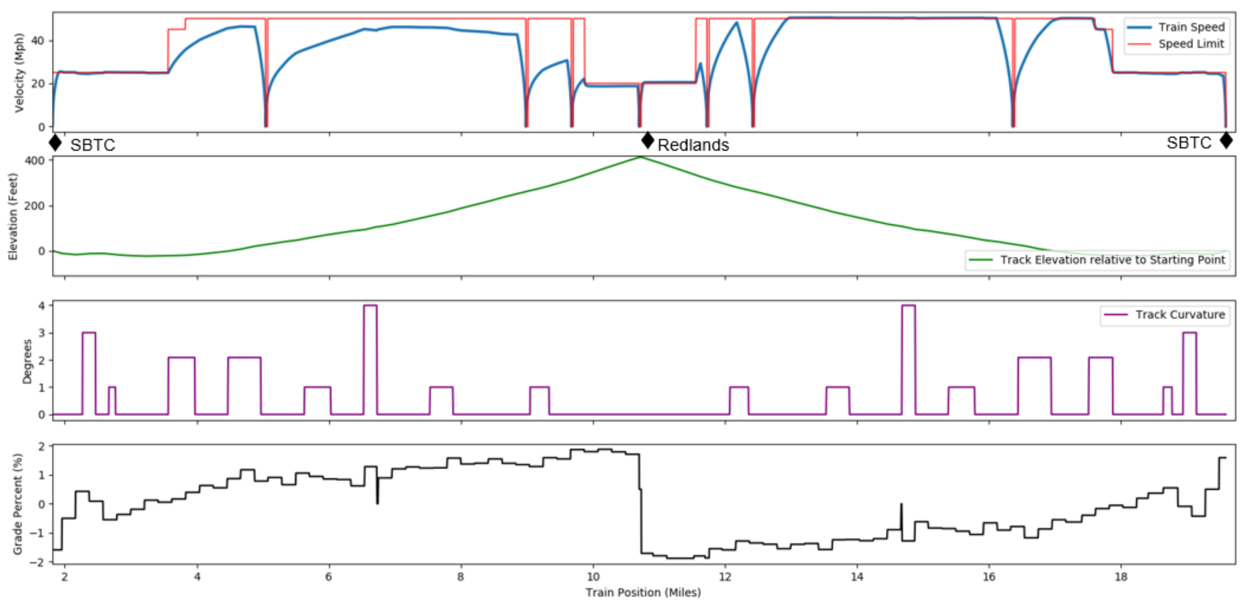
The Scenario 2 simulations were run with the following vehicle parameters in addition to the general conditions noted in Section 2:

- 4-Car ZEMU vehicle weight with one power module, AW3 loading condition (6 standees per square meter as defined in SBCTA's DMU specifications) + 20 % contingency (248.6 metric tons total);
- 4-Car ZEMU with 12 axles, including 4 driven and 8 trailer axles; and
- A constant 207 kVA auxiliary power load at a power factor of 0.89, resulting in 184 kW of real load. This represents a worst case with Heating, Ventilation, and Air Conditioning (HVAC) in full operation.

4.1 RPRP Corridor Simulations

The figures below illustrate the potential 4-Car ZEMU's performance, energy, and power demands for the RPRP Corridor from SBTC to Redlands and back as indicated on the graphs from left to right. As can be seen, the 4-Car ZEMU does not reach the 50-mph speed limit from Tippecanoe Station all the way to Downtown Redlands Station.

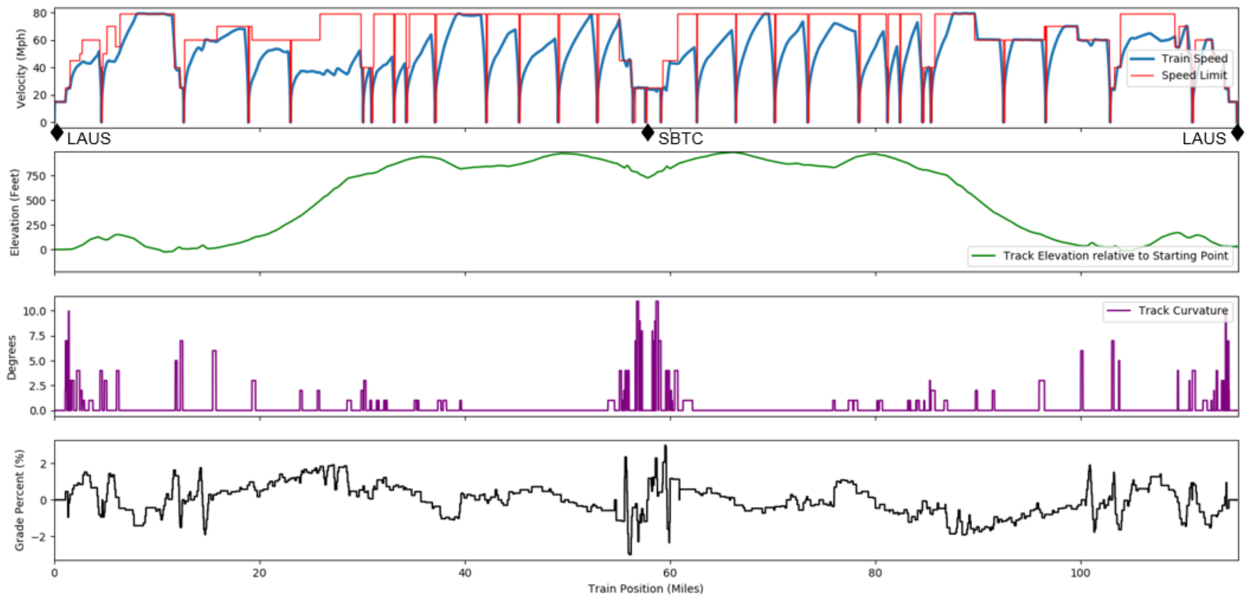
Figure 6: RPRP – 4-Car ZEMU Performance



4.2 San Bernardino Line Simulations

The figures below show a potential 4-Car ZEMU's performance, energy, and power demands for the Metrolink alignment along the San Bernardino Line from Los Angeles Union Station to SBTC and back. Similar to the results on the RPRP corridor, the increased mass of the 4-Car ZEMU significantly decreases the acceleration, particularly on uphill grades. It can be observed that for numerous sections the speed limit cannot be reached.

Figure 7: San Bernardino Line – 4-Car ZEMU Performance



4.3 Scenario 2 – Summary of Results

The table below summarizes the energy requirements for a 4-Car ZEMU between terminals. The results for tractive energy, auxiliary energy, and energy sum columns are given without any regenerative braking. The Regenerative Capability column denotes the amount of energy that could be produced with regenerative braking, negative values represent energy that is recovered and would reduce the total energy consumed for each journey. For brevity of this document, detailed energy result tables and graphs for Scenario 2 are provided in Appendix A.

Table 5: Energy Results between Terminal Stations for a 4-Car ZEMU

Journey		Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Energy Sum (kWh)	Regenerative Capability (kWh)
SBTC	Redlands	8.89	157.83	67.07	224.90	-19.44
Redlands	SBTC	8.89	51.11	61.76	112.88	-64.84
LA	SBTC	57.63	759.58	298.75	1058.33	-175.78
SBTC	LA	57.63	578.51	279.09	857.60	-243.53
Total		**133.04**	**1547**	**707**	**2254**	**-504**

5 Scenario 3 – 2-Car ZEMU + 2-Car DMU

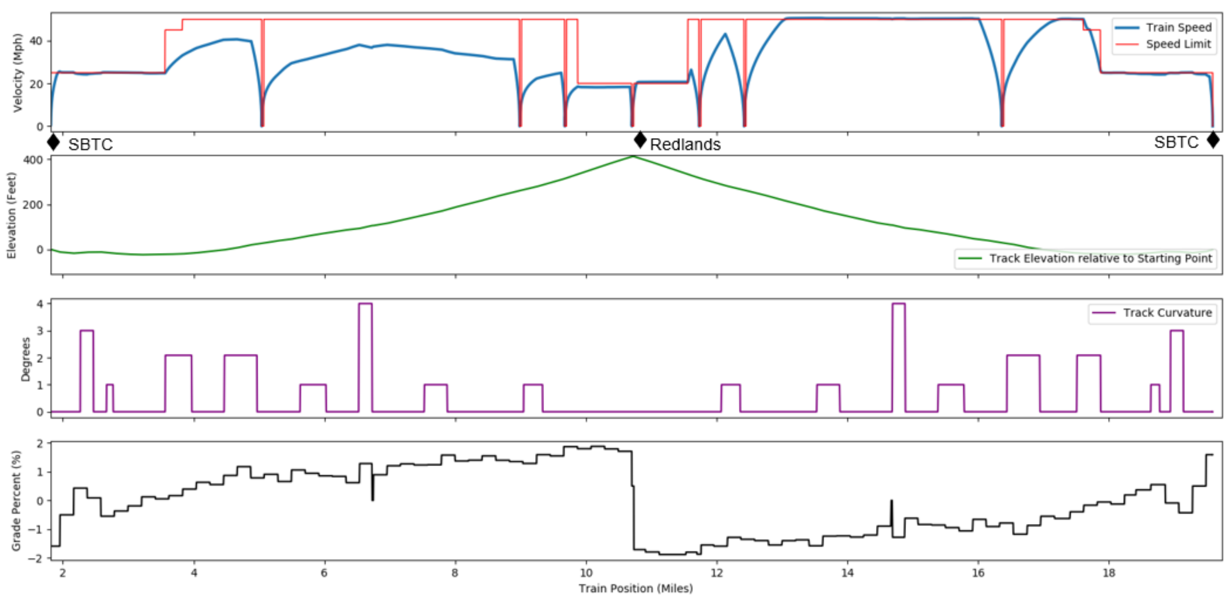
The Scenario 3 simulations were run with the following vehicle parameters in addition to the general conditions noted in Section 2:

- 2-Car ZEMU vehicle (as described in Section 3) plus the weight of a 2-Car DMU per the Arrow vehicles assumed to be inoperable for traction. Both vehicles at AW3 loading condition (6 standees per square meter as defined in SBCTA's DMU specifications) + 20 % contingency (337.4 metric tons total);
- 4-Car ZEMU with 16 axles, including 4 driven and 12 trailer axles; and
- A constant 132 kVA auxiliary power load (the same as a 2-Car ZEMU load) at a power factor of 0.89, resulting in 117.5 kW of real load. This represents the Heating, Ventilation, and Air Conditioning (HVAC) in full operation on the ZEMU, however this scenario assumes that the DMU is able to provide power for its own auxiliary load, representing the engine(s) at least idling but not providing traction power.

5.1 RPRP Corridor Simulations

The figure below illustrate the performance, energy, and power demands for the RPRP Corridor of a 2 car ZEMU pulling the weight of an unpowered 2 car DMU. Note, that on the uphill grades the train speeds are slower than the 4-Car ZEMU.

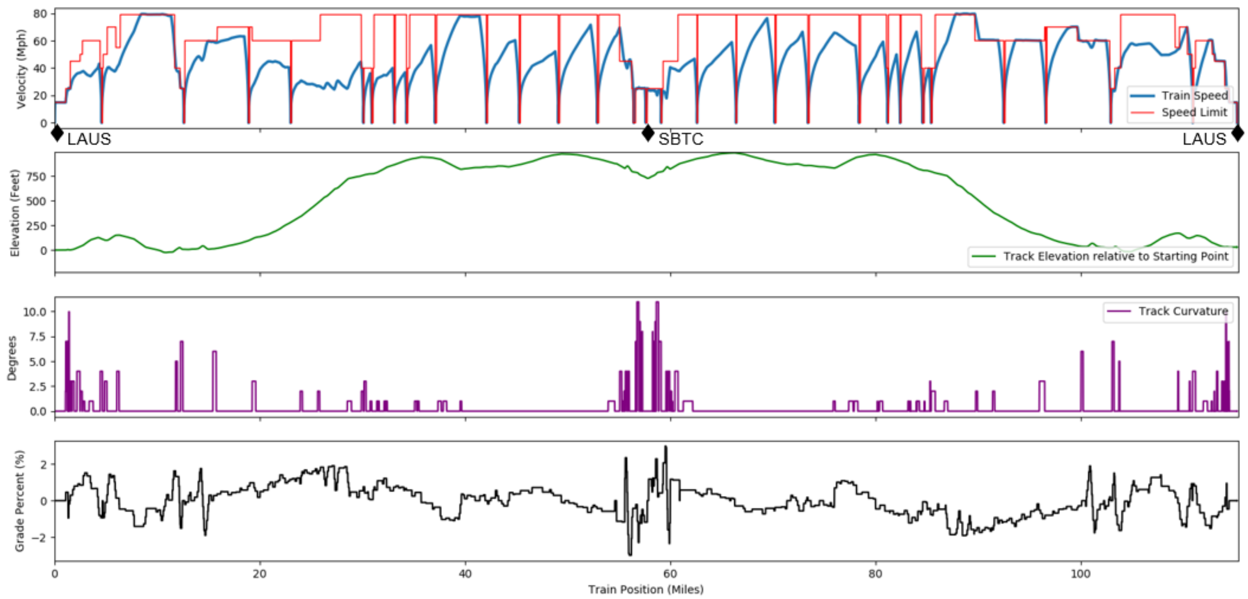
Figure 6: RPRP – 2-Car + 2-Car ZEMU Performance



5.2 San Bernardino Line Simulations

The figure below depicts the potential performance, energy, and power demands for the Metrolink alignment of a 2-Car ZEMU pulling the weight of an unpowered 2-Car DMU. Similar to the RPRP corridor, the train speeds are slower again than the 4-Car ZEMU.

Figure 6: San Bernardino Line – 2-Car + 2-Car ZEMU Performance



5.3 Scenario 3 – Summary of Results

The table below summarizes the energy requirements for a 2-Car ZEMU towing an inoperable 2-Car DMU between terminals. The results for tractive energy, auxiliary energy, and energy sum columns are given without any regenerative braking. The Regenerative Capability column denotes the amount of energy that could be produced with regenerative braking, negative values represent energy that is recovered and would reduce the total energy consumed for each journey. For brevity of this document, detailed energy result tables and graphs for Scenario 3 are provided in Appendix A.

Table 6: Energy Results between Terminal Stations for a 2-Car ZEMU + 2-Car DMU

Journey		Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Energy Sum (kWh)	Regenerative Capability (kWh)
SBTC	Redlands	8.89	192.64	46.86	239.50	-19.21
Redlands	SBTC	8.89	59.17	40.42	99.58	-104.32
LA	SBTC	57.63	947.21	216.62	1163.83	-204.70
SBTC	LA	57.63	723.80	195.60	919.40	-299.86
Total		**133.04**	**1923**	**500**	**2422**	**-628**

6 Comparison of Scenarios

The table below provides a useful comparison of the overall energy consumption values calculated for the scenarios described above. It can be seen from the results that the 4-Car ZEMU consumes approximately 30% more energy than a 2-Car ZEMU for a round trip from Redlands-SBTC-LAUS and back again. This is however, a more efficient use of energy per passenger. It should be noted that the efficiency is gained at the expense of speed, as the 4-Car ZEMU will take considerably longer to make the same trip due to its lower power to weight ratio. The 2-Car ZEMU coupled to a 2-Car DMU (the DMU providing auxiliary power but not traction) will consume more energy than the 4-Car ZEMU due to its addition weight, being a 40% increase over just the 2-Car ZEMU. This would be higher still if the ZEMU also had to power the auxiliaries of the DMU, however no facility exists for transferring auxiliary power through the coupler so that would not be a realistic case.

Table 7: Simulation results comparison

Journey		Section Length (Miles)	Energy Between Terminals					
			Scenario 1 2-Car ZEMU		Scenario 2 4-Car ZEMU		Scenario 3 2-Car + 2-Car	
			No Regen. Braking (kWh)	With Regen. Braking (kWh)	No Regen. Braking (kWh)	With Regen. Braking (kWh)	No Regen. Braking (kWh)	With Regen. Braking (kWh)
SBTC	Redlands	8.89	157.59	140.93	224.90	205.45	239.50	220.29
Redlands	SBTC	8.89	78.36	32.13	112.88	48.04	99.58	14.47
LA	SBTC	57.63	811.77	672.23	1058.33	882.55	1163.83	959.13
SBTC	LA	57.63	680.56	496.54	857.60	614.06	919.40	619.55
Total		**133.04**	**1728**	**1342**	**2254**	**1750**	**2422**	**1813**

7 Conclusions

7.1 General Observations

The simulations conducted as part of this scope of work have provided valuable insight into the energy usage of multiple ZEMU vehicle scenarios within San Bernardino and Los Angeles Counties rail corridors. The data generated can be used as an input to both the vehicle and infrastructure sides of the feasibility and project planning efforts aimed towards implementing a ZEMU service in California.

It can be seen from the simulations that the majority of energy usage, an average of 76% of the simulated trips, is demanded by the propulsion (traction) system. However, in higher proportion to the tractive energy than expected, the results show significant energy consumption by the auxiliaries. Although this is a worst-case scenario presented, the data is not entirely unrealistic considering that high power loads, e.g. the HVAC unit, may be required to operate at a 100% duty cycle for long periods of the day due to the local climatic conditions.

The tractive energy required is considerably higher for the routes that are mostly uphill (Redlands-SBTC and LAUS-SBTC) due to higher grade forces that resist the train's motion, and therefore need to be overcome by more tractive power. It should be noted that the routes assessed in this investigation show clear trends in the track gradients, i.e. there is a predominately uphill direction and a predominantly downhill direction for each. This results in there being a clear worst-case scenario for the routes (the uphill direction) from an energy consumption perspective.

Mott MacDonald found that in both Scenarios 2 and 3, the heavier vehicle mass drove a need to model the vehicle with friction braking supplementing the electrodynamic braking due to the downhill sections of the alignments. When operating at higher speeds (i.e. 40 to 79 mph), there is not enough available force from dynamic braking to overcome the force of gravity on the grade to satisfactorily decelerate the vehicles for the curvature and stops required at each stations. It should be noted that this use of blended (electrodynamic plus friction) braking does decrease the amount of energy that can be recovered through regenerative braking.

7.2 Scenario 1 – 2-Car ZEMU Simulations

7.2.1 RPRP Corridor feasibility with Battery ZEMU

The total energy consumed by a 2-car ZEMU for the Redlands to SBTC and back on the RPRP corridor is calculated to be 236 kilowatt hour (kWh) with the worst-case single direction being from SBTC to Redlands (uphill) using 158 kWh. This does not include the additional dwell times at terminal stations, which would increase the energy requirements due to the extended time for powering auxiliary loads, however it is assumed that end terminals will include charging points (if a battery ZEMU is selected) so that the energy consumption while waiting at terminals will not be drawn from the OESS.

Based on these energy consumption calculations, and considering extra contingency requirements such as: extended operational delays away from charge points, degradation of battery capacity over its lifetime, and the allowable depth of battery discharge to avoid shortening battery life; it is likely that a battery powered ZEMU vehicle with a notional energy storage capacity in the range of 400 to 600 kWh is a feasible option for SBTCA to consider for the future zero emission Arrow service.

7.2.2 San Bernardino Line feasibility with Battery ZEMU

The modelling work described above has also evaluated the energy consumption requirements for the 2-car ZEMU vehicle along the San Bernardino Line. The total energy consumed for the SBTC to LA Union Station and back is calculated to be 1,492 kWh with the worst-case single direction being LA Union Station to SBTC (uphill) using 812 kWh. Again, this does not include dwell times at terminal stations as stated in Section 7.1 above.

Based on these energy consumption calculations and taking into account the contingency requirements noted above, it is considered unlikely that a battery only ZEMU is a feasible option to operate these types of 60-mile service trips without any en-route charging. For the limiting design case (LAUS to SBTC), even when a best-case amount of regenerative braking is assumed, the energy consumption is still 600 kWh meaning that a minimum 1,200 kWh on-board battery system may be desired to account for the contingency factors. Following our engagement with technology providers, we are advised that the current level of battery technology would result in an on-board system size of over 13 metric tons and take up over seven cubic meters of space and is unlikely to be feasible to integrate into the Stadler FLIRT power module or other suppliers' regional multiple unit products.

Ultimately, if the ZEMU is planned for any extended routes significantly beyond the nine miles of the proposed RPRP track, a trade-off should be considered between battery OESS storage capacity, the use of different technology in hybrid with batteries (specifically hydrogen fuel cells) or the use of charging stations en-route. If en-route charging is considered, attention should be given to the likely extension of timetables to allow for sufficient charging during dwell times.

7.2.3 Regenerative Braking

The effect of regenerative braking was investigated. The scenario that was simulated, i.e. regenerative braking was prioritized over friction braking, resulted in an energy consumption reduction of 22% averaged over all routes for Scenario 1 (2-Car consist) simulated. However, it should be noted that the results show that regenerative braking is most effective on the downhill routes as relatively more braking is required than the uphill routes. On the uphill routes the saving was only 11% and 17% for SBTC to Redlands and LAUS-

SBTC, respectively. Therefore, regenerative braking has less of a positive effect for reducing the energy demand on the routes that will effectively become the design cases (uphill routes) used for specifying procurement of an OESS system.

Additionally, as the figures quoted above are for the best-case scenario, it is unrealistic to assume braking will always be done entirely by regenerative means, therefore it is recommended that OESS capacities be specified for the worst-case scenario. Regenerative braking can however be considered a positive in reducing the net energy usage (and power cost) of the system.

7.3 Scenario 2 – 4-Car ZEMU Simulations

The total energy for a 4-Car consist was 338 kWh on the RPRP corridor and 1,916 kWh on the Metrolink San Bernardino line. This denotes increases of 43.2% and 28.4% respectively in the total energy along these routes in comparison to a 2-Car ZEMU, however the passenger carrying capacity is considerably higher. The speeds achieved by the 4-Car ZEMU during these journeys are also significantly less than a 2-Car ZEMU, so increases in runtime should be accounted for in any operating timetable proposed.

7.3.1 Feasibility of a Battery 4-Car ZEMU

From purely an energy consumption perspective, the simulations suggest a 4-Car ZEMU could be a feasible option on the RPRP corridor. With single worst-case direction between terminals (SBTC to Redlands) consuming 225 kWh, this would appear to be within the capability of a nominal 600 kWh battery system discussed above. There would be a definite need to provide charging points at both terminals and potentially one en-route as a risk mitigation and to reduce charging requirements at terminal. The charging time to replace the 225 kWh of energy at the Redlands terminal will be approximately 11-12 minutes at best. Fortunately, on the return journey to SBTC much less energy is used and there is ample opportunity to recover energy through braking, so setting off from Redlands without a completely full battery may not be a serious operational concern.

7.4 Scenario 3 – 2-Car ZEMU + 2-Car DMU (traction inoperable)

The results for a 2-Car ZEMU towing a (inoperable except auxiliaries) 2-Car DMU depict even larger energy demands as the total weight is the greatest in this scenario. The total energy demands along the RPRP corridor and Metrolink alignment were 339 kWh and 2,422 kWh respectively, with even longer runtimes than the 4-Car ZEMU.

7.4.1 Feasibility for demonstrating the concept for a 4-Car ZEMU

The extra mass in Scenario 3 provided by a second power module and additional cab cars and trucks (compared to Scenario 2) result in much more traction power being required to undertake each journey. However, this scenario has been assessed primarily for two reasons:

1. As an option to demonstrate the feasibility of a 4-Car ZEMU by utilizing a 2-Car ZEMU and a spare 2-Car DMU; and
2. As a check of the capability of the 2-Car ZEMU to “recover” a broken-down vehicle.

From both these perspectives, the simulation results suggest this is a feasible option. The tractive energy demands are clearly higher than the 4-Car scenario above, however in both situations the second vehicle is assumed to provide its own auxiliary power. For demonstration purposes the DMU would leave one or both engines idling, and in the recovery scenario passengers would likely have been disembarked so that HVAC and other amenities are not critical. In either case, the relative reduction of auxiliary loads on the ZEMU’s battery system compared to the 4-Car scenario results in only a moderate increase in energy needed for the heavier configuration to travel on the SBTC to Redlands uphill journey, 239 kWh relative to the 225 kWh discussed in 7.3.1 above. This also appears a feasible path with the battery technology available.

8 Recommendations

Following the preliminary analysis presented above, Mott MacDonald recommend the following next steps be considered as the ZEMU program progresses:

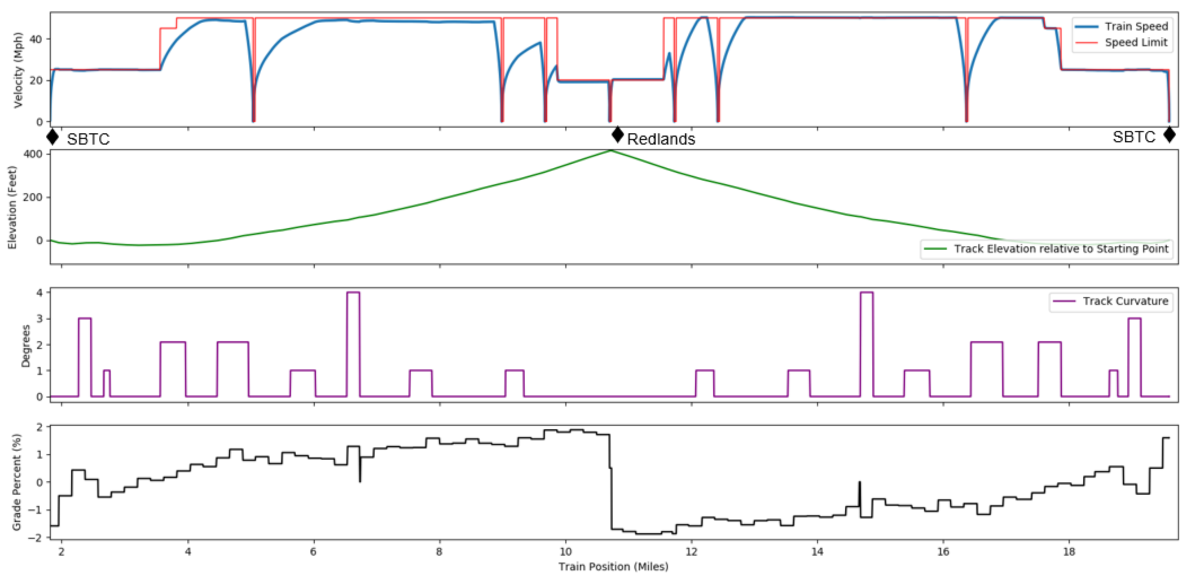
1. Further consideration should be given to the day to day operation of the ZEMU vehicles to ensure there are no routine scenarios in their service timetable, stabling or maintenance strategy that is a more severe design case than the service simulations presented above.
2. Further consideration should be given to develop realistic energy capacity contingency requirements to account for potential unplanned events. The requirements should include sufficient redundancy for the application while aiming to avoid SBCTA paying a severe cost premium for the system over its life cycle. This could include options such as simulating different driving styles, e.g. economical (efficient) vs minimize runtime (speed) to assess the likely regular energy usage versus worst case, further investigating the use of regenerative braking as it is known to reduce energy consumption but will also increase the number of charging cycles which could reduce battery life.
3. Further model development is recommended. The model itself can be updated to simulate OESS of various types and capabilities (batteries, supercapacitors, hydrogen fuel cells for example). This will allow greater clarity into the investigation of the following:
   a. Effectiveness of various options for en-route charging,
   b. Develop minimum charge level guidance for operation before allowed to leave the charging point,
   c. Calculation of hydrogen fuel consumption and re-fueling frequency, and
   d. Simulate the contingency scenarios related to unplanned delays or depleted power systems, etc.

ZEMU Performance & Energy Simulations Appendices

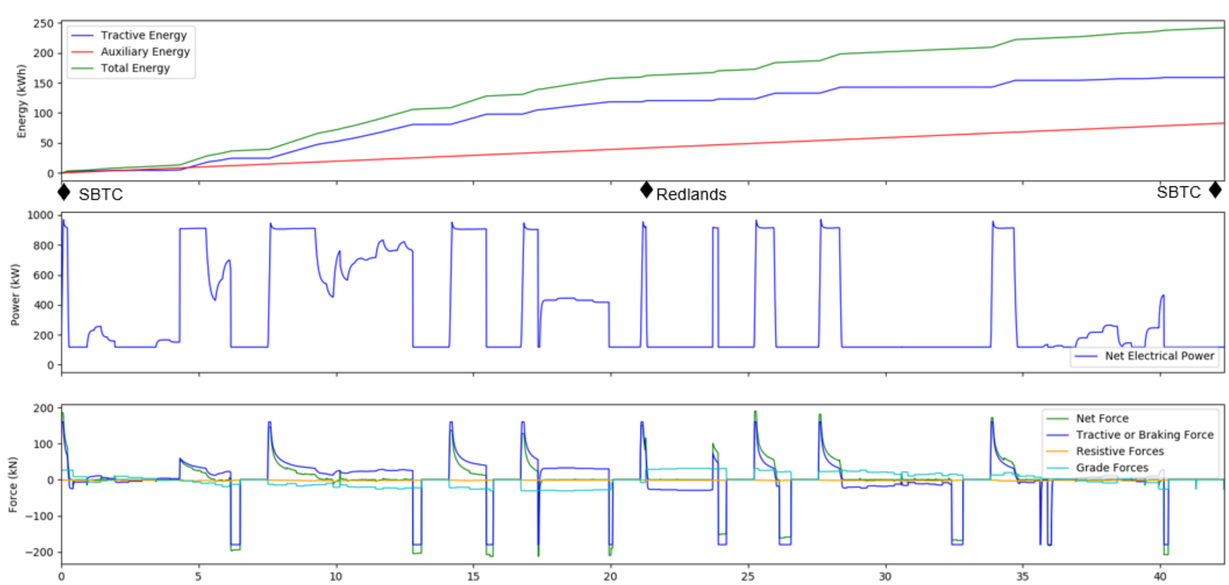
Appendix A - Scenario 1 - 2-Car ZEMU Data

Plots

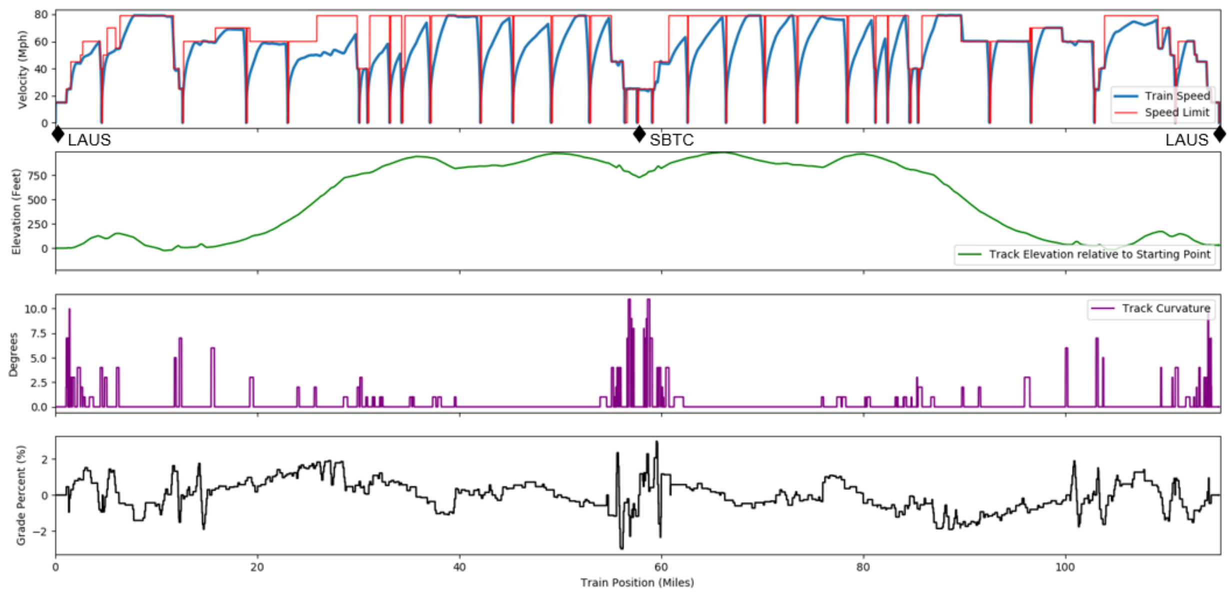
1. RPRP Corridor – ZEUMU Speed, Track Elevation, & Horizontal Curvature vs. ZEMU Position



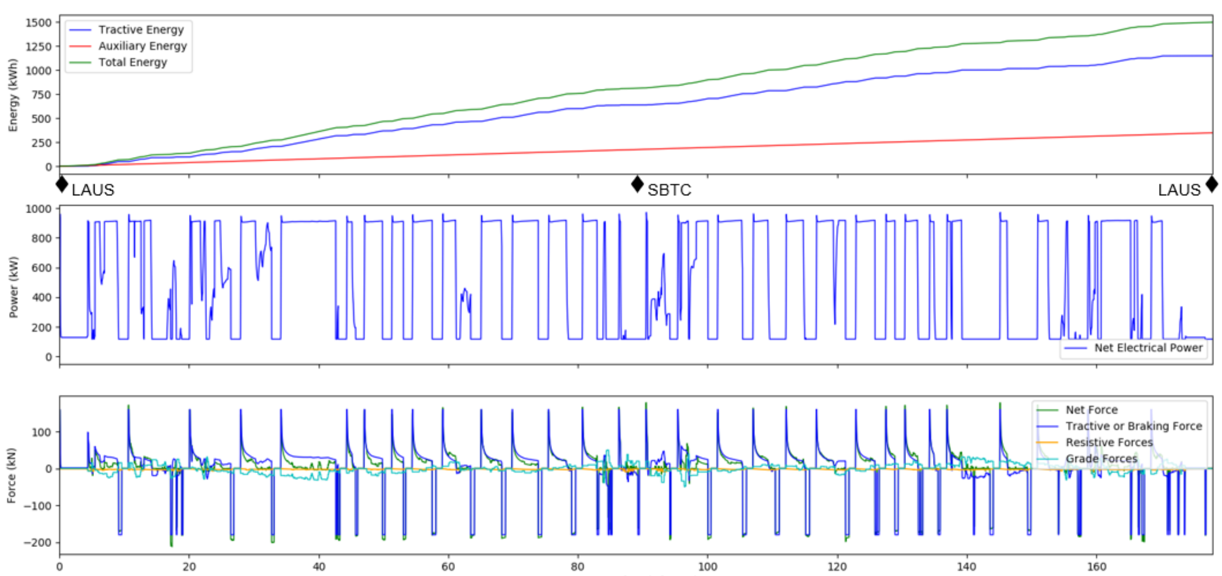
2. RPRP Corridor – ZEMU Energy, Power and Horizontal Forces vs. Journey Time



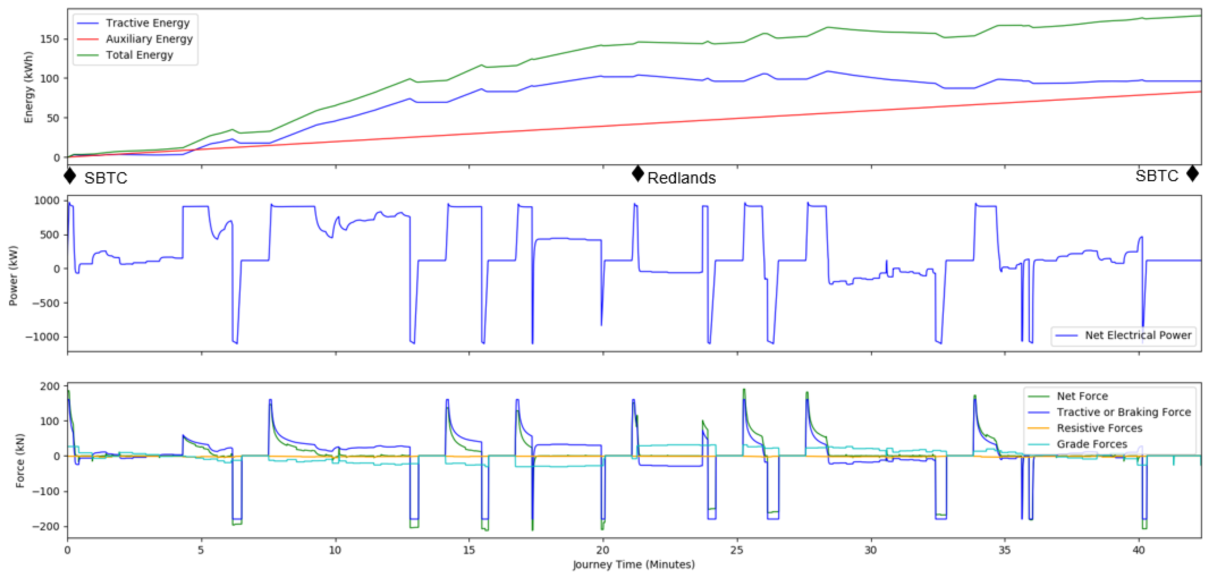
3. **San Bernardino Line – ZEMU Speed, Track Elevation, & Horizontal Curvature vs. ZEMU Position:**



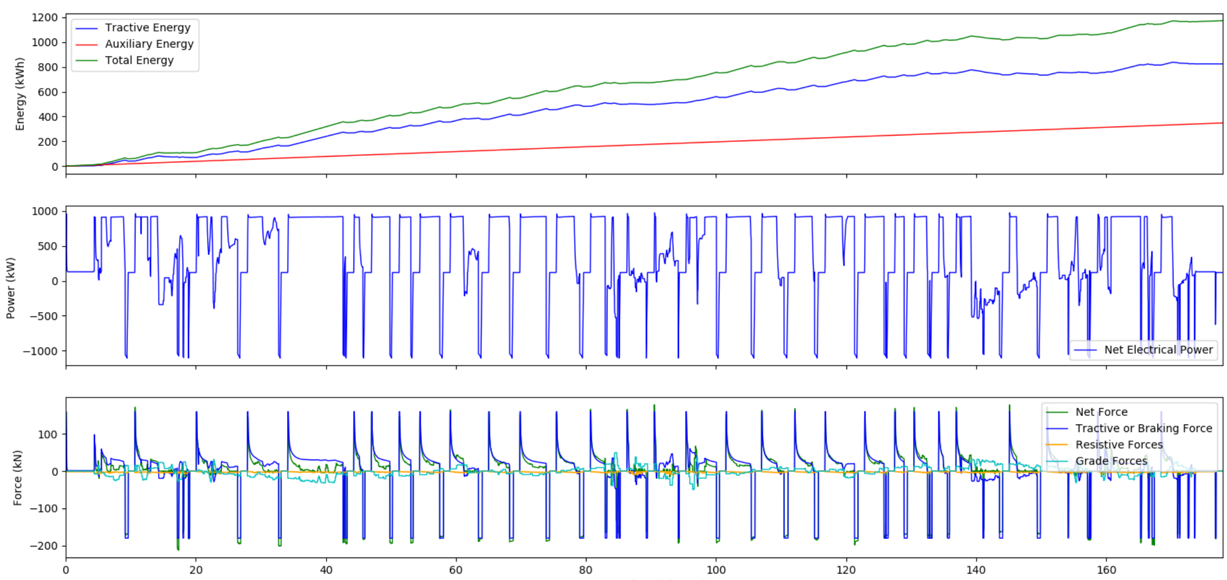
4. **San Bernardino Line – ZEMU Energy, Power and Horizontal Forces vs. Journey Time**



5. RPRP Corridor – ZEMU Energy, Power, Forces with regenerative braking



6. San Bernardino Line – ZEMU Energy, Power, Forces with regenerative braking



Tables

1. RPRP Corridor – Energy Required Between Stations

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
SBTC	Tippecanoe	3.23	24.50	12.74	37.24	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Tippecanoe	New York	3.95	56.28	10.95	67.22	-
Dwell	1 minute	-	0.00	1.97	1.97	-
New York	Downtown Redlands	0.69	17.06	3.13	20.19	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Downtown Redlands	University Redlands	1.03	20.46	6.54	27.00	-
Sub Total		**8.89**	**118**	**39**	**158**	**-**
University Redlands	Downtown Redlands	1.03	4.96	6.14	11.09	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Downtown Redlands	New York	0.69	9.58	2.63	12.21	-
Dwell	1 minute	-	0.00	1.97	1.97	-
New York	Tippecanoe	3.95	10.03	10.28	20.31	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Tippecanoe	SBTC	3.22	16.17	12.66	28.83	-
Sub Total		**8.89**	**41**	**38**	**78**	**-**
Total Round Trip		**17.78**	**159**	**77**	**236**	**-**

2. San Bernardino Line– Energy Required Between Stations

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
LA Union	Cal State LA	4.60	48.80	18.83	67.63	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Cal State LA	El Monte	8.01	47.99	16.51	64.50	-
Dwell	1 minute	-	0.00	1.97	1.97	-
El Monte	Baldwin Park	6.31	55.24	13.43	68.67	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Baldwin Park	Covina	4.10	54.55	10.18	64.73	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Covina	Fairplex	7.10	112.05	17.90	129.95	-

Dwell	1 minute	-	0.00	1.97	1.97	-
Fairplex	Pamona	0.81	12.66	3.34	16.00	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Pamona	Claremont	2.19	36.89	6.35	43.23	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Claremont	Montclair	1.20	23.24	4.24	27.48	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Montclair	Upland	2.80	40.25	7.15	47.40	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Upland	Rancho Cucamonga	5.01	34.31	9.66	43.97	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rancho Cucamonga	Speedway	3.20	42.10	7.41	49.51	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Speedway	Fontana	3.80	53.21	8.97	62.19	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fontana	Rialto	3.80	37.69	8.29	45.98	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rialto	SB Depot	3.50	34.05	9.04	43.09	-
Dwell	1 minute	-	0.00	1.97	1.97	-
SB Depot	SBTC	1.23	3.56	6.23	9.79	-
Sub Total		**57.63**	**637**	**176**	**812**	**-**
SBTC	SB Depot	1.49	16.37	7.59	23.96	-
Dwell	1 minute	-	0.00	1.97	1.97	-
SB Depot	Rialto	3.50	51.03	10.08	61.11	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rialto	Fontana	3.80	50.48	8.75	59.23	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fontana	Speedway	3.79	31.56	7.98	39.54	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Speedway	Rancho Cucamonga	3.22	36.51	7.16	43.67	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rancho Cucamonga	Upland	4.98	55.89	9.95	65.84	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Upland	Montclair	2.81	39.07	7.10	46.17	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Montclair	Claremont	1.20	18.71	3.80	22.51	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Claremont	Pamona	2.20	26.21	5.45	31.66	-
Dwell	1 minute	-	0.00	1.97	1.97	-

Pamona	Fairplex	0.82	9.64	3.28	12.92	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fairplex	Covina	7.08	27.96	14.06	42.03	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Covina	Baldwin Park	4.10	14.92	9.37	24.28	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Baldwin Park	El Monte	6.30	28.94	13.23	42.17	-
Dwell	1 minute	-	0.00	1.97	1.97	-
El Monte	Cal State LA	8.00	79.87	17.13	97.00	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Cal State LA	LA Union	4.34	24.21	16.61	40.82	-
Sub Total		**57.63**	**511**	**169**	**681**	**-**
Total Round Trip		**115.26**	**1148**	**344**	**1492**	**-**

3. Energy between Terminal Stations and Total Sum

Journey		Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Total Energy (kWh)
SBTC	Redlands	8.89	118	39	158
Redlands	SBTC	8.89	41	38	78
LA	SBTC	57.63	637	175	812
SBTC	LA	57.63	511	169	681
Total		**133.04**	**1307**	**421**	**1728**

4. RPRP – Energy between Stations with regenerative braking

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
SBTC	Tippecanoe	3.23	17.78	12.74	30.53	-6.72
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Tippecanoe	New York	3.95	51.51	10.95	62.45	-4.77
Dwell	1 minute	-	0.00	1.97	1.97	0.00
New York	Downtown Redlands	0.69	13.68	3.13	16.81	-3.38
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Downtown Redlands	University Redlands	1.03	18.67	6.54	25.21	-1.79
Sub Total		**8.89**	**102**	**39**	**141**	**-17**

University Redlands	Downtown Redlands	1.03	-5.69	6.14	0.45	-10.64
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Downtown Redlands	New York	0.69	2.66	2.63	5.29	-6.92
Dwell	1 minute	-	0.00	1.97	1.97	0.00
New York	Tippecanoe	3.95	-11.51	10.28	-1.23	-21.53
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Tippecanoe	SBTC	3.22	9.03	12.66	21.69	-7.14
Sub Total		**8.89**	**-5**	**38**	**32**	**-46**
Total Round Trip		**17.78**	**96**	**77**	**173**	**-63**

5. San Bernardino Line – Energy between stations with regenerative braking

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
LA Union	Cal State LA	4.60	41.02	18.83	59.85	-7.78
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Cal State LA	El Monte	8.01	28.81	16.51	45.33	-19.18
Dwell	1 minute	-	0.00	1.97	1.97	0.00
El Monte	Baldwin Park	6.31	45.04	13.43	58.47	-10.21
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Baldwin Park	Covina	4.10	48.38	10.18	58.56	-6.17
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Covina	Fairplex	7.10	104.64	17.90	122.54	-7.41
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Fairplex	Pamona	0.81	8.55	3.34	11.90	-4.10
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Pamona	Claremont	2.19	30.46	6.35	36.80	-6.43
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Claremont	Montclair	1.20	17.80	4.24	22.04	-5.44
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Montclair	Upland	2.80	30.90	7.15	38.04	-9.35
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Upland	Rancho Cucamonga	5.01	22.43	9.66	32.09	-11.88
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Rancho Cucamonga	Speedway	3.20	32.90	7.41	40.31	-9.21

Dwell	1 minute	-	0.00	1.97	1.97	0.00
Speedway	Fontana	3.80	44.54	8.97	53.52	-8.67
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Fontana	Rialto	3.80	26.72	8.29	35.01	-10.98
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Rialto	SB Depot	3.50	17.06	9.04	26.10	-16.99
Dwell	1 minute	-	0.00	1.97	1.97	0.00
SB Depot	SBTC	1.23	-2.19	6.23	4.04	-5.75
Sub Total		**57.63**	**497**	**175**	**672**	**-140**
SBTC	SB Depot	1.49	14.36	7.59	21.95	-2.01
Dwell	1 minute	-	0.00	1.97	1.97	0.00
SB Depot	Rialto	3.50	43.16	10.08	53.24	-7.87
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Rialto	Fontana	3.80	40.81	8.75	49.56	-9.67
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Fontana	Speedway	3.79	19.82	7.98	27.80	-11.74
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Speedway	Rancho Cucamonga	3.22	26.60	7.16	33.76	-9.91
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Rancho Cucamonga	Upland	4.98	46.89	9.95	56.85	-9.00
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Upland	Montclair	2.81	29.08	7.10	36.18	-9.99
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Montclair	Claremont	1.20	10.80	3.80	14.60	-7.91
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Claremont	Pamona	2.20	15.64	5.45	21.09	-10.58
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Pamona	Fairplex	0.82	4.77	3.28	8.05	-4.86
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Fairplex	Covina	7.08	-12.75	14.06	1.32	-40.71
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Covina	Baldwin Park	4.10	-2.48	9.37	6.89	-17.40
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Baldwin Park	El Monte	6.30	15.53	13.23	28.76	-13.41
Dwell	1 minute	-	0.00	1.97	1.97	0.00
El Monte	Cal State LA	8.00	65.77	17.13	82.90	-14.11
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Cal State LA	LA Union	4.34	9.36	16.61	25.97	-14.86
Sub Total		**57.63**	**327**	**169**	**497**	**-184**
Total Round Trip		**115.26**	**824**	**344**	**1169**	**-324**

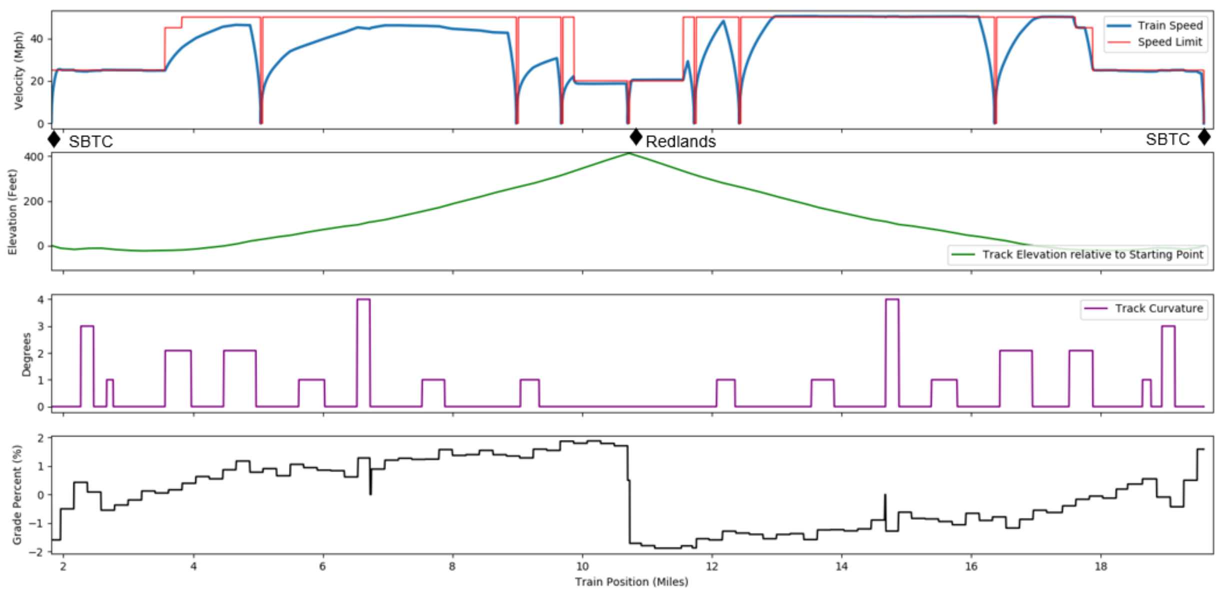
6. Total Energy between Terminal Stations with Regenerative Braking

Journey		Section Length (Miles)	Total Energy - No Regen Braking (kWh)	Total Energy - With Regen Braking (kWh)	Net Decrease in Energy (%)
SBTC	Redlands	8.89	158	141	11%
Redlands	SBTC	8.89	78	32	59%
LA	SBTC	57.63	812	672	17%
SBTC	LA	57.63	681	497	27%
Total		**133.04**	**1728**	**1342**	**22%**

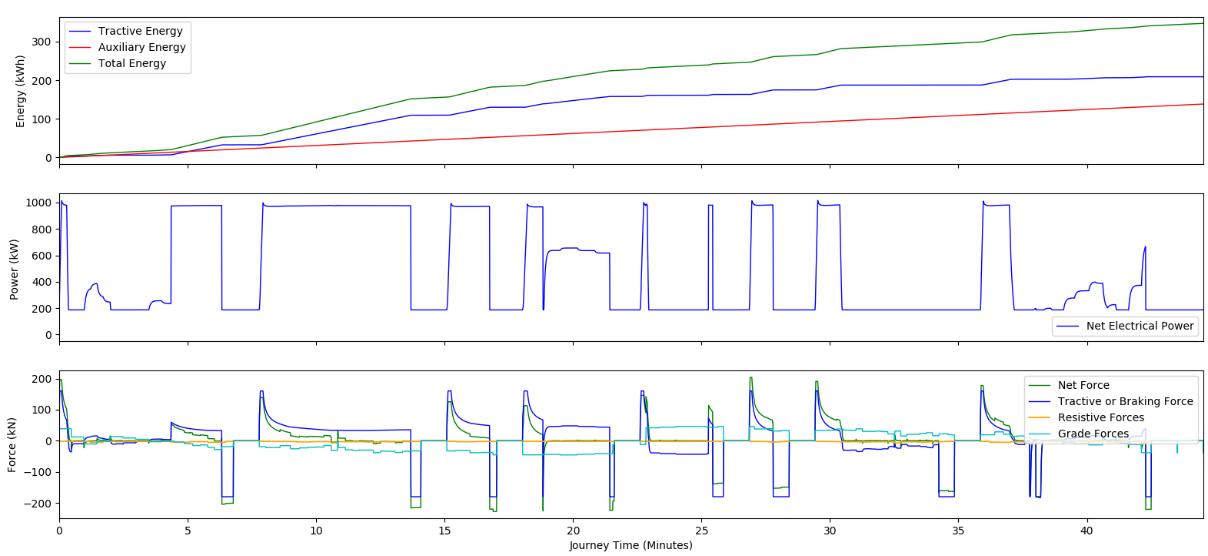
Appendix B - Scenario 2 – 4-Car ZEMU Data

Plots

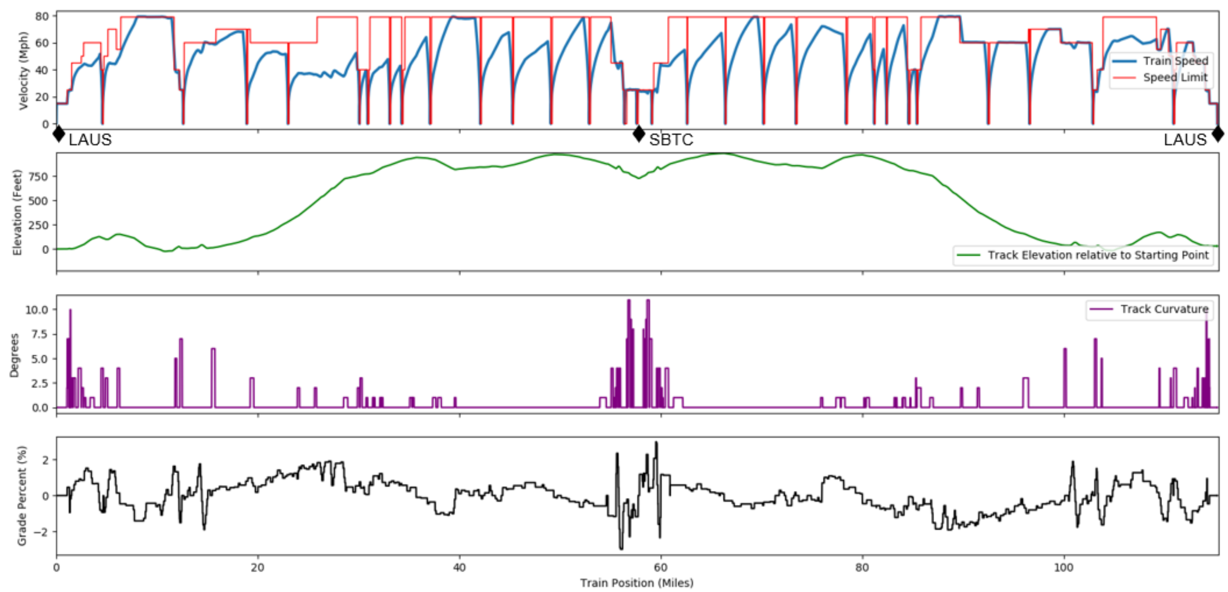
1. RPRP – 4-Car ZEMU Performance



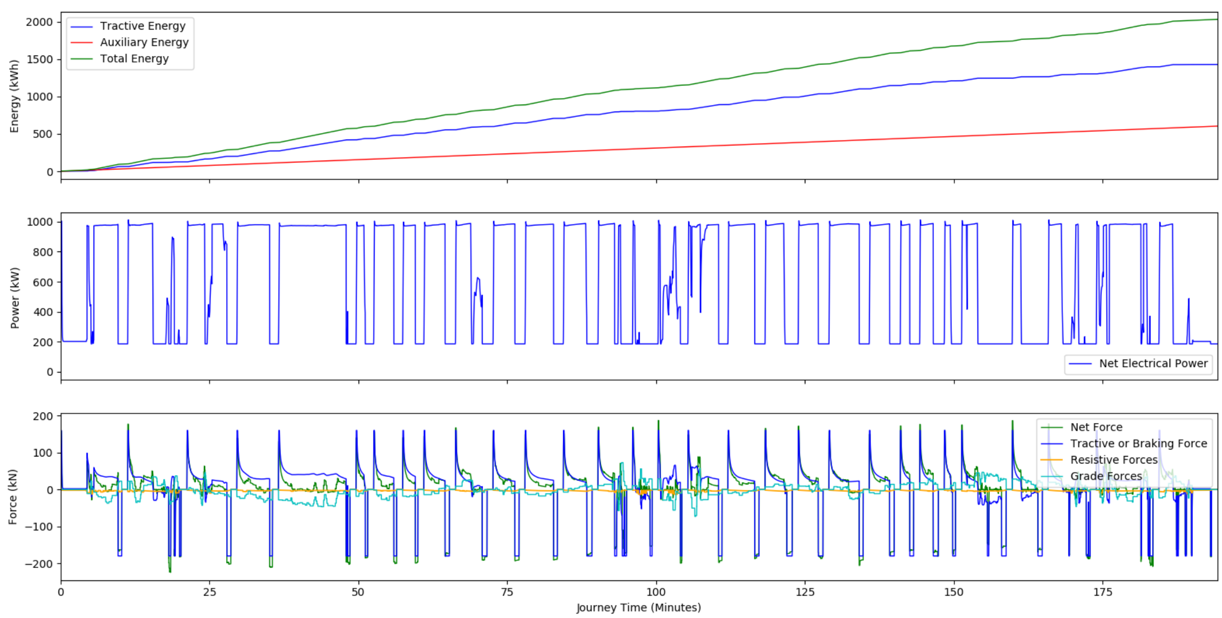
2. RPRP – 4-Car ZEMU Energy, Power, Forces vs. Journey Time



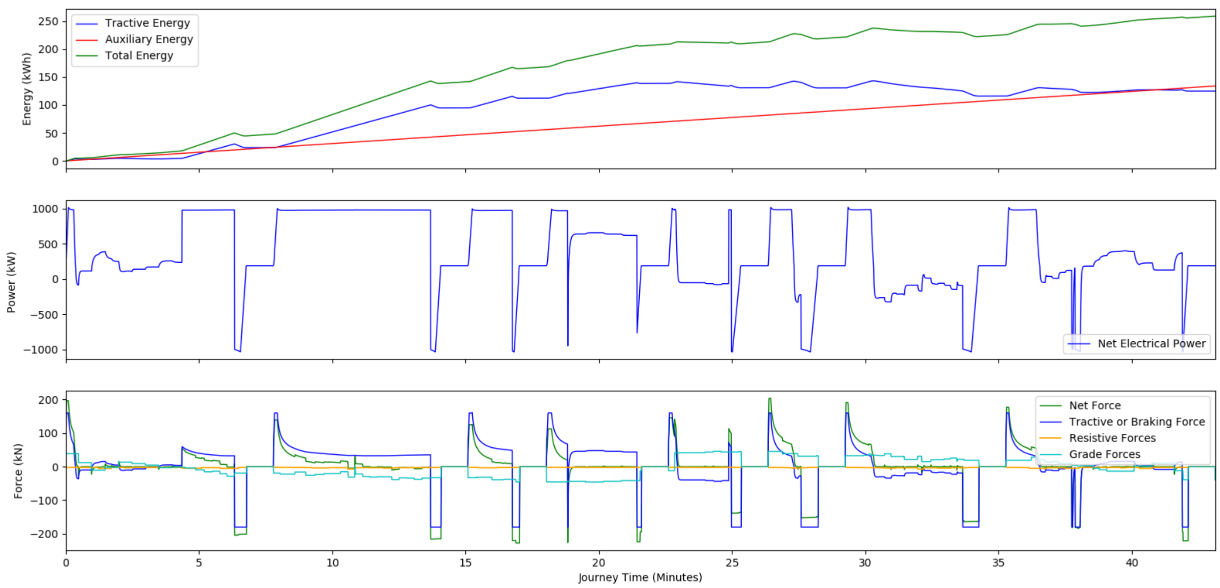
3. San Bernardino Line – 4-Car ZEMU Performance



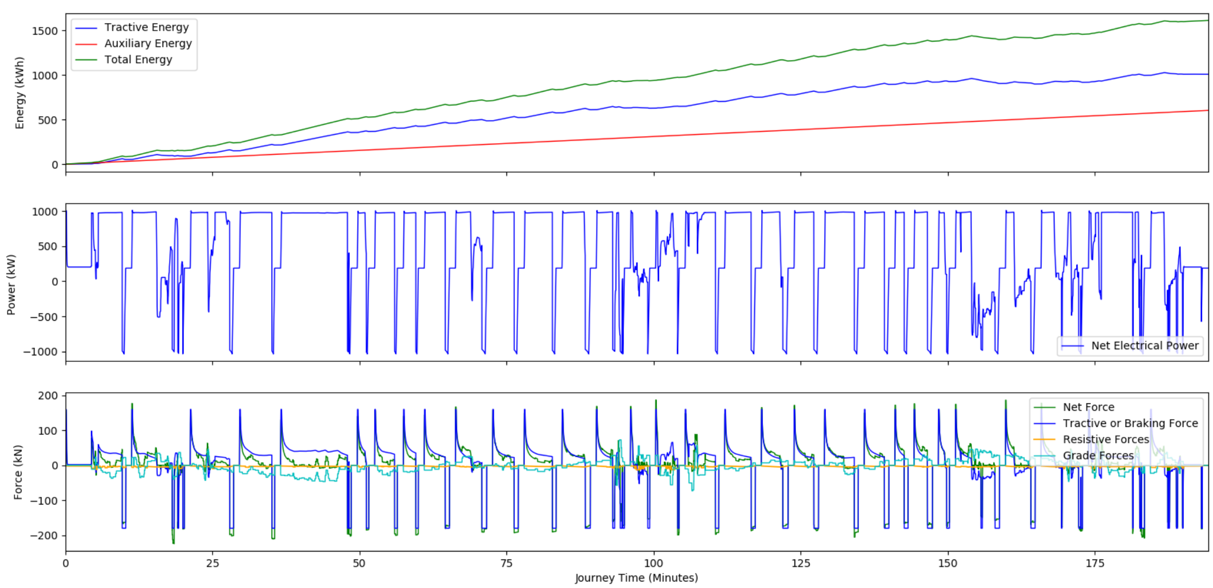
4. San Bernardino Line – 4-Car ZEMU Energy, Power, & Forces vs. Journey Time



5. RPRP – 4-Car ZEMU Energy, Power, Forces with regenerative braking



6. San Bernardino Line – 4-Car ZEMU Energy, Power, Forces with regenerative braking



Tables

1. RPRP – 4-Car ZEMU Energy between Stations

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
SBTC	Tippecanoe	3.23	32.63	21.04	53.67	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Tippecanoe	New York	3.95	76.64	19.54	96.17	-
Dwell	1 minute	-	0.00	3.13	3.13	-
New York	Downtown Redlands	0.69	20.66	6.03	26.69	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Downtown Redlands	University Redlands	1.03	27.90	11.07	38.98	-
Sub Total		**8.89**	**158**	**67**	**225**	**-**
University Redlands	Downtown Redlands	1.03	5.25	10.07	15.32	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Downtown Redlands	New York	0.69	11.63	4.81	16.44	-
Dwell	1 minute	-	0.00	3.13	3.13	-
New York	Tippecanoe	3.95	12.59	16.84	29.44	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Tippecanoe	SBTC	3.22	21.64	20.65	42.29	-
Sub Total		**8.89**	**51**	**62**	**113**	**-**
Total Round Trip		**17.78**	**209**	**129**	**338**	**-**

2. San Bernardino Line - 4-Car ZEMU Energy between Stations

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
LA Union	Cal State LA	4.60	60.45	31.28	91.73	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Cal State LA	El Monte	8.01	58.21	26.94	85.14	-
Dwell	1 minute	-	0.00	3.13	3.13	-
El Monte	Baldwin Park	6.31	70.22	22.10	92.32	-
Dwell	1 minute	-	0.00	3.13	3.13	-

Baldwin Park	Covina	4.10	69.24	17.75	86.99	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Covina	Fairplex	7.10	146.13	36.56	182.69	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Fairplex	Pamona	0.81	15.90	5.72	21.62	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Pamona	Claremont	2.19	42.12	11.36	53.48	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Claremont	Montclair	1.20	25.94	7.48	33.41	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Montclair	Upland	2.80	43.94	12.50	56.43	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Upland	Rancho Cucamonga	5.01	38.06	15.81	53.87	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Rancho Cucamonga	Speedway	3.20	45.25	12.65	57.90	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Speedway	Fontana	3.80	59.73	15.91	75.64	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Fontana	Rialto	3.80	43.93	14.05	57.98	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Rialto	SB Depot	3.50	36.31	14.80	51.11	-
Dwell	1 minute	-	0.00	3.13	3.13	-
SB Depot	SBTC	1.23	4.17	10.01	14.18	-
Sub Total		**57.63**	**759.58**	**298.75**	**1058.33**	**-**
SBTC	SB Depot	1.49	22.88	12.26	35.14	-
Dwell	1 minute	-	0.00	3.13	3.13	-
SB Depot	Rialto	3.50	61.11	17.34	78.45	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Rialto	Fontana	3.80	55.93	15.29	71.23	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Fontana	Speedway	3.79	35.35	13.27	48.62	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Speedway	Rancho Cucamonga	3.22	41.35	12.06	53.41	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Rancho Cucamonga	Upland	4.98	63.50	16.82	80.32	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Upland	Montclair	2.81	42.35	12.21	54.56	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Montclair	Claremont	1.20	19.13	6.47	25.60	-

Dwell	1 minute	-	0.00	3.13	3.13	-
Claremont	Pamona	2.20	27.66	9.03	36.69	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Pamona	Fairplex	0.82	11.51	5.54	17.05	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Fairplex	Covina	7.08	30.00	22.69	52.69	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Covina	Baldwin Park	4.10	15.88	15.16	31.04	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Baldwin Park	El Monte	6.30	33.09	21.35	54.43	-
Dwell	1 minute	-	0.00	3.13	3.13	-
El Monte	Cal State LA	8.00	89.98	28.80	118.77	-
Dwell	1 minute	-	0.00	3.13	3.13	-
Cal State LA	LA Union	4.34	28.78	26.96	55.74	-
Sub Total		**57.63**	**579**	**279**	**858**	**-**
Total Round Trip		**115.26**	**1338**	**578**	**1916**	**-**

3. Energy Results between Terminal Stations for a 4-Car ZEMU

Journey		Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Energy Sum (kWh)	Regenerative Capability (kWh)
SBTC	Redlands	8.89	157.83	67.07	224.90	-19.44
Redlands	SBTC	8.89	51.11	61.76	112.88	-64.84
LA	SBTC	57.63	759.58	298.75	1058.33	-175.78
SBTC	LA	57.63	578.51	279.09	857.60	-243.53
Total		**133.04**	**1547**	**707**	**2254**	**-504**

4. RPRP – 4-Car ZEMU Energy between Stations with regenerative braking

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
SBTC	Tippecanoe	3.23	23.70	21.04	44.74	-8.93
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Tippecanoe	New York	3.95	71.04	19.54	90.57	-5.60
Dwell	1 minute	-	0.00	3.13	3.13	0.00
New York	Downtown Redlands	0.69	17.32	6.03	23.35	-3.34
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Downtown Redlands	University Redlands	1.03	26.33	11.07	37.40	-1.58

Sub Total		8.89	26	11	37	-19
University Redlands	Downtown Redlands	1.03	-9.65	10.07	0.42	-14.90
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Downtown Redlands	New York	0.69	2.20	4.81	7.01	-9.43
Dwell	1 minute	-	0.00	3.13	3.13	0.00
New York	Tippecanoe	3.95	-18.25	16.84	-1.40	-30.84
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Tippecanoe	SBTC	3.22	11.97	20.65	32.62	-9.67
Sub Total		**8.89**	**125**	**132**	**257**	**-84**
Total Round Trip		**17.78**	**151**	**143**	**294**	**-104**

5. San Bernardino Line – 4-Car ZEMU Energy between Stations with Regenerative Braking

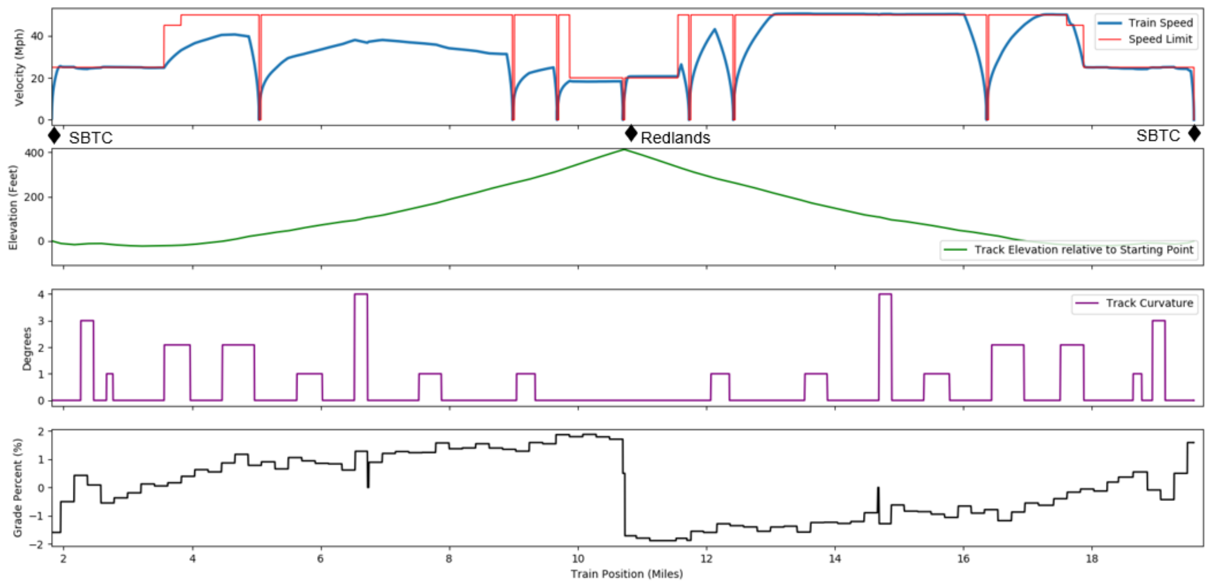
Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
LA Union	Cal State LA	4.60	52.86	31.80	84.66	-9.73
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Cal State LA	El Monte	8.01	36.65	27.76	64.41	-26.24
Dwell	1 minute	-	0.00	3.13	3.13	0.00
El Monte	Baldwin Park	6.31	61.14	22.85	83.99	-13.07
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Baldwin Park	Covina	4.10	64.24	18.60	82.84	-7.39
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Covina	Fairplex	7.10	140.21	37.29	177.50	-8.00
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Fairplex	Pamona	0.81	12.04	6.08	18.12	-5.88
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Pamona	Claremont	2.19	36.57	11.98	48.55	-7.10
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Claremont	Montclair	1.20	20.90	7.94	28.85	-6.14
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Montclair	Upland	2.80	34.35	13.30	47.65	-11.67
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Upland	Rancho Cucamonga	5.01	27.68	16.51	44.19	-14.98
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Rancho Cucamonga	Speedway	3.20	36.39	13.53	49.92	-11.29

Dwell	1 minute	-	0.00	3.13	3.13	0.00
Speedway	Fontana	3.80	52.16	16.82	68.98	-10.08
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Fontana	Rialto	3.80	35.57	14.98	50.55	-14.73
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Rialto	SB Depot	3.50	20.23	14.85	35.08	-21.10
Dwell	1 minute	-	0.00	3.13	3.13	0.00
SB Depot	SBTC	1.23	-3.43	10.19	6.76	-8.38
Sub Total		**57.63**	**628**	**308**	**936**	**-176**
SBTC	SB Depot	1.49	20.72	12.39	33.12	-2.64
Dwell	1 minute	-	0.00	3.13	3.13	0.00
SB Depot	Rialto	3.50	54.89	17.78	72.66	-8.61
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Rialto	Fontana	3.80	46.58	16.22	62.80	-11.87
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Fontana	Speedway	3.79	26.10	14.13	40.23	-15.85
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Speedway	Rancho Cucamonga	3.22	30.91	12.94	43.85	-13.06
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Rancho Cucamonga	Upland	4.98	55.57	17.85	73.42	-10.90
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Upland	Montclair	2.81	32.01	13.04	45.05	-12.43
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Montclair	Claremont	1.20	9.95	6.99	16.94	-10.33
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Claremont	Pamona	2.20	15.50	9.70	25.21	-14.04
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Pamona	Fairplex	0.82	6.56	5.87	12.43	-6.92
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Fairplex	Covina	7.08	-22.16	23.29	1.13	-56.76
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Covina	Baldwin Park	4.10	-5.55	15.65	10.10	-24.46
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Baldwin Park	El Monte	6.30	19.65	21.92	41.57	-18.69
Dwell	1 minute	-	0.00	3.13	3.13	0.00
El Monte	Cal State LA	8.00	77.91	29.52	107.44	-16.82
Dwell	1 minute	-	0.00	3.13	3.13	0.00
Cal State LA	LA Union	4.34	11.74	27.43	39.17	-20.17
Sub Total		**57.63**	**380**	**289**	**669**	**-244**
Total Round Trip		**115.26**	**1008**	**597**	**1605**	**-419**

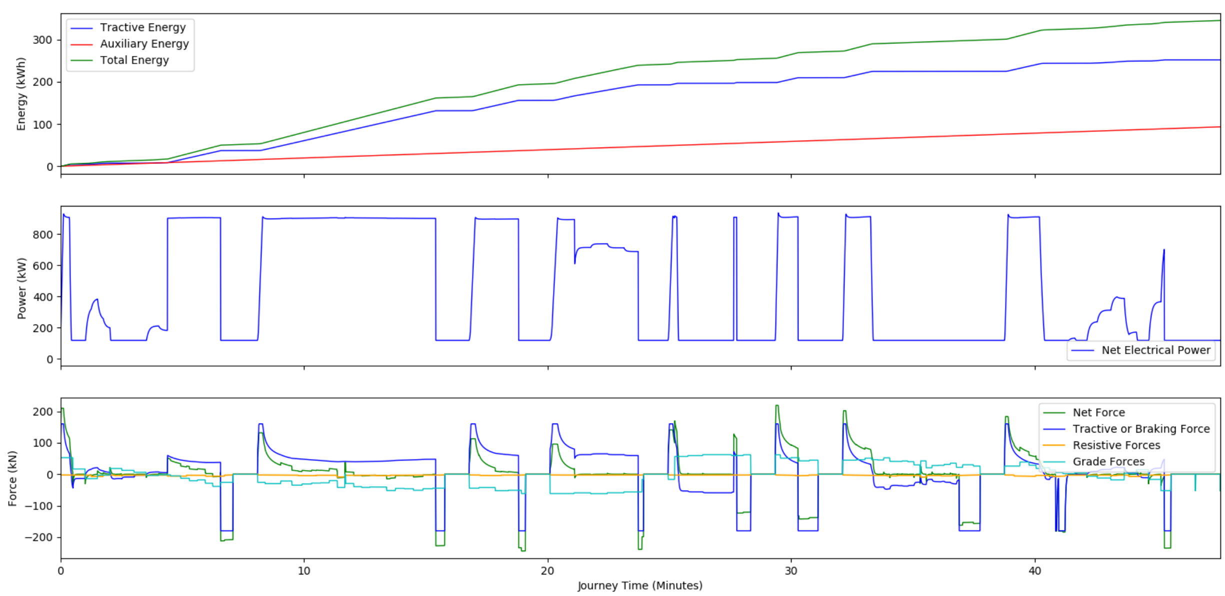
Appendix C - Scenario 3 – 2-Car ZEMU + Inoperable 2-Car DMU Data

Plots

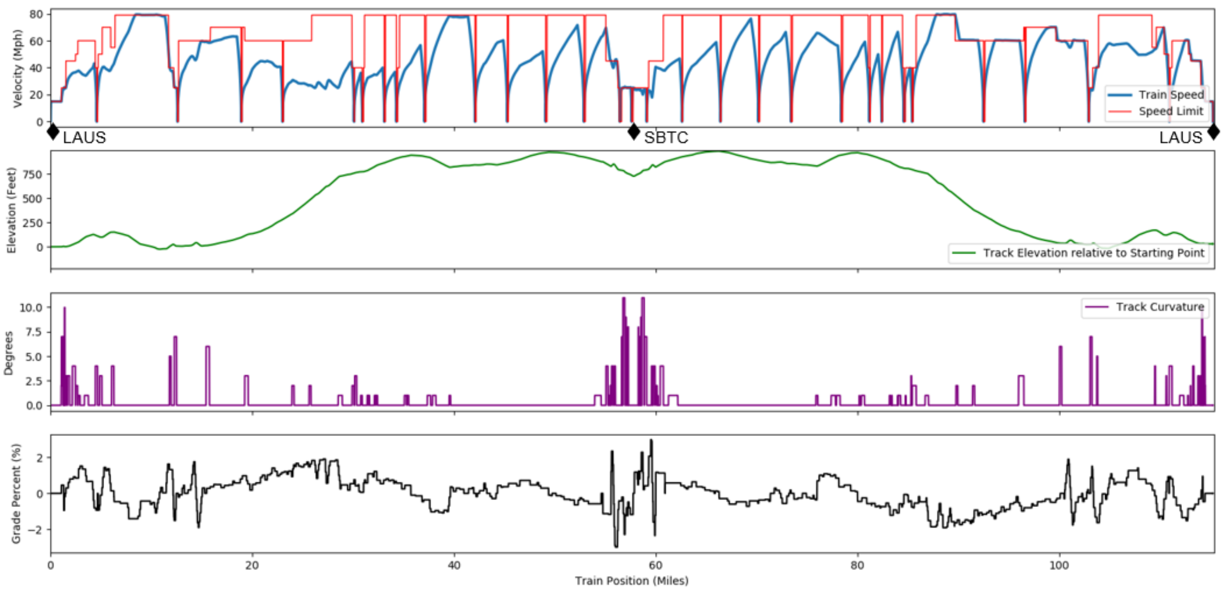
1. RPRP – 2-Car ZEMU + 2 Car DMU Performance



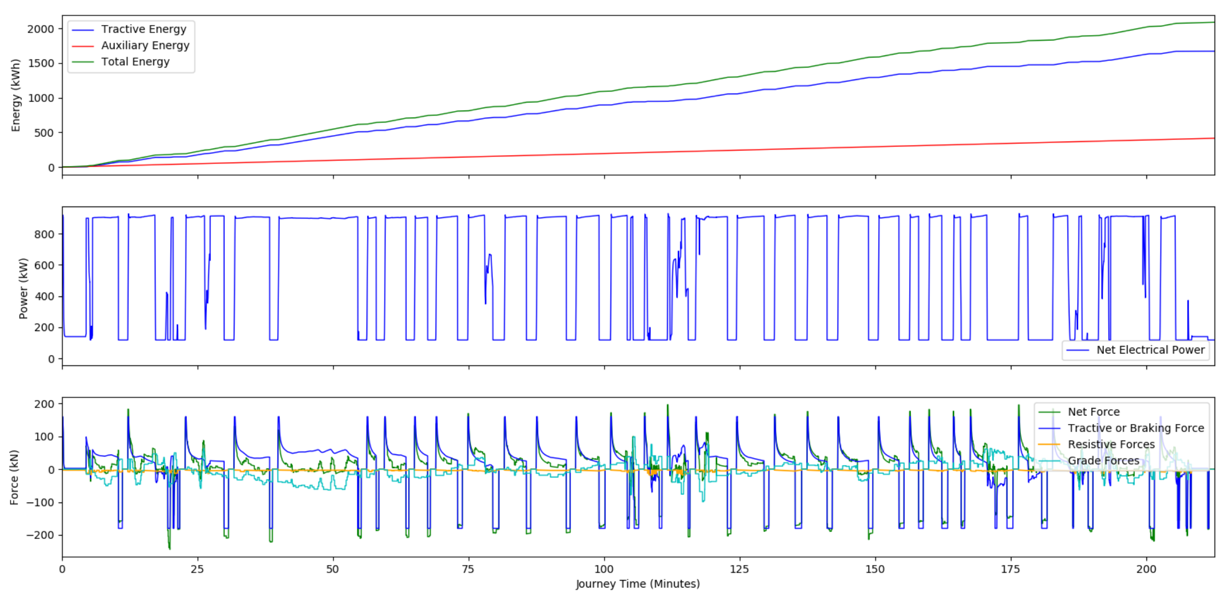
2. RPRP – 2-Car ZEMU + 2 Car DMU Energy, Power, Forces vs Journey Time



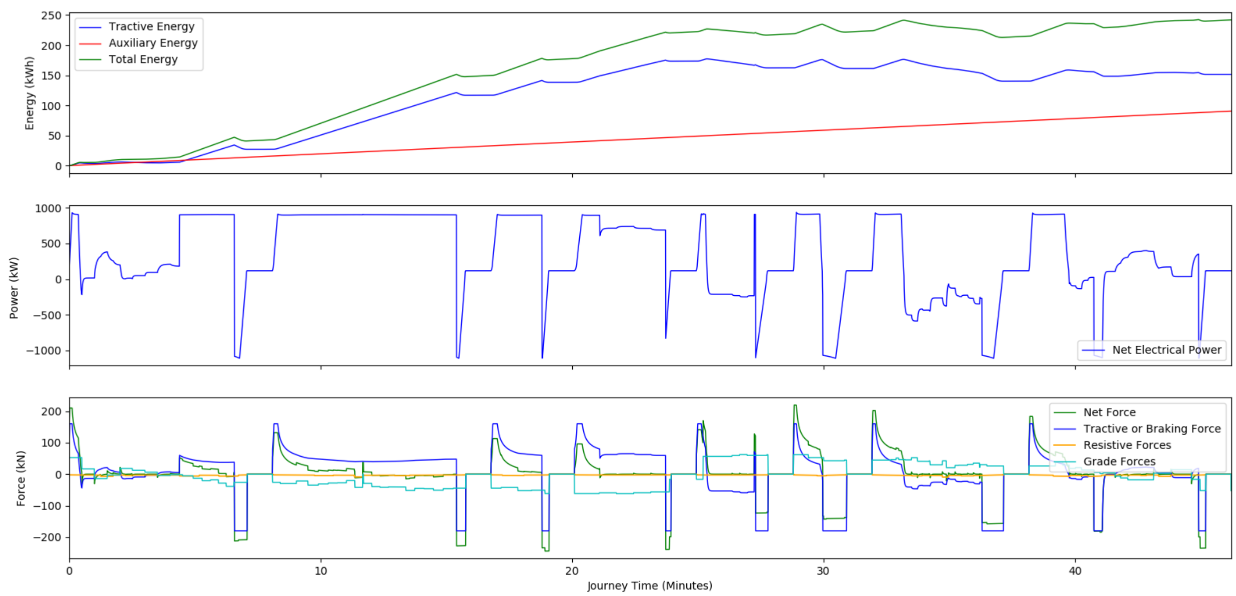
3. San Bernardino Line – 2-Car ZEMU + 2 Car DMU Performance



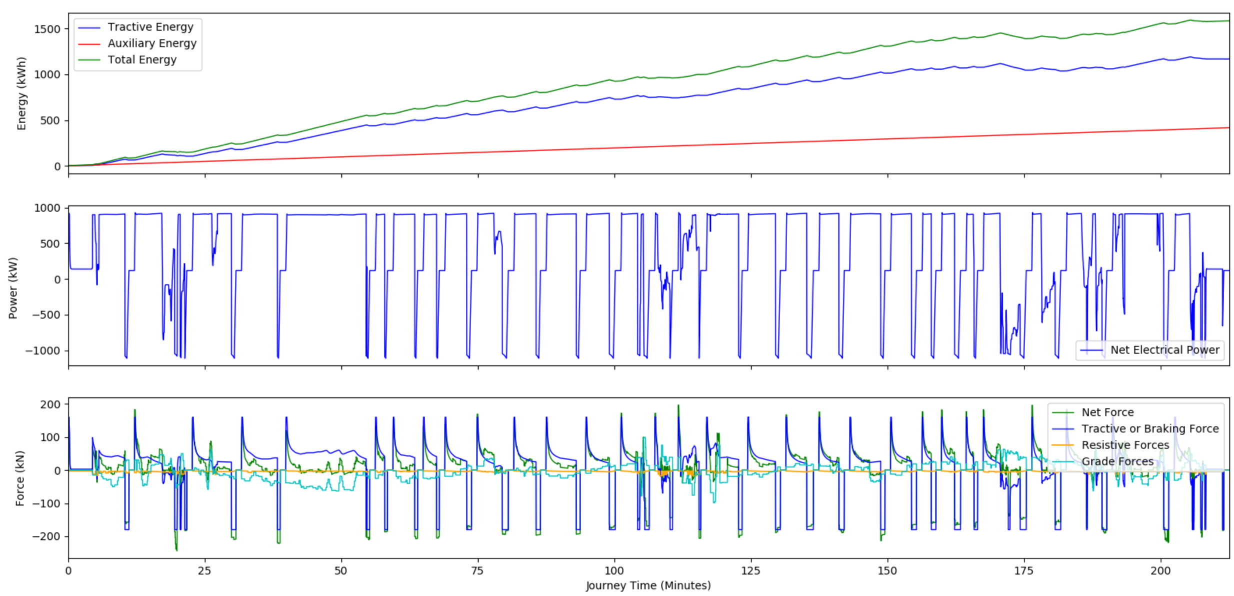
4. San Bernardino Line - 2-Car ZEMU + 2 Car DMU Energy, Power, Forces vs Journey Time



5. RPRP - 2-Car ZEMU + 2 Car DMU Energy, Power, Forces with regenerative braking



6. San Bernardino Line - 2-Car ZEMU + 2 Car DMU Energy, Power, Forces with regenerative braking



Tables

1. RPRP - 2-Car ZEMU + 2 Car DMU Energy between Stations

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
SBTC	Tippecanoe	3.23	37.03	13.85	50.88	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Tippecanoe	New York	3.95	94.34	15.04	109.39	-
Dwell	1 minute	-	0.00	1.97	1.97	-
New York	Downtown Redlands	0.69	24.57	4.52	29.09	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Downtown Redlands	University Redlands	1.03	36.70	7.52	44.23	-
Sub Total		**8.89**	**193**	**47**	**240**	**-**
University Redlands	Downtown Redlands	1.03	5.42	6.64	12.06	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Downtown Redlands	New York	0.69	11.56	3.44	15.00	-
Dwell	1 minute	-	0.00	1.97	1.97	-
New York	Tippecanoe	3.95	14.92	11.05	25.97	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Tippecanoe	SBTC	3.22	27.27	13.36	40.63	-
Sub Total		**8.89**	**59**	**40**	**100**	**-**
Total Round Trip		**17.78**	**252**	**87**	**339**	**-**

2. San Bernardino Line - 2-Car ZEMU + 2 Car DMU Energy between Stations

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
LA Union	Cal State LA	4.60	74.54	21.77	96.30	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Cal State LA	El Monte	8.01	73.31	18.76	92.07	-
Dwell	1 minute	-	0.00	1.97	1.97	-
El Monte	Baldwin Park	6.31	85.65	15.65	101.30	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Baldwin Park	Covina	4.10	84.99	13.85	98.84	-

Dwell	1 minute	-	0.00	1.97	1.97	-
Covina	Fairplex	7.10	190.79	30.14	220.93	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fairplex	Pamona	0.81	21.25	4.41	25.66	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Pamona	Claremont	2.19	51.03	8.81	59.85	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Claremont	Montclair	1.20	30.96	5.79	36.75	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Montclair	Upland	2.80	51.37	9.56	60.93	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Upland	Rancho Cucamonga	5.01	51.71	11.24	62.95	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rancho Cucamonga	Speedway	3.20	52.50	9.56	62.06	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Speedway	Fontana	3.80	71.74	12.27	84.01	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fontana	Rialto	3.80	55.65	10.61	66.26	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rialto	SB Depot	3.50	45.26	10.17	55.43	-
Dwell	1 minute	-	0.00	1.97	1.97	-
SB Depot	SBTC	1.23	6.46	6.40	12.85	-
Sub Total		**57.63**	**947**	**217**	**1164**	**-**
SBTC	SB Depot	1.49	30.82	8.14	38.96	-
Dwell	1 minute	-	0.00	1.97	1.97	-
SB Depot	Rialto	3.50	76.08	12.82	88.91	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rialto	Fontana	3.80	66.10	11.73	77.83	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fontana	Speedway	3.79	49.77	9.87	59.64	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Speedway	Rancho Cucamonga	3.22	47.57	9.09	56.66	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Rancho Cucamonga	Upland	4.98	74.01	12.61	86.62	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Upland	Montclair	2.81	49.29	9.37	58.66	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Montclair	Claremont	1.20	21.29	4.96	26.25	-
Dwell	1 minute	-	0.00	1.97	1.97	-

Claremont	Pamona	2.20	30.87	6.85	37.73	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Pamona	Fairplex	0.82	17.35	4.16	21.51	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Fairplex	Covina	7.08	40.14	15.45	55.59	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Covina	Baldwin Park	4.10	22.44	10.38	32.82	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Baldwin Park	El Monte	6.30	47.83	14.55	62.38	-
Dwell	1 minute	-	0.00	1.97	1.97	-
El Monte	Cal State LA	8.00	112.69	20.23	132.92	-
Dwell	1 minute	-	0.00	1.97	1.97	-
Cal State LA	LA Union	4.34	37.54	17.74	55.28	-
Sub Total		**57.63**	**724**	**196**	**919**	**-**
Total Round Trip		**115.26**	**1671**	**412**	**2083**	**-**

3. Energy Results between Terminal Stations for a 2-Car ZEMU + 2-Car DMU

Journey		Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Energy Sum (kWh)	Regenerative Capability (kWh)
SBTC	Redlands	8.89	192.64	46.86	239.50	-19.21
Redlands	SBTC	8.89	59.17	40.42	99.58	-104.32
LA	SBTC	57.63	947.21	216.62	1163.83	-204.70
SBTC	LA	57.63	723.80	195.60	919.40	-299.86
Total		**133.04**	**1923**	**500**	**2422**	**-628**

4. RPRP - 2-Car ZEMU + 2-Car DMU Energy between Stations with regenerative braking

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
SBTC	Tippecanoe	3.23	27.05	13.85	40.90	-9.98
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Tippecanoe	New York	3.95	89.71	15.04	104.75	-4.64
Dwell	1 minute	-	0.00	1.97	1.97	0.00
New York	Downtown Redlands	0.69	21.58	4.52	26.10	-2.99
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Downtown Redlands	University Redlands	1.03	35.10	7.52	42.62	-1.61

Sub Total		**8.89**	**173**	**47**	**220**	**-19**
University Redlands	Downtown Redlands	1.03	-14.31	6.64	-7.67	-19.74
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Downtown Redlands	New York	0.69	-0.47	3.44	2.97	-12.03
Dwell	1 minute	-	0.00	1.97	1.97	0.00
New York	Tippecanoe	3.95	-26.16	11.05	-15.12	-41.08
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Tippecanoe	SBTC	3.22	15.00	13.36	28.36	-12.27
Sub Total		**8.89**	**147**	**89**	**237**	**-104**
Total Round Trip		**17.78**	**321**	**136**	**457**	**-124**

5. San Bernardino- 2-Car ZEMU + 2-Car DMU Energy between Stations with regenerative braking

Station A	Station B	Section Length (Miles)	Tractive Energy (kWh)	Auxiliary Energy (kWh)	Section Energy Sum (kWh)	Section Regenerated Energy (kWh)
LA Union	Cal State LA	4.60	63.61	21.77	85.38	-10.92
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Cal State LA	El Monte	8.01	41.94	18.76	60.70	-31.37
Dwell	1 minute	-	0.00	1.97	1.97	0.00
El Monte	Baldwin Park	6.31	72.40	15.65	88.04	-13.26
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Baldwin Park	Covina	4.10	77.98	13.85	91.83	-7.01
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Covina	Fairplex	7.10	182.06	30.14	212.20	-8.73
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Fairplex	Pamona	0.81	14.19	4.41	18.60	-7.06
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Pamona	Claremont	2.19	43.62	8.81	52.43	-7.42
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Claremont	Montclair	1.20	24.37	5.79	30.16	-6.59
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Montclair	Upland	2.80	37.43	9.56	47.00	-13.93
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Upland	Rancho Cucamonga	5.01	33.26	11.24	44.50	-18.45
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Rancho Cucamonga	Speedway	3.20	39.30	9.56	48.86	-13.20

Dwell	1 minute	-	0.00	1.97	1.97	0.00
Speedway	Fontana	3.80	60.56	12.27	72.83	-11.18
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Fontana	Rialto	3.80	37.26	10.61	47.87	-18.39
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Rialto	SB Depot	3.50	19.20	10.17	29.37	-26.06
Dwell	1 minute	-	0.00	1.97	1.97	0.00
SB Depot	SBTC	1.23	-4.69	6.40	1.71	-11.15
Sub Total		**57.63**	**743**	**217**	**959**	**-205**
SBTC	SB Depot	1.49	27.53	8.14	35.67	-3.29
Dwell	1 minute	-	0.00	1.97	1.97	0.00
SB Depot	Rialto	3.50	66.67	12.82	79.49	-9.41
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Rialto	Fontana	3.80	52.23	11.73	63.97	-13.87
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Fontana	Speedway	3.79	29.59	9.87	39.47	-20.18
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Speedway	Rancho Cucamonga	3.22	31.63	9.09	40.72	-15.94
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Rancho Cucamonga	Upland	4.98	62.06	12.61	74.68	-11.94
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Upland	Montclair	2.81	34.19	9.37	43.55	-15.10
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Montclair	Claremont	1.20	8.41	4.96	13.37	-12.88
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Claremont	Pamona	2.20	12.90	6.85	19.76	-17.97
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Pamona	Fairplex	0.82	8.29	4.16	12.45	-9.06
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Fairplex	Covina	7.08	-31.51	15.45	-16.06	-71.65
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Covina	Baldwin Park	4.10	-9.39	10.38	0.99	-31.83
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Baldwin Park	El Monte	6.30	23.87	14.55	38.43	-23.96
Dwell	1 minute	-	0.00	1.97	1.97	0.00
El Monte	Cal State LA	8.00	94.52	20.23	114.76	-18.16
Dwell	1 minute	-	0.00	1.97	1.97	0.00
Cal State LA	LA Union	4.34	12.92	17.74	30.66	-24.62
Sub Total		**57.63**	**424**	**196**	**620**	**-300**
Total Round Trip		**115.26**	**1166**	**412**	**1579**	**-505**

6. Comparison of Energy Results for each Scenario

Journey		Section Length (Miles)	Energy Between Terminals					
			Scenario 1 2-Car ZEMU		Scenario 2 4-Car ZEMU		Scenario 3 2-Car + 2-Car	
			No Regen. Braking (kWh)	With Regen. Braking (kWh)	No Regen. Braking (kWh)	With Regen. Braking (kWh)	No Regen. Braking (kWh)	With Regen. Braking (kWh)
SBTC	Redlands	8.89	157.59	140.93	224.90	205.45	239.50	220.29
Redlands	SBTC	8.89	78.36	32.13	112.88	48.04	99.58	14.47
LA	SBTC	57.63	811.77	672.23	1058.33	882.55	1163.83	959.13
SBTC	LA	57.63	680.56	496.54	857.60	614.06	919.40	619.55
Total		**133.04**	**1728**	**1342**	**2254**	**1750**	**2422**	**1813**

C. Power Transfer and Charging Infrastructure Evaluation Matrix

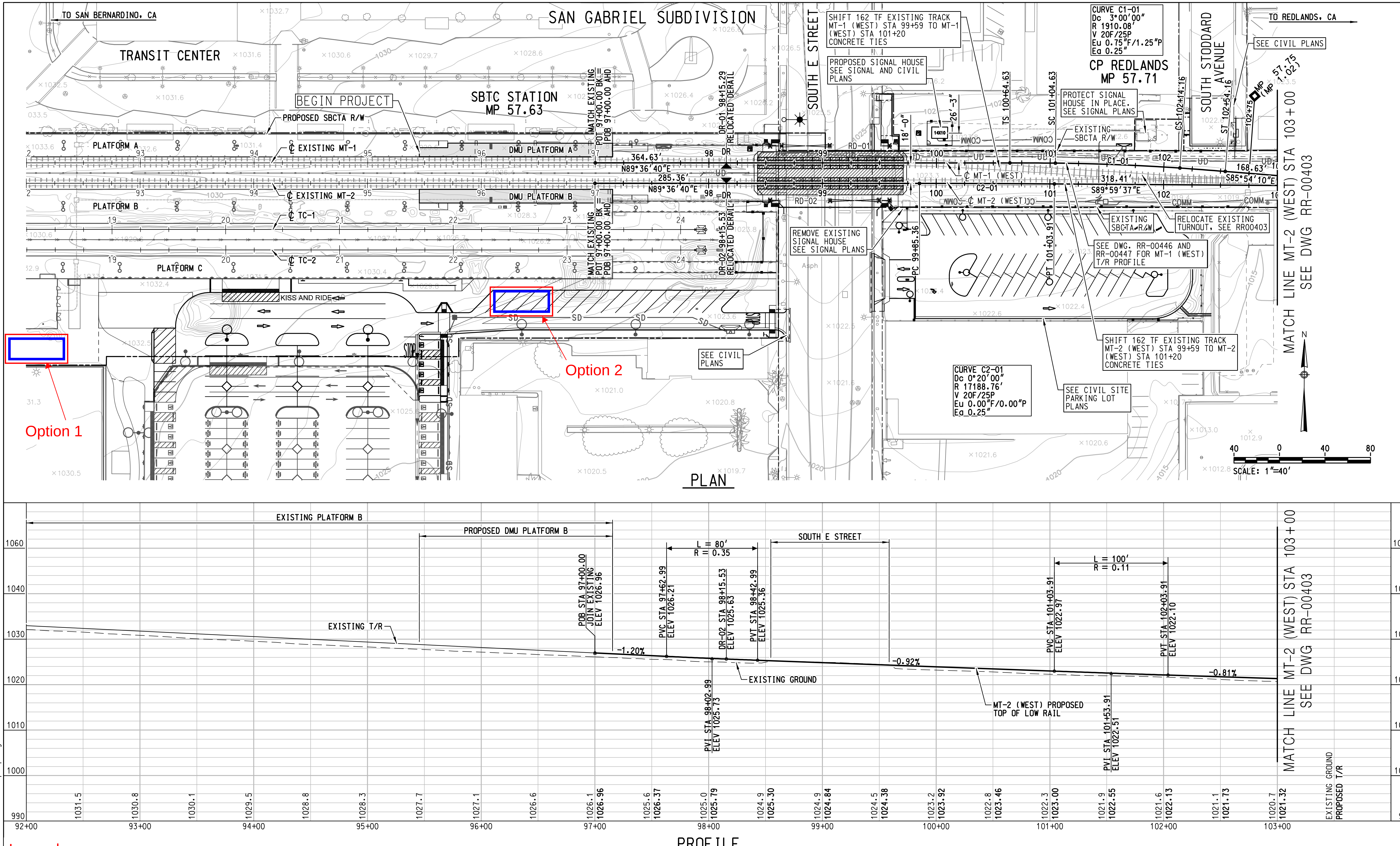
				Aspects of Charging						
Technology Alternatives for Vehicle Power Supply				Power Supply			Power Transfer (Power Supply to Train Station)		Station to Vehicle Interface	
Specific Types				Wayside Energy Storage System (WESS)	TPSS + WESS	Traction Power Sub-Station (TPSS)	Underground Cabling	Overhead Cabling	Conductive	Inductive
Description				A bank of energy storage devices (battery, supercapacitor, flywheel) that receives power from the grid to be stored until transferred at high rates into the vehicle. Enables a lower peak power demand from the grid than traditional TPSS.	A combination of WESS and a TPSS. Both could be utilized to charge a ZEMU. A WESS bank could be slow charged by 400V/120-240V at lower power. The WESS would discharge power to charge the ZEMU, while the TPSS could be utilized for fast charging alternatively. There are a multitude of schemes regarding this dual method.	A substation specifically designed to convert high voltage AC power from the grid to lower voltage DC power that is directly supplied to the vehicle.	Electrical cabling buried under the ground used for power transmission and distribution.	Electrical cabling that is suspended and utilized for power transmission or distribution.	The vehicle draws electrical power from an overhead catenary system or charging pad/bar at a specific stoppped location, to recharge the OESS.	Means of wireless power transfer utilized to charge the energy storage device on a vehicle dynamically or statically. Inductor coils located in the track bed (primary) induce current in pick-up coils (secondary) located onboard the train, which then deliver power to charge an energy storage device. Inductive charging devices today also contain resonant circuits (LC circuits) to improve signal strength and range.
Suppliers				ABB, Centum Adetel, Maxwell, SAFT. *Generally any manufacturer of batteries, supercapacitors, and/or flywheel technology.	/	ABB, Centum Adetel, Utilities, Construction firms.	/	/	All major vehicle suppliers, Furrer+Frey (RailBaar), SchaeferPower	WAVE *Has not been implemented, but could be done.
Evaluation Criteria										
	Weighting		*Weighting*							
Cost	**0.20**	Cost - Capital	0.08	Moderate to expensive. Depends on the type of energy storage utilized (new battery/SC/flywheel system vs second life batteries, etc) and its size. Ideally a 1-3 MWh energy storage bank will be used for the ZEMU project to minimize power demand requirements from the grid. Expected to cost $1-3 million per system at each terminal station.	Highest cost due to the upfront cost of a TPSS + the WESS bank.	The general number of components required for a substation specific to charging a battery ZEMU will be less than a typical TPSS, but cost will likely be $1-$3 million per system at each terminal station. High upfront cost for transformer and rectifier + protection circuitry and installation.	Underground electrcial routing is more expensive and varies based on system voltage. These extra cost ranges in comparison to overhead lines are common: Transmission ($V_{line} \geq 69kV$): 4-20 times extra cost, Subtransmission ($25kV \leq V_{line} \leq 69kV$): 4 - 20 times extra cost, Distribution ($V_{line} <$ 25kV): 2-10 times extra cost. Extra cost can be attributed to extra cable insulation, underground surveying/excavation, splicing vaults , concrete-encased conduit to protect cabling.	Generally half the cost of underground powerlines due to less overall equipment and lower construction cost. It should be noted that both the construction for underground/overhead power are both considerably expensive.	The overall cost of implementing charging for an OESS depends on a multitude of factors. One key area is how much power will be required from the Utility line and if there is current infrastructure that can deliver this required power. If a substation is required to power the charging segement, cost will significantly increase. Design with overhead charging is simple and could result in lowest cost of the charging alternatives.	The overall cost of implementing charging for an OESS depends on a multitude of factors. One key area is how much power will be required from the utility line and if there is current infrastructure that can deliver this required power. If a modular substation is required to power the charging segement, cost will significantly increase. The upfront cost of the circuitry for inductive charging is high and the technology is still immature.
		Cost - Operations (energy + power costs)	0.06	Can significantly reduce electricity costs by lowering utility demand charges ($/kW).	Higher than the operations cost of a WESS only, but lower than operation cost of intermittently drawing high grid power in the case of TPSS. Highly dependent on how often the TPSS would be utilized.	Very high demand charges ($/kW) supplying an intermittent service is an inefficient use of the power demand.	If properly sized/suited for the application, should have little effect on the energy efficiency and generally should only be small addition to operations cost.	If properly sized/suited for the application, should have little effect on the energy efficiency and generally should only be small addition to operations cost.	Depends on number of charging points and level of power they draw from the grid. Greater amounts of charging stations drawing high power within short intervals may result in higher than expected operations cost from an energy standpoint.	Depends on number of charging points and level of power they draw from the grid. Greater amounts of charging stations drawing high power within short intervals may result in higher than expected operations cost from an energy standpoint.
		Cost - Life Cycle (maintenance)	0.06	Will depend on the type of energy storage utilized. Adequate charge levels will need to be maintained for supercapacitors/batteries to prolong the lifespan in a similar manner to an OESS. Replacement cost may be mitigated by using second life batteries.	More maintenance due to having two systems with more equipment.	Generally low maintenance. Mostly required for the substation transformers.	Life span of buried cables are generally about half that of overhead lines. More scheduled maintenance is needed to prolong system life and is more expensive. This may also disrupt utility service and/or impact other utility structures.	Generally low maintenance.	Moderate. Depends if the conductive charging is overhead or ground based. Ground based components may need more regular maintenance, which may effect service schedule. Also, highly dependent on number of charging points.	Moderate. System is wireless, but the amount of additional control electronics that require maintenance may increase life cycle costs in addition to the high upfront cost.
Infrastructure	**0.10**	Additional ROW or land acquisition required	0.02	WESS's anticipated to fit within ROW or station area because of smaller size than TPSS's.	Some options may not fit within ROW, but can be in close proximity to ROW and/or station. The options are still within final EIR study area, so a supplemental EIR is not required.	Some options may not fit within ROW, but can be in close proximity to ROW and/or station. The options are still within final EIR study area, so a supplemental EIR is not required.	Underground lines generally require less right of way and can reduce the amount of vegetation clearing. However, trench depth and excavation stockpiling widths require very similar ROW widths for overhead lines. For this reason, these are rated the same.	Need to refer to Utility Overhead power line standards/requirements.	Anticipated to be within station area, no land acquisition is anticipated.	Anticipated to be within station area, no land acquisition is anticipated.

Specific Types				Wayside Energy Storage System (WESS)	TPSS + WESS	Traction Power Sub-Station (TPSS)	Underground Cabling	Overhead Cabling	Conductive	Inductive
Environmental Considerations	**0.15**	Land use compatibility	0.01	Additional infrastructure anticipated to be within area zoned for transportation land use.	Additional infrastructure anticipated to be within area zoned for transportation land use.	Additional infrastructure anticipated to be within area zoned for transportation land use.	Additional infrastructure anticipated to be within area zoned for transportation land use.	Additional infrastructure anticipated to be within area zoned for transportation land use.	Additional infrastructure anticipated to be within area zoned for transportation land use.	Additional infrastructure anticipated to be within area zoned for transportation land use.
		Potential Greenhouse Gas Emissions (at point of use)	0.06	Zero-Emission solution at point of use.	Zero-Emission solution at point of use.	Zero-Emission solution at point of use.	Zero-Emission solution at point of use.	Zero-Emission solution at point of use.	Zero-Emission solution at point of use.	Zero-Emission solution at point of use.
		Recyclability of components	0.03	Battery and supercapacitor cells can be recycled to retrieve certain metals, however the applications and commercial viability can be limited. A WESS is an opportunity to reuse second life batteries.	Battery and supercapacitors cells can be recycled to retrieve certain metals, however the application and commercial viability can be limited. A WESS is an opportunity to reuse second life batteries.	Components can easily be reused.	Components can easily be reused.	Components can easily be reused.	Components can easily be reused.	Components can easily be reused.
		High voltage clearance requirements	0.01	Feasible clearance requirements.	Feasible clearance requirements.	Feasible clearance requirements.	Requirements for high/medium voltage buried cables are stricter. Refer to National Electrical Safety Code (NESC), IEEE, NEC.	Feasible clearance requirements.	Refer to National Electrical Safety Code (NESC)	Refer to National Electrical Safety Code (NESC)
		Socio-economic impacts of infrastructure	0.01	New propulsion technology has potential to create new supporting job opportunities for the local community. Energy availability for trickle charging intended for WESS and also for the local community should be considered. This should be done to avoid increasing costs for the local community due to increased energy consumption.	New propulsion technology has potential to create new supporting job opportunities for the local community. Energy availability for the local community should be considered, to avoid increasing costs for the local community due to increased energy consumption.	New propulsion technology has potential to create new supporting job opportunities for the local community. Energy availability for the local community should be considered, to avoid increasing costs for the local community due to increased energy consumption.	New propulsion technology has potential to create new supporting job opportunities for the local community.	New propulsion technology has potential to create new supporting job opportunities for the local community.	New propulsion technology has potential to create new supporting job opportunities for the local community.	New propulsion technology has potential to create new supporting job opportunities for the local community.
		Aesthetics	0.02	Container sized module required to be placed near station.	Container sized module required to be placed near station.	Container sized module required to be placed near station.	Good. Is becoming more desired by commercial and residential customers.	Moderate to poor. Depends on the complexity of design and envrionment which the overhead lines are implemented in.	Moderate. Having equipment in track bed or overhead conductive bar on platform could look not as aesthetically pleasing	Moderate. Having equipment in track bed or overhead conductive bar on platform could look not as aesthetically pleasing
		Noise	0.02	Low acoustical noise.	Will have acoustical noise characteristics in between that of a WESS and TPSS. The larger the substation, the larger the hum.	Medium Voltage substation equipment does cause light amount of noise (typical substation buzz or hum) due to EMF, but this will only be at the substation that would provide power to the actual ground based charging equipment.	Low acoustical noise.	Likely more acoustic noise compared to buried cables that are isolated, but still insignificant.	Medium Voltage substation equipment does cause light amount of noise (typical substation buzz) due to electromotive force (emf) , but this will only be at the substation that would provide power to the actual ground based charging equipment.	May have sufficient acoustic noise at the vehicle when charging. Large amounts of current induced in pick-up coils results in large induced emf that may cause louder 'humming' during vehicle charging.

Specific Types				Wayside Energy Storage System (WESS)	TPSS + WESS	Traction Power Sub-Station (TPSS)	Underground Cabling	Overhead Cabling	Conductive	Inductive
		EMI / EMC	0.03	Will need to be assessed based on the technology chosen for the WESS. I.e. , but should be isolated enough to not disturb / cause interference to other systems.	The TPSS would be the main concern of EMI / EMC, but both systems together should still be relatively compatible.	Large magnetic fields of cabling due to high current draw, but EMI should be minimal if TPSS is properly isolated from other systems.	Since cabling is buried, EM fields are more isolated from other circuitry on ZEMU vehicle.	EMI is relatively minimal and is more of an issue with HV transmission systems.	EMI is low granted that equipment is properly isolated form other systems.	Higher inductance poses larger risk of EMI. Not many standards/testing done for these types of systems specific to rail applications.
		Performance (efficiency)	0.05	Losses due to internal impedance parameters of batteries/supercaps, but this is very minimal. Losses will increase over time as the WESS state of health and capacity diminishes.	Will depend on how much of the power is dissipated from the WESS. The more power delivered by the WESS (batteries or supercapacitors), the more losses due to state of charge and internal impedance.	TPSS should be as close to charging equipment as possible to minimize losses. Higher voltages/larger cabling is required to minimize losses if power must be delivered over longer distances.	Slightly inefficient at higher voltages/higher power compared to overhead cabling. Cables for power distribution/transmission applications are always sized/designed accordingly such that no greater than 5% voltage drop occurs.	Most efficient in power transfer. Cables are sized/designed for application to adhere to standards such that no more than 5% voltage drop occurs.	Small losses as power to conductive segements is continously supplied from the grid. Any charging source will be limited by max/continuous currents energy storage can accept.	Inductive technology today for EV and Bus charging has reached up to 95% efficiency. Any charging source will be limited by max/continuous currents energy storage can accept.
		Peak Power Demand from Utility	0.08	Can reduce peak demand from utility. The amount of power utilized to charge up the WESS before it charges the OESS on the ZEMU should be minimized.	Reduced utility demand in comparison to drawing high power from TPSS. Rated as 4 here in the case that high power is temporarily drawn directly from a TPSS to rapid charge the ZEMU or WESS.	The ZEMU will require sufficiently high power draw for charging. Drawing high power intermittently can result in increased utility rate and poses higher risk of outages in the local area.	Little effect on peak demand from utility.	Little effect on peak demand from utility.	Dependent on the power supply. If power is supplied intermittently from the grid instead of a WESS, yearly utility demand cost will be significantly higher.	Dependent on the power supply. If power is supplied continuously from the grid instead of a WESS, utility demand over time will be considerably higher.
		Operational Compatibility	0.01							
		Life span (before replacement)	0.01	Depends on combination/type of energy storage utilized.	Will need to replace the WESS components before substation components.	Mainly depends on the transformer. Life expectancy of 25-30 years.	Life span of buried cables are generally about half that of overhead lines. More scheduled maintenance is needed to prolong system life and is more expensive. This may also disrupt utility service and/or impact other utility structures.	Long life span if sized and maintained properly. 30-40 years.	Ground based conductive charging components are more susceptible to contaminants and dust, which may result in components needing replacement earlier than expected, but overhead charging will likely have long life span.	Ground based charging components are more suceptible to contaminants. But should have long life expectancy as long as properly enclosed and maintained.
Operations	**0.25**	Availability of Warranty	0.01	Warranty may be limited, due to maturity of the possible technologies utilized in a WESS bank.	The limited availability of warranty for a WESS reduces the overall ranking compared to a TPSS by itself.	Equipment manufacturer of substation components should all have available warranty.	Manufacturer should be able to provide warranty	Manufacturer should be able to provide warranty	Due to maturity of technology, warranty may be limited.	Due to maturity of technology, warranty may be limited.
		Reliability	0.05	Moderate reliability due to discharging nature of WESS. If WESS state of charge runs low unexpectedly or needs to charge multiple vehicles at the same time, it would be a wise option to have alternative fast charging from the grid.	Hybrid system results in more reliability. Either system can be used as an alternative means to provide charging power when one system fails or is interrupted. I.e. If the TPSS intermittently draws a large amount of power that results in a system outage, then the WESS could be used as a back-up and vice versa.	Reliable means of feeding power to charging system for a battery powered ZEMU.	Less reliable than overhead. Underground lines are much less susceptible to storm/weather related outages than overhead, but if an outage occurs the repair time is signficantly longer. Studies show that repair time could be up to a 50% increase.	Very reliable. More suceptible to storm/weather outages, but can generally be repaired with ease.	Reliability is based primarily on the supply system providing power to the conductive charging bar or undervehicle segments. However, ground based conductive pads may present more reliability if designed such that if one pad loses power, other segments still provide charge to the OESS.	Reliability is based primarily on the supply system providing power to the inductive segments. Should be designed such that if one inductive pad loses power, the other pads can still charge the OESS.
		Maturity of technology	0.03	Moderate. Depends on the type of energy source utilized (supercaps, batteries, flywheels etc.).	Rated as a four due to the maturity characteristics of a WESS.	Very Mature.	Mature. Distribution and subtransmission has been widely implemented underground for a long time, while HV buried transmission lines are becoming more prevalent if applicable/economical for better aesthetics.	Very Mature.	Moderate. Conductive charging pads placed under the vehicle are not widely implemented. Overhead charging schemes are the most prevalent in the rail industry to date.	Not prevalent in the rail vehicle industry thus far. Innovation and implementation is growing very quickly in the electric car and electric bus industry.
		Scalabillity (Network Extendability)	0.03	Easily scalable. Depends on what grid infrastructure is readily available. If connection to the grid is feasible, implementing multiple WESS is a feasible option.	In between the network extension characteristics of a WESS & TPSS alone.	Extending the electrification results in more construction and planning for additonal substations. Substations are generally 1-2 miles apart.	Underground systems are more physically challenging to modify than overhead systems.	Generally more feasible to install more overhead lines for network extendability compared to buried power lines.	Depends more so on the power supply infrastructure available. Feasible for network extensions as long as adequate grid power or WESS power is supplied.	Depends more so on the power supply infrastructure available. Feasible for network extensions as long as adequate grid power or WESS power is supplied.

Specific Types				Wayside Energy Storage System (WESS)	TPSS + WESS	Traction Power Sub-Station (TPSS)	Underground Cabling	Overhead Cabling	Conductive	Inductive
		Scalability (Increase throughput)	0.03	To increase throughput, the instantaneous power needed to charge a ZEMU would be the same, but it would be done more often. To do this reliably with a WESS, the size of the bank would need to increase. I.e. if the headways were to decrease by half, then the energy density of the WESS would need to double.	In between the network extension characteristics of a WESS & TPSS alone.	Good scalability in terms of throughput. Grid can easily supply necessary instantaneous power during charging for extended periods of time, whereas decreasing headways with a WESS would require a much more energy dense system.	Good. This area depends primarily on the power supply and station to vehicle interface for the complete charging system.	Good. This area depends primarily on the power supply and the station to vehicle interface for the complete charging system.	As long as the system is receiving adequate power from a supply, increasing throughput should not be an issue.	As long as the system is receiving adequate power from a supply, increasing throughput should not be an issue.
Regulatory Compliance	**0.10**	FRA, NFPA, CFR, Electrical Codes etc.	0.10	Currently, no specific power source standards for rail industry. There is more direction in the UK/Europe from examples where WESS has been implmented to recover regenerative braking energy on overhead electrified networks.	Standards readily available for TPSS, but no specific standards for WESS application.	Standards readily available and easily compliant.	Many standards/codes available. Easily compliant.	Many codes standards/codes available. Easily compliant.	Not many applicable standards, but there are a a small number of examples where an overhead charging bar has been implemented with buses or light rail vehicles, which may give guidance.	Requirements/standards may need to be developed specifically for rail vehicle applications. This type of charging has been only implemented for buses. Some standards that may have useful information or be referenced are SAE - J2954, J2847/6, J1773, IEEE - P2100.1, C95.1, and ISO - 19,363
Implementaion Schedule	**0.10**	Time for Planning, Design, Construction Phases	0.10	Will depend on the size of the WESS bank. Assuming the physical footprint of a WESS enclosure is smaller than a typical TPSS, this may result in less time for construction.	Requires considerable time for planning for both systems.	Will require considerable time and planning for installation.	Considerable planning will be needed to find most feasible routing path that does not decrease energy efficiency, interfere with other systems, and that complies with standards.	Considerable planning will be needed to find most feasible routing path that does not decrease energy efficiency, interfere with other systems, and that complies with standards.	Considerable amount of planning will need to be done ensuring the power supply and method of transfer interface properly with the charging circuitry.	Considerable amount of planning will need to be done ensuring the power supply and method of transfer interface properly with the charging circuitry.
Risk Analysis	**0.10**	Impact on Utility Service or Infrastructure	0.02	Poses less risk due to the ability of a WESS to reduce demand from grid at peak times during the day.	Will depend on how much of the power is delivered from the WESS at peak times. Favoring the WESS in the hybrid system will help mitigate the risks on utility service/infrastructure.	It is likely the ZEMU will require 500-1500 kW of possible charging power. If only a TPSS were utilized, drawing this amount of range of kW intermittently poses risk of service outages as well as the possibility of increased energy cost rate for the SBCTA if it will adversely affect the power distribution to other customers.	Should be planned/designed to not impact utility service or infrstrucutre by adhering to correct standards/clearances. As noted, maintenance on underground cables is more likely to cause service interuptions however, it is better protected from hazardous weather conditions that may cause outages.	Should be planned/designed to not impact utility service or infrstrucutre by adhering to correct standards/clearances.	Should be designed/maintained such that this type of system does not effect local utility service and/or other infrastructure.	Should be designed/maintained such that this type of system does not effect local utility service and/or other infrastructure.
		Identify and document risks for further analysis	0.10							
Total Weighted Scores	**1.00**		**1.00**	**3.47**	**3.10**	**3.21**	**3.42**	**3.67**	**2.99**	**2.56**

D. Substation concept plans



Legend:

(blue box)	Battery Substation - 20' x 50' x 15' (W x L x H)
(red box)	3' Wide Access Walkway

DESIGNED BY	MIHALOVICH/BROWN
DRAWN BY	LAI/MIHALOVICH
CHECKED BY	B. RYAN
APPROVED BY	R. KLOVSKY
DATE	5-18-2018

San Bernardino County Transportation Authority

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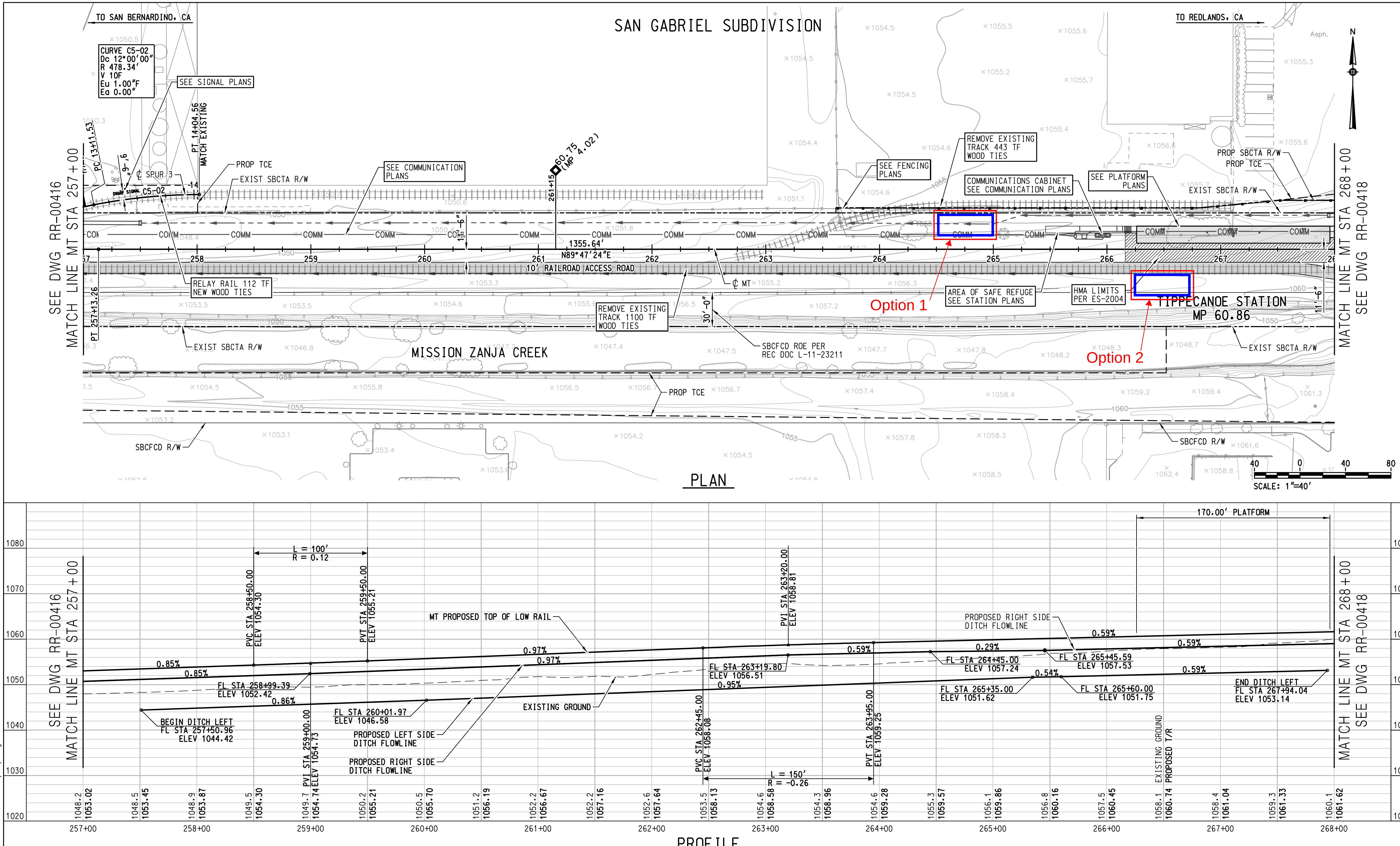
(951) 320-7300

REGISTERED PROFESSIONAL ENGINEER JASON W. BROWN No. C84914 Exp. 3-31-20 CIVIL STATE OF CALIFORNIA

REDLANDS PASSENGER RAIL PROJECT

TRACK PLAN AND PROFILE
MT-2 (WEST) STA 97+00 TO STA 103+00

CONTRACT NO.	17-1001705
DRAWING NO.	RR00402
REVISION	
SHEET NO.	99 OF 2425
SCALE	HORIZ 1"=40' VERT 1"=10'



Legend:

Blue box	Battery Substation - 20' x 50' x 15' (W x L x H)
Red box	3' Wide Access Walkway

DESIGNED BY	MIHALOVICH/BROWN
DRAWN BY	LAI/MIHALOVICH
CHECKED BY	B. RYAN
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REDLANDS PASSENGER RAIL PROJECT

TRACK PLAN AND PROFILE
MT STA 257+00 TO STA 268+00

CONTRACT NO.	17-1001705
DRAWING NO.	RR00417
REVISION	
SHEET NO.	114 OF 2425
SCALE	HORIZ 1"=40' VERT 1"=10'

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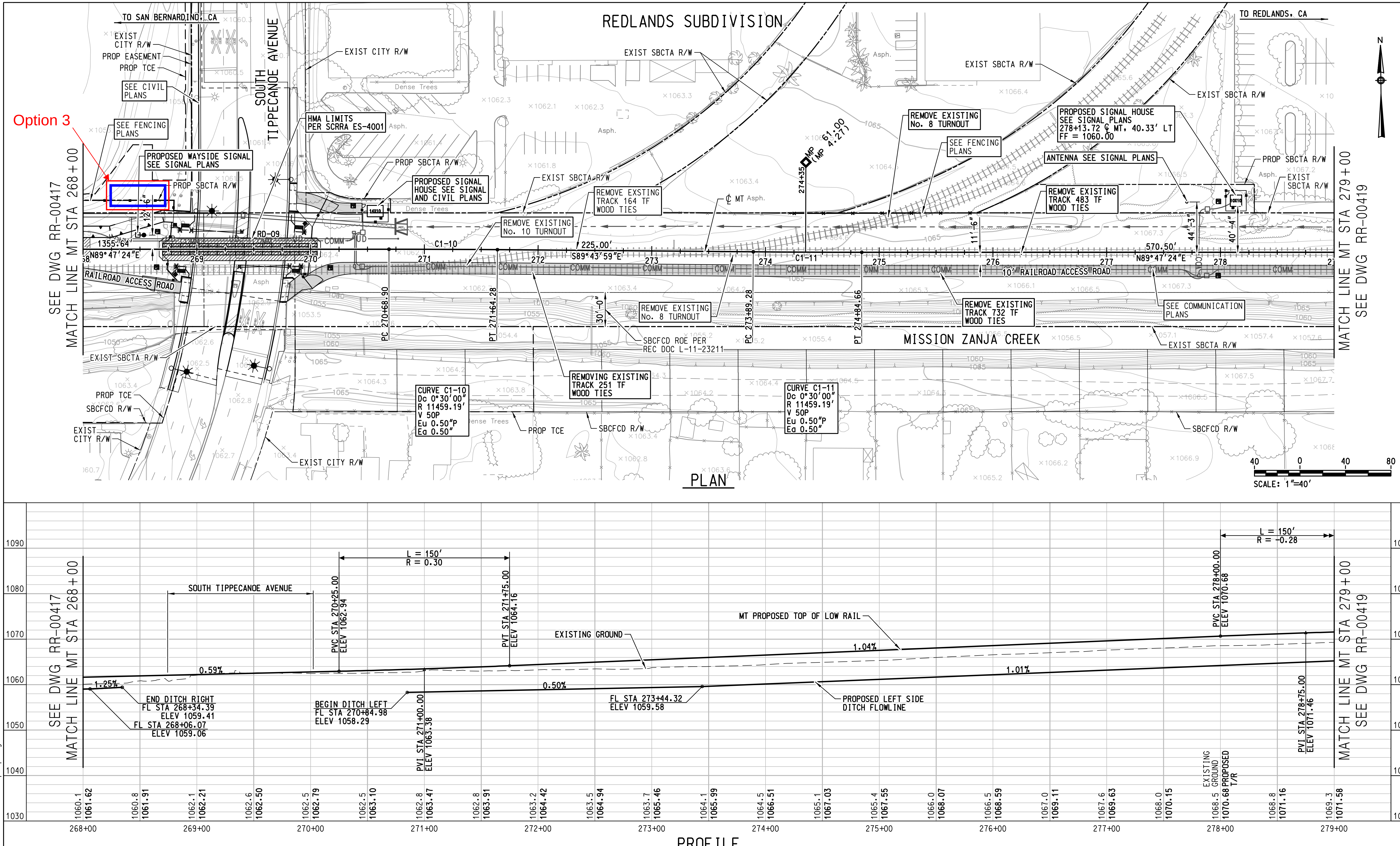

Legend:

Battery Substation - 20' x 50' x 15' (W x L x H)

3' Wide Access Walkway

DESIGNED BY	MIHALOVICH/BROWN
DRAWN BY	LAI/MIHALOVICH
CHECKED BY	B. RYAN
APPROVED BY	R. KLOVSKY
DATE	5-18-2018

BY | SUB. | APP.

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REDLANDS PASSENGER RAIL PROJECT

TRACK PLAN AND PROFILE
MT STA 268+00 TO STA 279+00

CONTRACT NO.	17-1001705
DRAWING NO.	RR00418
REVISION	SHEET NO. 115 OF 2425
SCALE	HORIZ 1"=40' VERT 1"=10'

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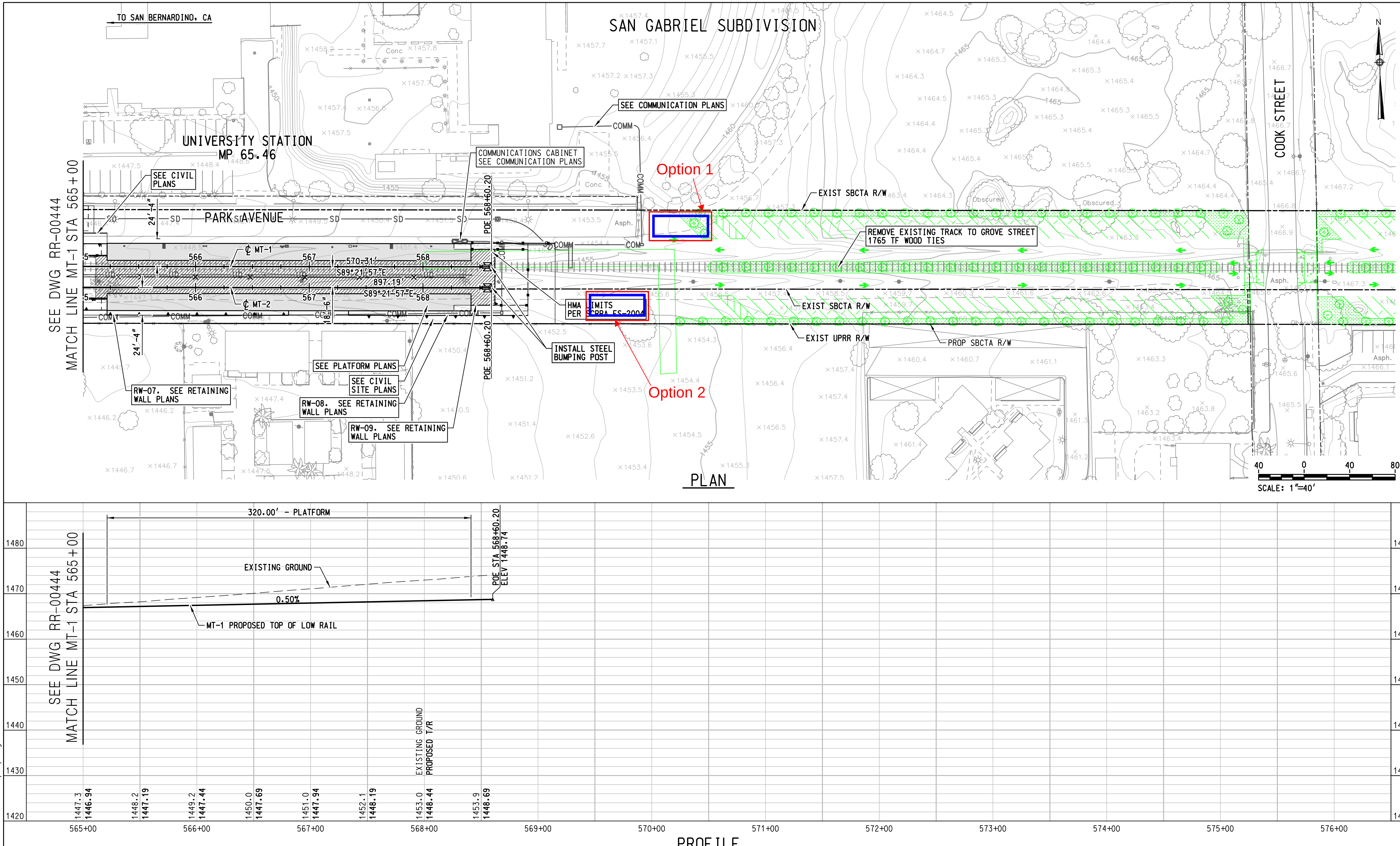

Legend:

Battery Substation - 20' x 50' x 15' (W x L x H)

3' Wide Access Walkway

DESIGNED BY	MIHALOVICH/BROWN
DRAWN BY	LAI/MIHALOVICH
CHECKED BY	B. RYAN
APPROVED BY	R. KLOVSKY
DATE	5-18-2018

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STATE OF CALIFORNIA

REDLANDS PASSENGER RAIL PROJECT

TRACK PLAN AND PROFILE
MT-1 STA 565+00 TO STA 568+60

CONTRACT NO.	17-1001705
DRAWING NO.	RR00445
REVISION	
SHEET NO.	142 OF 2425
SCALE	HORIZ 1"=40' VERT 1"=10'

E. Cost estimates for Battery

MOTT MACDONALD

Project: SBCTA - ZEMU

ZEMU COST ESTIMATE SUMMARY - PHASE 1 PLANNING

Date of Review: May 31, 2019

Vehicle Technology Option	Battery ZEMU		Hydrogen Fuel Cell Hybrid ZEMU		
Infrastructure Technology Option	TPSS	WESS	Electrolysis	SMR	Liquid Delivery
Capital Costs	$ 29,000,000	$ 31,000,000	$ 34,600,000	$ 33,800,000	$ 33,000,000
O&M Costs	$ 769,000	$ 690,000	$ 856,000	$ 540,000	$ 1,152,000

MOTT MACDONALD

Project: SBCTA - ZEMU

BATTERY ZEMU COST ESTIMATE - PHASE 1 PLANNING

Date of Review: May 31, 2019

ITEM No	DESCRIPTION	UNIT	QUANTITY	MM Final Estimate UNIT PRICE	MM Final Estimate TOTAL	REMARKS		
PART 1 - GENERAL								
G.1	Environmental & Permitting	Ea	1	$ 109,491	$ 109,491		5%	
G.2	Project Management (including regulatory management and commissioning)	Ea	1	$ 2,148,041	$ 2,148,041		10%	
G.3	Construction Management	Ea	1	$ 328,472	$ 328,472		15%	
G.4	Public Outreach Campaign	Ea	1	$ 107,402	$ 107,402		0.5%	
	Total				$ 2,693,405			
PART 2 - WORK SUMMARY								
1 - Vehicles								
1.1	Engineering and Design	Ea	1	$ 5,554,500	$ 5,554,500	Refer to BEMU Vehicle Non-Recurring ICE		
1.2	Vehicle Production	Ea	1	$ 8,700,000	$ 8,700,000	Stadler budgetary price		
1.3	Vehicle Propulsion System	Ea	1	$ 1,534,100	$ 1,534,100	LTO of 667Wh at $2300/kWh, which includes battery monitoring system and cooling, stadler's budget was 2.5 million.		
1.4	Spare Parts for ZEMU specific components	Ea	1	$ 1,000,000	$ 1,000,000	Assume at least a partial battery system as spares, and any unique elements of cooling, energy mgt and pantograph. Plus suspension elements, if different to DMU.		
1.6	Testing and Commisioning	Ea	1	$ 2,502,000	$ 2,502,000	Refer to BEMU Vehicle Non-Recurring ICE		
	Total				$ 19,290,600			
2 - Infrastructure						Includes FRA coordination and approval		
2.1	Engineering and Design (PE & Final)	Ea	1	$ 180,810	$ 180,810	Consistent with Transit Cooperative Research Program (TCRP) Report 138: "Estimating Soft Costs for Major Public Transportation Fixed Guideway Project."	9%	
2.2	Charging Unit (Substation to Conductive Charging)	Ea	2	$ 750,000	$ 1,500,000	- 500 kW fast charger at Foothill Transit. NREL Foothill Transit Battery Electric Bus Demonstration Results, Jan 2016. http://www.nrel.gov/docs/fy16osti/65274.pdf (p. 13). TPSS in USA aroun $500/kW. Cost is for 1500kW Substation. http://onlinepubs.trb.org/Onlinepubs/circulars/ec058/14_04_Hastings.pdf	$500	1500
2.3	Station Retrofit	Ea	2	$ 126,716	$ 254,000	See Site Retrofit		
2.4	Utility Service	Ea	2	$ 75,000	$ 150,000	Zach - Construction outside of the station footprint. http://onlinepubs.trb.org/Onlinepubs/circulars/ec058/14_04_Hastings.pdf - The cost of connecting to the grid will be around the same for either a TPSS or WESS, but there will be higher cost for the WESS due to configuring the batteries and testing them.Using 10% of the equipment cost of the TPSS equipment here so the costing stays consistent.	10%	
2.5	MSF Retrofit	Ea	1	$ 105,000	$ 105,000	See MSF Retrofit tab		

2.6	ROW Impacts				$ -	None	
	Total				$ 2,189,810		
	Contingency - Assume 20% for Planning Level Estimate (will come from risk assessment)(				$ 4,834,763		20%
	CAPITAL TOTAL				$ 29,000,000		
3 - Annual Operations and Maintenace							
3.1	Power Requirements		1	$ 450,616	$ 450,616	https://calstart.org/wp-content/uploads/2018/10/Peak-Demand-Charges-and-Electric-Transit-Buses.pdf	
3.1.1	Power Demand		1	$ 314,078	$ 314,078	SCE Time of Use (TOU) 8 Plan - Critical Peak Pricing (CPP) - Option D	
3.1.2	Energy Consumption		1	$ 136,538	$ 136,538	Average rate of $0.0811/kWh - SCE TOU 8 - CPP	
3.2	Vehicle Battery Maintenance, Overhaul and Replacement (annualized over 30 year life)		2	$ 4,000,000	$ 266,667	Battery replacement 5 times through 30 year life of the vehicle * 2 vehicles	
3.3	TPSS replacement / overhaul		2	$ 375,000	$ 25,000	1 $375,000 overhaul cost at 15 year * 2 TPSS	
3.4	Station equipment maintenance		2	$ 10,000	$ 20,000	WAG	
3.5	Station equipment overhaul		2	100000	$ 6,667	50,000 every 15 years * 2 stations	
	Total				$ 768,949		
							20%
	ANNUALIZED OPERATING COST				$ 769,000		

MOTT MACDONALD

Project: SBCTA - ZEMU

BATTERY ZEMU COST ESTIMATE - PHASE 1 PLANNING

Date of Review: May 31, 2019

				MM Final Estimate			
ITEM No	DESCRIPTION	UNIT	QUANTITY	UNIT PRICE	TOTAL	REMARKS	
PART 1 - GENERAL							
G.1	Environmental & Permitting	Ea	1	$ 172,613	$ 172,613		5%
G.2	Project Management (including regulatory management and commissioning)	Ea	1	$ 2,274,287	$ 2,274,287		10%
G.3	Construction Management	Ea	1	$ 517,840	$ 517,840		15%
G.4	Public Outreach Campaign	Ea	1	$ 113,714	$ 113,714		0.5%
	Total				$ 3,078,455		
PART 2 - WORK SUMMARY							
1 - Vehicles							
1.1	Engineering and Design	Ea	1	$ 5,554,500	$ 5,554,500	Refer to BEMU Vehicle Non-Recurring ICE	
1.2	Vehicle Production	Ea	1	$ 8,700,000	$ 8,700,000	Stadler budgetary price	
1.3	Vehicle Propulsion System	Ea	1	$ 1,534,100	$ 1,534,100	LTO of 667Wh at $2300/kWh, which includes battery monitoring system and cooling, stadler's budget was 2.5 million.	2300
1.4	Spare Parts for ZEMU specific components	Ea	1	$ 1,000,000	$ 1,000,000	Assume at least a partial battery system as spares, and any unique elements of cooling, energy mgt and pantograph. Plus suspension elements, if different to DMU.	
1.6	Testing and Commisioning	Ea	1	$ 2,502,000	$ 2,502,000	Refer to BEMU Vehicle Non-Recurring ICE	
	Total				$ 19,290,600		
2 - Infrastructure						Includes FRA coordination and approval	
2.1	Engineering and Design (PE & Final)	Ea	1	$ 285,050	$ 285,050	Consistent with Transit Cooperative Research Program (TCRP) Report 138: "Estimating Soft Costs for Major Public Transportation Fixed Guideway Project."	9%
2.2	Charging Unit (Wayside Energy Storage Bank (LTO Batteries) to Overhead Conductive Charging)	Ea	2	$ 1,458,200	$ 2,916,400	- 500 kW fast charger at Foothill Transit. NREL Foothill Transit Battery Electric Bus Demonstration Results, Jan 2016. http://www.nrel.gov/docs/fy16osti/65274.pdf (p. 13). Using figure of $2300/kWh. Information provided from supplier engagement interview, which includes batteries + other systems (i.e. cooling, energy management). WESS bank is assumed to be 760 kWh at Univ. Redlands, and 500 kWh at SBTC. Overall Cost is about 2.9 million.	634
2.3	Station Retrofit	Ea	2		$ -	See Site Retrofit	

2.4	Utility Service		2	$ 72,910	$ 145,820	Field Installation/Connection to grid for the charging unit will vary based on grid voltage connecting to and the distance located from the transformer rectifier. The cost of connecting to the grid will be around the same for either a TPSS or WESS. Using 5% of the upfront cost of the equipment. http://onlinepubs.trb.org/Onlinepubs/circulars/ec058/14_04_Hastings.pdf,	5%
2.5	MSF Retrofit	Ea	1	$ 105,000	$ 105,000	See MSF Retrofit tab	
2.6	ROW Impacts				$ -	None	
	Total				$ 3,452,270		
	Contingency - Assume 20% for Planning Level Estimate (will come from risk assessment)(				$ 5,164,265		20%
	CAPITAL TOTAL				$ 31,000,000		
3 - Annual Operations and Maintenace							
3.1	Power Requirements		1	$ 206,263	$ 206,263	https://calstart.org/wp-content/uploads/2018/10/Peak-Demand-Charges-and-Electric-Transit-Buses.pdf	
3.1.1	Power Demand Costs		1	$ 69,725	$ 69,725	SCE Time of Use (TOU) 8 Plan - Critical Peak Pricing (CPP) - Option D	
3.1.2	Energy Consumption Costs		1	$ 136,538	$ 136,538	Average rate of $0.0811/kWh - SCE TOU 8 - CPP	
3.2	Vehicle Battery Maintenance, Overhaul and Replacement (annualized over 30 year life)		2	$ 4,000,000	$ 266,667	Battery replacement 5 times through 30 year life of the vehicle * 2 vehicles	
3.3	WESS replacement / overhaul		1	$ 5,715,000	$ 190,500	Battery replacement 3 times in 30 years, (every 7.5 years) * 2 WESS at $1500 kWh. 762 kWh at Univ. Redlands + 505 kWh at SBTC = 1270 kWh. 3*1270*$1500/kWh = $5714286. Treating both systems as 1 combined sytem.	
3.4	Station equipment maintenance		2	$ 10,000	$ 20,000	WAG	
3.5	Station equipment overhaul		2	$ 100,000	$ 6,666.67	50,000 every 15 years * 2 stations	
	Total				$ 690,096		
							20%
	ANNUALIZED OPERATING COST				$ 690,000		

F. Battery Applications

F.1 Midlands Metro conversion in UK

The Midland Metro light rail fleet operating in Birmingham, UK is being retrofitted with rechargeable batteries to allow for OCS free operation on segments of its existing and future extensions.[38] The CAF Urbos 3 vehicle is used on the network and when they were first purchased in 2012, provision had been made in the contract for retrofitting, which enabled easier integration when it was decided to retrofit the batteries into the vehicle. The catenary-free sections allowed the light rail vehicles to operate in locations where there may be heritage considerations or provision of an OCS would incur significant cost due to relocation of major infrastructure. The first retrofitted vehicles have been in commercial service since July 2018.

F.2 Stadler FLIRT platform in Germany

Stadler has developed a battery version of its FLIRT platform with the traction equipment and most mechanical components as in a FLIRT EMU vehicle. The unit is anticipated to have a maximum speed of 87 mph and a range of 50 miles. Approvals for passenger service have been obtained and the train is expected to be in service on selected routes in Germany in 2019.[39] The development of this technology has been supported with 2 million euros of funding from the Federal Ministry of Economic Affairs & Energy and could potentially be used on 80% of non-electrified routes in Germany.

The Stadler FLIRT DMU platform has already been procured for the Arrow Service and this battery version of the FLIRT platform may support ZEMU conversion efforts by highlighting key interfaces with the battery and lessons learned from the design perspective.

F.3 Bombardier TALENT 3 platform in Germany

The prototype train was debuted in September 2018 and the battery-operated train is expected to have a reduction in total costs across a service life of 30 years. The current prototype has a range of approximately 25 miles, with charging from overhead lines where available. The next generation prototype expected to have a range of up to 62 miles. Deutsche Bahn will start a 12-month trial with the current prototype in 2019 in the Alb-Lake Constance region. The development of the train is supported by the German innovation program for electromobility with €4 million.[40]

[38] Midland Metro trams to be converted for catenary-free operation, February 2016. https://www.railwaygazette.com/news/urban/single-view/view/midland-metro-trams-to-be-converted-for-catenary-free-operation.html

[39] Flirt Akku battery multiple-unit unveiled, Railway Gazette, October 2018. https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/flirt-akku-battery-multiple-unit-unveiled.html

[40] Bombardier Transportation Presents a New Battery-Operated Train, Bombardier Press Release, September 2018. https://www.bombardier.com/en/media/newsList/details.bt_20180912_world-premiere--bombardier-transportation-presents-a.bombardiercom.html

G. Single Train Simulator

The Single Train Simulator (STS) is a piece of computer code written in MATLAB that calculates the energy and power consumed by a train for a specified journey. The simulation contains a model of a vehicle or train including its mass, installed power and resistance characteristics, and a basic 'map' of the line including line speeds, gradients and stopping points. It uses a distance-stepping algorithm to then calculate energy values 'at the wheel', based on the fundamental equations of motion.

This 'software' has been developed over several years and has been well-validated across a wide range of applications and projects. It is also used to support the Birmingham Centre for Railway Research and Education's teaching activities at master level.

G.1 Typical Simulation Output

Typical output from the STS includes a series of charts as shown and explained below:

Figure H-1: Typical STS Speed Profile Chart

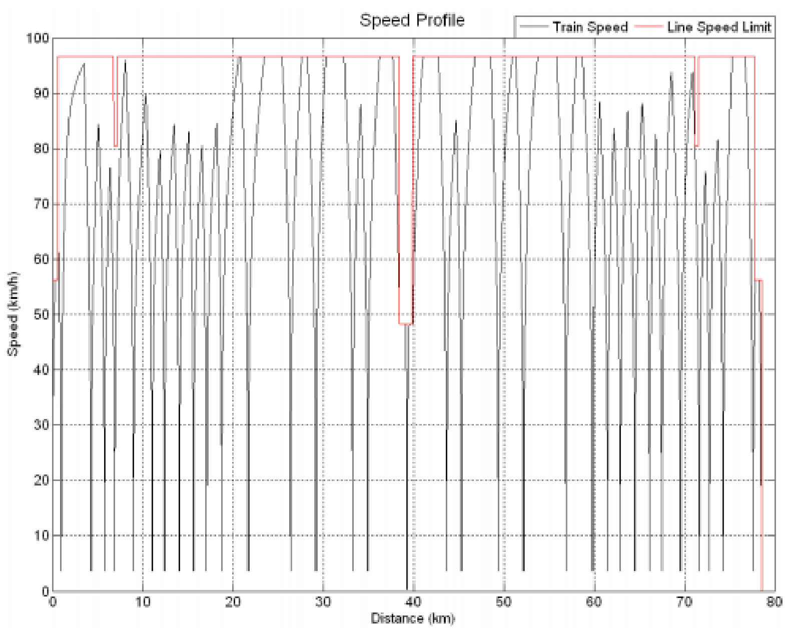


Figure H-1 shows the speed of the train during the journey in black, with the maximum permissible speed indicated in red. The downward 'spikes' are generally where the train has decelerated to stop at a station along the route.

Figure H-2: Typical STS Train Running Diagram

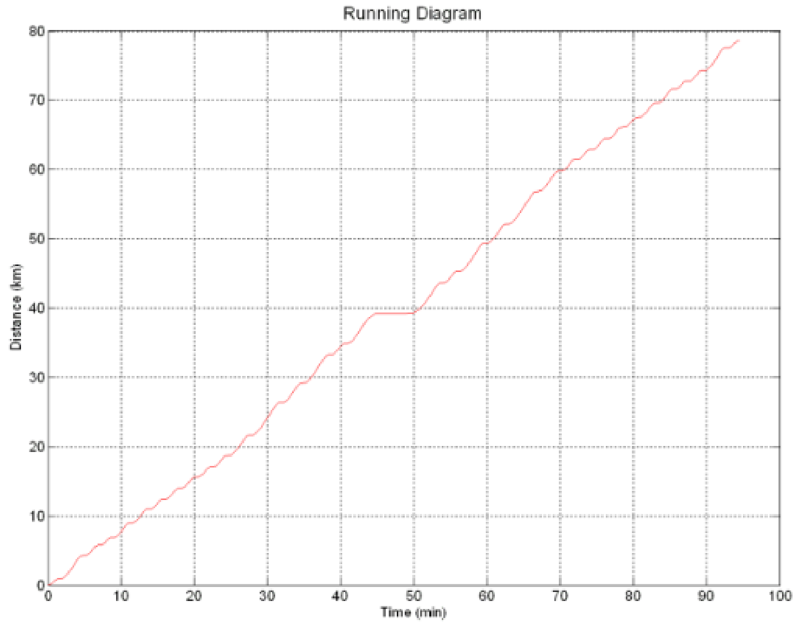


Figure H-2 shows a typical running diagram, where the distance travelled is plotted against time (the flat section represents the extended dwell time at a terminal station). The overall journey time (for a round trip in this case) is indicated both on the chart, and also as a numerical output.

Figure H-3: Typical STS Tractive Effort vs Train Resistance Chart (Hoffrichter, 2013)

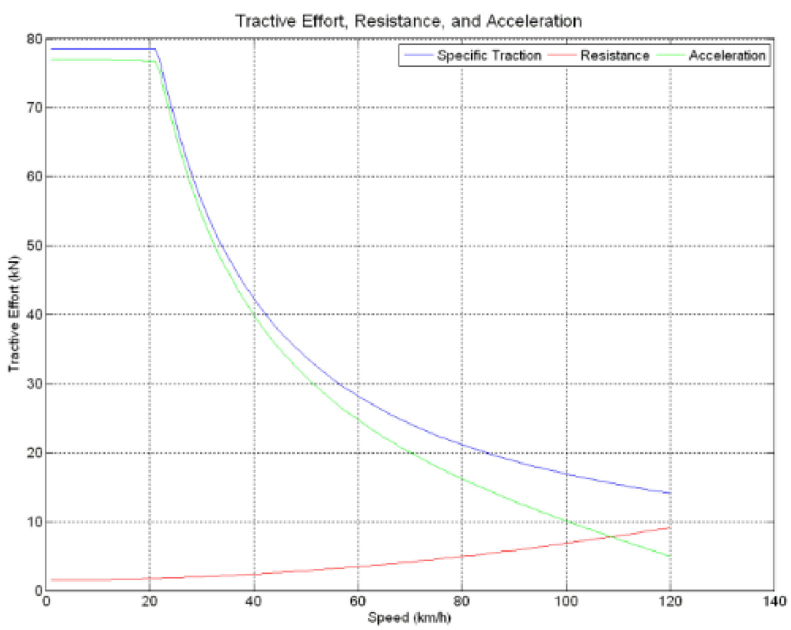


Figure H-3 shows how the tractive effort produced by the train changes as the speed of the train increases (the blue line). Commonly, a modern train produced a defined maximum tractive effort up to a given speed (approximately 20 km/h in this case), which is achieved through power increases until the maximum power of the train is reached. From this point onwards power is constant as the speed increases further, which leads to a reduction in Tractive Effort. The train resistance is the line shown in red and increases with higher speed, and the overall effect of the falling tractive effort and rising resistance on the train's acceleration is shown in green.

Figure H-4: Typical STS Traction & Braking Power Chart

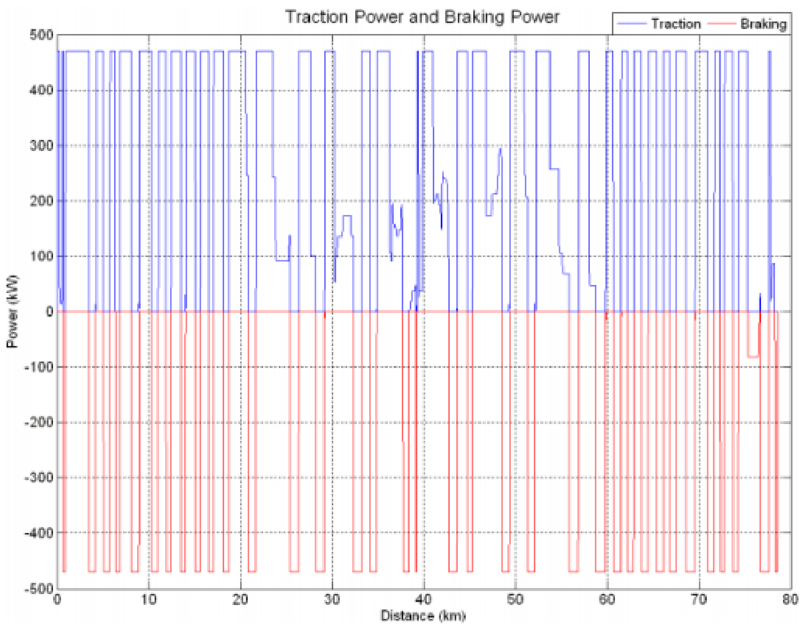
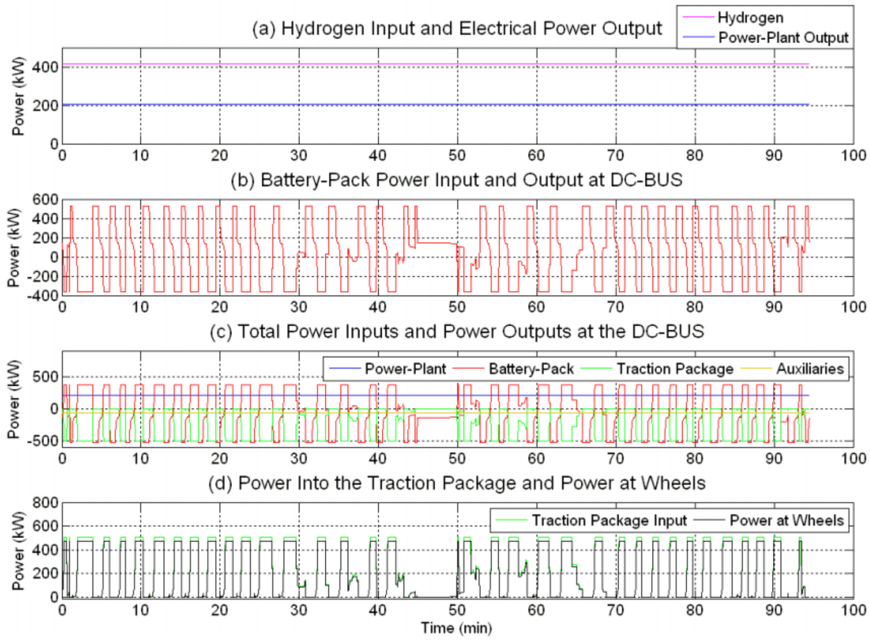


Figure H-4 shows the tractive power at the wheel for the journey (blue line) to be provided by the traction package. The amount of power that the braking system needs to absorb is shown in red. The braking power is either be dissipated by friction or rheostatic braking, or can be stored and re-used with regenerative braking. The total traction energy consumed and the total braking energy dissipated / stored is also indicated numerically at the end of the simulation.

Figure H-5: Enhanced STS Output Showing Energy Flow Through the Powertrain



Custom charts such as Figure H-5 can also be produced either in MATLAB or by exporting the simulation data to a package such as Microsoft Excel. The example shown above is for a hybrid fuel cell powered train and shows the power through the powertrain during the journey, for example, power flows in and out of the traction batteries are illustrated.

G.2 Notable Assumptions & Simplifications

The train is ‘driven’ using the full power available to accelerate up to the line speed, with full braking then applied at a specified rate (typically UK Step 2 brake application ≈ 0.6 m/s^2) in order to stop precisely at the specified stopping points (usually stations) along the route. Dwell times are specified for each station, as are terminal dwell times prior to making a round trip, as in the example shown above.

The simulation can take curving forces into account where curvature data is available for a given route. However, where this data is not available, the simulations remain realistic as the impact of curvature on energy consumption predictions for passenger trains is limited. This assumption may not be valid for longer heavy haul freight trains where a higher proportion of the resistance relates to curving forces.

H. Hydrogen Fuel Cell Simulation and Emission Results

Calculations in attached Excel file

I. Cost estimates for Hybrid Hydrogen Fuel Cell

Project: SBCTA - ZEMU

HYDROGEN FUEL CELL BATTERY HYBRID ZEMU COST ESTIMATE - PHASE 1 PLANNING **Date of Review: May 31, 2019**

Electrolysis

ITEM No	DESCRIPTION	UNIT	QUANTITY	UNIT PRICE (MM Final Estimate)	TOTAL (MM Final Estimate)	REMARKS	
PART 1 - GENERAL							
G.1	*Environmental & Permitting*	Ea	1	$ 166,000	$ 166,000		5%
G.2	*Project Management (including regulatory management and commissioning)*	Ea	1	$ 2,548,900	$ 2,548,900		10%
G.3	*Construction Management*	Ea	1	$ 498,000	$ 498,000		15%
G.4	*Public Outreach Campaign*	Ea	1	$ 127,445	$ 127,445		0.5%
	Total				**$ 3,340,345**		
WORK SUMMARY							
1 - Vehicles							
1.1	*Engineering and Design*			**7,000,000**	**$ 7,000,000**		
1.2	*Vehicle Powerplant/Propulsion System Cost*			**$ 1,000,000**	**$ 1,000,000**	Based on budget numbers provided by potential suppliers for a 400 kW system at $2500/kW.	
1.3	*Onboard Fuel Storage Equipment*			**$ 176,000**	**$ 176,000**	Based on 220 kg of storage, gives a 10% buffer on vehicle daily demand for 16 RPRP round trips.	
1.4	*Non-Powerplant Components (e.g. body shell, trucks, traction motors*			**$ 9,720,000**	**$ 9,720,000**		
1.5	*Batteries*			**$ 273,000**	**$ 273,000**	140 kWh @ $1300/kWh + 50% for cooling / control	
1.6	*Spare Parts for ZEMU specific components*			**$ 1,000,000**	**$ 1,000,000**	At least 1 spare fuel cell system (200 kW), spare battery pack and other individual components.	
1.7	*Testing and Commisioning*			**$ 3,000,000**	**$ 3,000,000**		
	Total				**$ 22,169,000**		
2 - Infrastructure						Includes FRA coordination and approval	
2.1	*Engineering and Design (and/or Installation)*			**$ 100,000**	**$ 100,000**		
2.2	*Fueling/Production Infrastructure*			**$ 2,060,000**	**$ 2,060,000**		
2.5	*Fuel Storage at Station*			**$ 660,000**	**$ 660,000**	[1] This assumes 660 kg of primary storage (bar), at $130,000 per 220 kg; and 162 kg buffer storage (feeds the dispenser), via 27 6 kg containers, each at $10,000	
2.6	*ROW Impacts*			**$ -**	**$ -**		
2.7	*MSF retrofit*		1	**$ 500,000**	**$ 500,000**	estimate on open maintenance facility	
	Total				**$ 3,320,000**		
	Contingency - Assume 20% for Planning Level Estimate (will come from risk assessment)(				**$ 5,765,869**		20%
	Capital Cost Total				**$ 34,600,000**		
3 - Annual Operations and Maintenace				DAILY	ANNUAL		
3.1	*Hydrogen Costs*			**$ 1,394.26**	**$ 508,905**	Electricity and water costs of 322 kg of H2 (~0.09 USD per kWh, ~ 0.01 cent per gallon); ~$4.30 per kg H2	
3.1.1.	*Electrical Compression Costs*			**$ 32.94**	**$ 12,023**	~366 kWh at 0.09 USD per kWh	
3.1.2	*Long-term powertrain maintenance*			**$ 570.23**	**$ 208,133**	Replacement of FC 3 times during 30-year lifetime period; Tanks 1 time; $400k for 200kW FCS; Calcs are in columns K-O.	
3.1.3	*Infrastructure Maintenance*			**$ 349.13**	**$ 127,432**	$0.50 per kg (manufacturer estimate; fairly close to the value---using capital cost percentage---from another manufacturer) plus long-term infrastructure maintenance costs (see Columns K-O)	
	Total				**$ 856,493**		
	Annualized Operating Cost				**$ 856,000**		

Project: SBCTA - ZEMU

HYDROGEN FUEL CELL BATTERY HYBRID ZEMU COST ESTIMATE - PHASE 1 PLANNING — **Date of Review: May 31, 2019**

SMR — **MM Final Estimate**

ITEM No	0.25	UNIT	QUANTITY	UNIT PRICE	TOTAL	REMARKS	
PART 1 - GENERAL							
G.1	*Environmental & Permitting*	Ea	1	$ 141,400	$ 141,400		5%
G.2	*Project Management (including regulatory management and commissioning)*	Ea	1	$ 2,499,700	$ 2,499,700		10%
G.3	*Construction Management*	Ea	1	$ 424,200	$ 424,200		15%
G.4	*Public Outreach Campaign*	Ea	1	$ 124,985	$ 124,985		0.5%
	Total				**$ 3,190,285**		
WORK SUMMARY							
1 - Vehicles							
1.1	*Engineering and Design*			**7,000,000**	**$ 7,000,000**		
1.2	*Vehicle Powerplant/Propulsion System Cost*			**$ 1,000,000**	**$ 1,000,000**	Based on budget numbers provided by potential suppliers for a 400 kW system at $2500/kW.	
1.3	*Onboard Fuel Storage Equipment*			**$ 176,000**	**$ 176,000**	Based on 220 kg of storage, gives a 10% buffer on vehicle daily demand for 16 RPRP round trips.	
1.4	*Non-Powerplant Components (e.g. body shell, trucks, traction motors*			**$ 9,720,000**	**$ 9,720,000**		
1.5	*Batteries*			**$ 273,000**	**$ 273,000**	140 kWh @ $1300/kWh + 50% for cooling / control	
1.6	*Spare Parts for ZEMU specific components*			**$ 1,000,000**	**$ 1,000,000**	At least 1 spare fuel cell system (200 kW), spare battery pack and other individual components.	
1.7	*Testing and Commisioning*			**$ 3,000,000**	**$ 3,000,000**		
	Total				**$ 22,169,000**		
2 - Infrastructure						Includes FRA coordination and approval	
2.1	*Engineering and Design (and/or Installation)*			**$ 100,000**	**$ 100,000**	12%	
2.2	*Fueling/Production Infrastructure*			**$ 1,568,000**	**$ 1,568,000**		
2.5	*Fuel Storage at Station*			**$ 660,000**	**$ 660,000**	[1] This assumes 660 kg of primary storage (bar), at $130,000 per 220 kg; and 162 kg buffer storage (feeds the dispenser), via 27 6 kg containers, each at $10,000	
2.6	*ROW Impacts*			**$ -**	**$ -**		
2.7	*MSF retrofit*		**1**	**$ 500,000**	**$ 500,000**	estimate on open maintenance facility	
	Total				**$ 2,828,000**		
	Contingency - Assume 20% for Planning Level Estimate (will come from risk assessment)(				**$ 5,637,457**		20%
	Capital Cost Total				**$ 33,800,000**		
3 - Annual Operations and Maintenace				DAILY	ANNUAL		
3.1	*0.05*			**$ 569.94**	**$ 208,028**	Electricity and water costs of 322 kg of H2 (~0.09 USD per kWh, ~ 0.01 cent per gallon); ~1.77 per kg H2	
3.1.1.	*0.1*			**$ 32.94**	**$ 12,023**	~366 kWh at 0.09 USD per kWh	
3.1.2	*Long-term powertrain maintenance*			**$ 570.23**	**$ 208,133**	Replacement of FC 3 times during 30-year lifetime period; Tanks 1 time; $400k for 200kW FCS; Calcs are in columns K-O.	
3.1.3	*Infrastructure Maintenance*			**$ 304.20**	**$ 111,032**	$0.50 per kg (manufacturer estimate; fairly close to the value---using capital cost percentage---from another manufacturer) plus long-term infrastructure maintenance costs (see Columns K-O)	
	Total				**$ 539,216**		
	Annualized Operating Cost				**$ 540,000**		

Project: SBCTA - ZEMU

HYDROGEN FUEL CELL BATTERY HYBRID ZEMU COST ESTIMATE - PHASE 1 PLANNING — **Date of Review: May 31, 2019**

Liquid Delivery

ITEM No	DESCRIPTION	UNIT	QUANTITY	UNIT PRICE	TOTAL	REMARKS	
				MM Final Estimate			
PART 1 - GENERAL							
G.1	*Environmental & Permitting*	Ea	1	$ 114,000	$ 114,000		5%
G.2	*Project Management (including regulatory management and commissioning)*	Ea	1	$ 2,444,900	$ 2,444,900		10%
G.3	*Construction Management*	Ea	1	$ 342,000	$ 342,000		15%
G.4	*Public Outreach Campaign*	Ea	1	$ 122,245	$ 122,245		0.5%
	Total				**$ 3,023,145**		
WORK SUMMARY							
1 - Vehicles							
1.1	*Engineering and Design*				**$ 7,000,000**		
1.2	*Vehicle Powerplant/Propulsion System Cost*				**$ 1,000,000**	Based on budget numbers provided by potential suppliers for a 400 kW system at $2500/kW.	
1.3	*Onboard Fuel Storage Equipment*				**$ 176,000**	Based on 220 kg of storage, gives a 10% buffer on vehicle daily demand for 16 RPRP round trips.	
1.4	*Non-Powerplant Components (e.g. body shell, trucks, traction motors*				**$ 9,720,000**		
1.5	*Batteries*				**$ 273,000**	140 kWh @ $1300/kWh + 50% for cooling / control	
1.6	*Spare Parts for ZEMU specific components*				**$ 1,000,000**	At least 1 spare fuel cell system (200 kW), spare battery pack and other individual components.	
1.7	*Testing and Commisioning*				**$ 3,000,000**		
	Total				**$ 22,169,000**		
2 - Infrastructure						Includes FRA coordination and approval	
2.1	*Engineering and Design (and/or Installation)*			**$ -**	**$ -**	Installation costs already included in 2.2-2.5	
2.2	*Fueling/Production Infrastructure*			**$ 807,000.00**	**$ 807,000.00**		
2.5	*Fuel Storage at Station*			**$ 973,000.00**	**$ 973,000.00**	622,000 for liquid hydrogen storage plus 351,000 for gaseous storage (installation included)	
2.6	*ROW Impacts*			**$ -**	**$ -**		
2.7	*MSF retrofit*		**1**	**$ 500,000.00**	**$ 500,000.00**	estimate on open maintenance facility	
	Total				**$ 2,280,000**		
	Contingency - Assume 20% for Planning Level Estimate (will come from risk assessment)(				**$ 5,494,429**		20%
	Capital Cost Total				**$ 33,000,000**		
3 - Annual Operations and Maintenace				DAILY	ANNUAL		
3.1	*Hydrogen Costs*			$ 2,415.00	**$ 881,475.00**	$7.50 per kg	
3.1.1.	*Electrical Compression Costs*			$ 16.47	**$ 6,011.55**	Assumed half of SMR and Electrolysis compression costs (using pump instead)	
3.1.2	*Long-term powertrain maintenance*			$ 570.23	**$ 208,133.33**	Replacement of FC 3 times during 30-year lifetime period; Tanks 1 time; $400k for 200kW FCS; Calcs are in columns K-O.	
3.1.3	*Infrastructure Maintenance*			$ 154.20	**$ 56,282.50**	$0.25 cents per kg; half of estimate for gaseous H2 plus long-term infrastructure maintenance costs (see Columns K-O)	
	Total				**$ 1,151,902.38**		
	Annualized Operating Cost				**$ 1,152,000**		

J. Hybrid Hydrogen Fuel Cell Applications

Several examples of implementation of hydrogen fuel cell technology in heavy duty applications are presented below:

1 - Los Angeles ‘Project Portal’ Semi (US)	
Sponsors: Toyota / Kenworth / Shell	Year Introduced: 2018/19
Sector: Road (Heavy Goods Vehicle)	Technology: Hybrid hydrogen fuel cell traction
Description: A prototype fuel cell semi (truck) designed to carry containers from Californian ports to distribution centres inland. The two fuel cell stacks based on those in Toyota’s Mirai car (just over 200kW in total) are combined with a 12 kWh battery to give the truck 670 horsepower and 1,325 foot-pounds of torque. This enables it to easily out-accelerate a conventional diesel semi, albeit with a much lower range of 300 miles for the second generation truck (first generation shown right). Key points to note: The combination of battery and modest fuel cell output is sufficient to out-accelerate a comparable diesel semi, albeit with a shorter range between refuelling. Toyota have previously been reluctant to apply their advanced fuel cell and hydrogen tank technology to non-car applications. But this development suggests that they are now looking seriously to engage with applications in the heavy duty transport market. With the first generation having done 10,000 miles or real world service, 10 trucks of the second generation design are now to be built.	 Source: Toyota (2018) – with permission
https://www.greencarreports.com/news/1118877_toyota-enters-82-million-partnership-to-roll-out-hydrogen-trucks-in-los-angeles-port	

<table>
<tr><td colspan="2">2 – Nikola Semi (US)</td></tr>
<tr><td>Sponsors: Nikola Motor Company</td><td>Year Introduced: 2020/21</td></tr>
<tr><td>Sector: Road (Heavy Goods Vehicle)</td><td>Technology: Hybrid hydrogen fuel cell traction</td></tr>
<tr><td>Description:

Nikola are developing a hydrogen fuel cell powered semi (truck), with a number of prototype vehicles already in operation. It incorporates a 320kWh battery and 300kW fuel cell to generate 1000 horsepower and 2000 foot-pounds of torque, which enables the truck to comfortable out-accelerate conventional diesel semis.

Each truck carries 100kg of hydrogen – sufficient to give a range of 1200 miles. Anheuser-Busch have ordered 800 for operation in the USA.

Key points to note:

Nikola plans to initially have 56 refuelling stations in operation by 2019, with the intention to expand this to 700 by 2028. They are partnering with NEL, one of the world's main electrolyser companies to deliver this.

The operating costs are expected to be considerably lower than for comparable diesel trucks.</td><td>

Source: Wikipedia “Nikola Motor Company” page (2019)</td></tr>
<tr><td colspan="2">https://en.wikipedia.org/wiki/Nikola_Motor_Company

https://www.trucks.com/2016/12/01/nikola-one-hydrogen-fuel-cell-electric-semi-truck-debuts/

https://www.theverge.com/2018/5/3/17314606/anheuser-busch-budweiser-hydrogen-trucks-zero-emission-startup-nikola</td></tr>
</table>

<table>
<tr><td colspan="2">3 - Aberdeen Fuel Cell Bus Fleet (UK)</td></tr>
<tr><td>Sponsors: Aberdeen City Council / EU</td><td>Year Introduced: 2015</td></tr>
<tr><td>Sector: Road (Passenger)</td><td>Technology: Hybrid hydrogen fuel cell traction</td></tr>
<tr><td>Description:

A fleet of 10 hydrogen fuel cell powered buses that are in daily service, running on hydrogen produced locally using Hydrogenics electrolysers. The buses are made by Van Hool, and are equipped with Ballard fuel cells, with an electric drive system from Siemens.

The fleet is part of the European-wide project called JIVE, deploying 144 fuel cell buses and seven large hydrogen refueling stations across five European cities

Key points to note:

Hydrogen production is limited to periods when the local wind farm is generating electricity.

The hydrogen production & refueling facilities are located adjacent to a residential area.

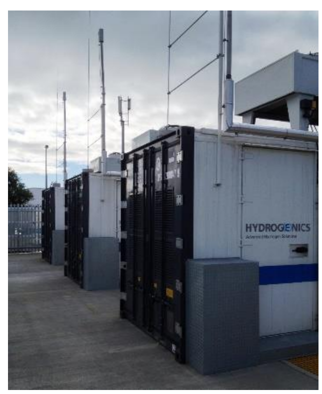
The hydrogen production facilities have achieved very high levels of availability, and the fleet is due to double in size later this year.

The local council have been highly supportive, with the buses owned by Aberdeen City Council and leased to Stagecoach and First Group (the local bus operators).

Aberdeen is investing heavily in alternative power, and Scotland as a whole is close to sourcing 100% of its electricity from renewable sources.

Aberdeen is the centre of the oil industry in the UK, servicing the numerous oil fields in the North Sea.

The fleet has now done over a million miles in service.</td><td>

Source: Stephen Kent (2015)</td></tr>
<tr><td colspan="2">https://news.aberdeencity.gov.uk/aberdeens-pioneering-hydrogen-bus-project-arrives-at-major-milestone/</td></tr>
</table>

4 – "Breeze" Regional Passenger Train Conversion (UK)	
Sponsors: Alstom / Eversholt Leasing	Year Introduced: 2022
Sector: Rail (passenger)	Technology: Hybrid hydrogen fuel cell traction
Description: A mid-life electric multiple unit (Class 321) that is being retro-fitted with hydrogen fuel cell traction intended for use in regional and branch line services in the UK. The train is intended to have a 600 mile range with a top speed of 90mph. The project is at the design stage, with a prototype expected on 2020/21. Key points to note: A proportion of the leading and trailing passenger salon is being used to accommodate the hydrogen tanks. This is likely to be driven (at least in part) by the restrictive loading gauge in the UK, which leaves insufficient space to accommodate storage tanks on the roof. The conversion will draw upon the experience that Alstom has gained through the development of the iLint multiple unit.	 Source: tbc
https://www.telegraph.co.uk/cars/news/hydrogen-fuel-cell-trains-run-british-railways-2022/amp/ https://www.cnbc.com/amp/2019/01/07/designs-unveiled-for-new-hydrogen-powered-trains-in-the-uk.html	

<table>
<tr><td colspan="2">5 – Alstom Coradia iLint Regional Passenger Train (Germany)</td></tr>
<tr><td>Sponsors: Alstom / the Lower Saxony Transport Provider (LNVG)</td><td>Year Introduced: 2018</td></tr>
<tr><td>Sector: Rail (passenger)</td><td>Technology: Hybrid hydrogen fuel cell traction</td></tr>
<tr><td>Description:

The world’s first hydrogen fuel cell powered passenger train to enter service. Two are in daily service in northern Germany, with the full fleet of 14 trains to follow into service in 2021.

The prototype has a top speed of 140km/h (approx. 90mph) and an operating range in excess of 800km.

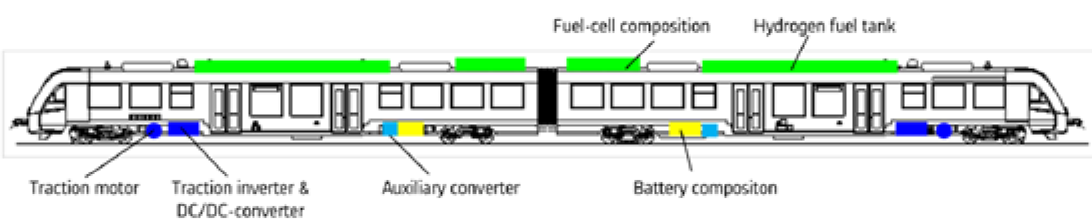
Key points to note:

The design is based on a converted Diesel Multiple Unit (DMU) designed for operation on regional lines. It has fuel cells from Hydrogenics, and is a hybrid, using lithium based battery packs from Akasol.

Alstom are taking responsibility for the delivery of the trains and also the supply of hydrogen fuel.

The trains are being introduced initially in areas where there is a local large-scale supply of hydrogen used for industrial purposes.

It is understood that the production versions will have an operating range of 1000km (approx. 650 miles).</td><td>

Source: Wikipedia “Hydrail” page (2019)</td></tr>
<tr><td colspan="2">
</td></tr>
<tr><td colspan="2">https://en.wikipedia.org/wiki/Alstom_Coradia_LINT

https://www.alstom.com/press-releases-news/2018/9/world-premiere-alstoms-hydrogen-trains-enter-passenger-service-lower</td></tr>
</table>

6 – HydroFlex Regional Passenger Train Demonstrator (UK)	
Sponsors:	Year Introduced: 2018
Sector: Rail (passenger)	Technology: Bi-mode hybrid hydrogen fuel cell traction
Description: A bi-mode fuel cell train, based on a mid-life Electric Multiple unit, the Class 319. The design is based on Porterbrook's recently launched Class 319 "Flex" bi-mode. This is a 4-car electric multiple unit that has been equipped with diesel generator sets mounted to the underframe of the leading and trailing vehicle. This enables it to run on both electrified and non-electrified lines. The new design is for a bi-mode hydrogen fuel cell hybrid, capable of drawing power from overhead lines wherever available, and swapping over to hydrogen elsewhere. Key points to note: The University of Birmingham is supporting the introduction of these units, with a demonstrator expected to be running in summer 2019. The fuel cells for the prototype are being supplied by Ballard and the lithium based traction batteries are being provided by Denchi (UK). The traction power available when running on overhead electric wires is 1000kW with a top speed of 100mph. When running on non-electrified lines, the traction power is expected to be lower, but appropriate for regional and branch line operation.	 Source: Porterbrook Leasing (2018)
https://masstransit.network/mass-transit-news/smartrail-world/porterbrookballard-signal-arrival-of-uks-1st-hydrogen-powered-train https://www.porterbrook.co.uk/innovation/case-studies/the-flex-family	

7 – Siemens Mireo Regional Train (Europe)	
Sponsors: Siemens	Year Introduced: 2021
Sector: Rail (passenger)	Technology: Hybrid hydrogen fuel cell traction
Description: Siemens are developing a hybrid hydrogen fuel cell version of their Mireo regional train in conjunction with Ballard. The train will be equipped with a 200kW fuel cells based on the next generation of Ballard fuel cell technology. The train is expected to enter service around 2021. Key points to note: The next generation of Ballard fuel cell stacks will be marginally more efficient, will have a longer service life predicted to be in excess of 30,000 hours, and will no longer require a shore supply for overnight stabling.	 Source: Wikipedia “Siemens Mireo” page (2019)
https://www.electrans.co.uk/siemens-ballard-fuel-cell-mireo-funded-germany/ https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/fuel-cell-mireo-multiple-unit-to-be-developed.html	

<table>
<tr><td colspan="2">8 – CRRC Hydrogen Trams (China)</td></tr>
<tr><td>Sponsors: CRRC</td><td>Year Introduced: 2016 & 2019</td></tr>
<tr><td>Sector: Light Rail (passenger)</td><td>Technology: Hydrogen fuel cell traction</td></tr>
<tr><td>Description:

A fleet of eight hydrogen fuel cell-powered trams have been ordered from CRRC, the world’s largest train manufacturer. This will operate in the city of Foshan. The design is based on the Skoda ForCity 15T, and the fuel cell system is from Ballard. The trams will operate the 17km line at speeds of up to 70km/h.

A similar fleet of 7 trams are already in service on a partly electrified 9km line in Qingdao.

Findings:

Hydrogen fuel cells enable trams to operate without overhead wires, which can be particularly important for congested city centers.</td><td>

Source: Wikipedia “Skoda 15 T” page (2018)</td></tr>
<tr><td colspan="2">https://www.metro-report.com/news/single-view/view/foshan-hydrogen-fuel-cell-tram-contract-signed.html

https://www.railwaygazette.com/news/single-view/view/qingdao-opens-fuel-cell-tram-route.html</td></tr>
</table>

9 – Zillertalbahn Narrow Gauge Train (Austria)	
Sponsors: ZVB (operator) & Stadler	Year Introduced: 2022
Sector: Narrow Gauge Rail (passenger)	Technology: Hydrogen fuel cell traction
Description: A fleet of five hydrogen fuel cell powered narrow-gauge trains have been ordered from Stadler for use on a 32km scenic rail network in Austria. The hydrogen will be produced locally using hydropower (i.e. hydroelectricity) and transported by tube trailers to the railway. Key points to note: Hydrogen was selected in preference to electrification due largely to the visual impact that overhead electrification equipment would have on the line.	 Source: tbc
https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/zillertalbahn-selects-hydrogen-train-supplier.html	

10 – Vivarail Proof of Concept (UK)	
Sponsors: Vivarail & Arcola Energy	Year Introduced: 2020
Sector: Regional passenger train	Technology: Hydrogen fuel cell traction
Description: Vivarail are currently repurposing a fleet of discussed London Underground train for use on the UK's regional and branch lines. These are being equipped with diesel generator sets on each motor car, but the company intend to offer a hydrogen fuel cell variant. A proof of concept is expected in 2020. Key points to note: The Vivarail trains are intended to provide a low-cost solution for operating on the UK's rural and branch lines.	 Source: tbc
https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/fuel-cell-proof-of-concept-train-to-be-tested.html	

11 – Fuel Cell Delivery Lorries (Switzerland)	
Sponsors: ESORO / Hyundai	Year Introduced: 2018 / 2019-23
Sector: Road (Heavy Goods Vehicle)	Technology: Hydrogen fuel cell traction
Description: The Swiss COOP currently operates a fleet of hybrid hydrogen fuel cell powered delivery trucks. These use a 100kW fuel cell from PowerCell of Sweden in conjunction with a 120kWh Lithium battery to drive 250kW motor mated to a four-speed automatic gearbox. Hyundai have recently signed a contract to deliver 1,000 fuel cell trucks for operation across Switzerland. They will feature a 190kW fuel cell system and will have a range of 400km. These are to be introduced into service starting 2019, with the full fleet by 2023. Key points to note: Switzerland has a plentiful supply of renewable energy, so hydrogen fuel cell trucks are a natural fit. Bosch has recently signed an agreement with PowerCell to mass produce fuel cells or heavy duty transport applications.	 Source: tbc
https://www.sciencedirect.com/science/article/pii/S1464285916303674 https://www.telegraph.co.uk/cars/news/hyundai-supply-1000-hydrogen-fuel-cell-lorries-switzerland/ https://www.hyundai.co.nz/hyundai-motor-and-h2-energy-to-bring-the-world-s-first-fleet-of-fuel-cell-electric-trucks-into-commercial-operation- https://uk.reuters.com/article/us-bosch-electric-fuelcell/bosch-signs-pact-with-swedens-powercell-to-mass-produce-fuel-cells-idUKKCN1S50LE	

K. Risk Analysis Matrix

LEVEL 2 - RISK REGISTER				Project Name:	SBCTA ZEMU PROJECT - BATTERY ZEMU RISK REGISTER		Owner:	SBCTA	Project Manager	Carrie Schindler						
Risk Identification							Risk Assessment						Risk Response			
Status	ID #	Type	Category	Title	Risk Statement	Current status/assumptions	Probability	Cost Impact	Cost Score	Time Impact	Time Score	Rationale	Strategy	Response Actions	Risk Owner	Updated
Active	R.1	Threat	Regulatory	FRA Compliance	Uncertainty regarding the FRA approval process - It is not clear as to whether a Waiver or Letter of Concurrence will be required in order to operate the ZEMU. The timeline to obtain each can vary signficantly. Our assumption is that a letter of concurrence is required. If a waiver is required, this could result in a signficiant delay to the schedule (in lieu of a Letter of Concurrence)	CNG approval (BNSF) required a Letter of Concurrence	3-Moderate	2 -Low	6	8 -High	24	coule result in 1 year delay and 25% increase in PM costs	Mitigate	Early Engagement with FRA after a technology decision has been made to develop a better understanding of the requirements and the schedule. CNG approval (BNSF) required a Letter of Concurrence	SBCTA	
Active	R.2	Threat	Regulatory	FRA Approval Timeline	Delays in issuance of approval to operate pilot due to new propulsion technology. FRA could extend the typical timelines.	CNG approval (BNSF) required a Letter of Concurrence. This took 6 months to obtain Letter of Conurrence to pilot the vehicle	3-Moderate	1 -Very Low	3	2 -Low	6	For a letter of concurrence assume 6 months. Risk could result in 1-4 months delay	Accept	Early Engagement with FRA after a technology decision has been made to develop a better understanding of the requirements and the schedule. Test vehicle on private track in advance of the Letter of Concurrence (similar to BNSF approach)	SBCTA	
Active	R.3	Threat	Regulatory	FRA Testing Requirements	Unknown lab testing requirements for battery technology	Midland Metro battery testing requirements were not onerous or signficiant relative to overall project costs	2-Low	1 -Very Low	2	1 -Very Low	2	Additional testing may be required but would not result in significant costs or schedule delays	Mitigate	Early Engagement with FRA after a technology decision has been made to develop a better understanding of the requirements and ensure contract with Stadler considers all FRA requirements as best as we can	Stadler	
Active	R.4	Threat	Regulatory	FRA Restrictions on Pilot Tests	Potential for unforseen restrictions for operating the pilot test ZEMU on the same track as the Arrow Service		2-Low	2 -Low	4	2 -Low	4	Could limit the operating time for ZEMU	Mitigate	Engage FRA through design process and laboratory testing and test on independent track in advance of letter of concurrence	Stadler/SBCTA	
Active	R.5	Opportunity	Regulatory	FRA Rule Making	ZEMU project could set the precedence for rule making for battery operated passenger rail vehicles. Could result in decreased time for approvals to operate with passengers		3-Moderate	4 -Moderate	12	2 -Low	6	could result in decreased timelines (<1 year) for approval to operate with passengers	Exploit	SBCTA to be involved with rule making for ZEMU rail vehicles	Stadler/SBCTA	
Active	TV.1	Threat	Technical - Vehicle	DMU Fleet Conversion to Battery	Potential for major vehicle modifications to existing DMU vehicles as a result of new wiring, additional weight on the vehicle axels etc. Design has not yet been developed by Stadler		2-Low	8 -High	16	4 -Moderate	8	If Stadler cannot incorporate design changes into current fleet; could result in signficant delays and costs during DMU to ZEMU Conversion	Avoid	Select technology by July Board Meeting in order to allow for Stadler to incorporate necessary design changes into existing DMU fleet. Solicit proposal from Stadler for this work in July.	SBCTA	
Active	TV.2	Threat	Technical - Vehicle	Batteries Longevity	Battery technology is continuing to change and has not been widely implemented in transit. There are limited studies which document reliability and longevity of batteries, or averages for distance traveled, power supply, lifetime replacement of batteries, performance of specific chemistries etc.		3-Moderate	2 -Low	6	4 -Moderate	12	Battery technologies could change during life of project resulting in design changes, if battery perform poorly, could result in design changes	Mitigate	Complete independent track testing to confirm longevity of batteries and reliability of service/power supply	Stadler/SBCTA	
Active	TV.3	Threat	Technical - Vehicle	Vehicle Charging - Overhead	Use of overhead vehicle battery charger in mixed-use corridor with passenger rail and freight. Larger clearances are required due to freight and Metrolink vehicles resulting in a more unique and/or expensive design for charging infrastructure. Should a malfunction occur during operations there could also be a conflict with freight vehicles/Metrolink vehicles in the corridor. This could result in additional review requirements by the FRA		3-Moderate	2 -Low	6	2 -Low	6	unknowns associated with design costs, design requirements, safety requirements, reliability	Mitigate	Engineering design required once a technology has been selected and vehicle design is advanced. Coordination with Stadler will be required. Design should consider detection in ROW to indiciate if there is a malfunction. Design should also consider manual retraction in the case of a mechanical malfunction	Stadler/SBCTA	
Active	TV.4	Threat	Technical - Vehicle	Battery ZEMU - Delivery Risk	Stadler design and engineering takes longer than estimated. Possibly due to FRA related changes or delays or insufficient resources committed to project by Stadler.	Stadler order book is quite busy.	3-Moderate	2 -Low	6	4 -Moderate	12	See risk R.3 for FRA related risk. Stadler may not see this project as a priority if only a single vehicle is procured	Mitigate	Regular communication with Stadler and regular project milestones where project progress is statused.	SBCTA	
Active	TV.5	Threat	Technical - Vehicle	Battery ZEMU - Design risk	The Stadler vehicle design is heavily influenced by unforseen FRA requirements significantly influencing the vehicle / propulsion system pricing.	Assuming a risk sharing approach to SBCTA/Stadler partnership in order to minimise Stalder's cost proposal.	2-Low	8 -High	16	4 -Moderate	8	Could result in claims, or delays to design due to new requirements or unforseen challenges	Mitigate	Risk sharing arrangement with Stadler to ensure they are incentivised to deliver but also do not overprice risk in base proposal. Ensure Stadler include all reasonable safety related design considerations in base scope. Early engagement with FRA.	Stadler/SBCTA	
Active	TV.6	Threat	Technical - Vehicle	Battery ZEMU - Battery design life over estimated	The battery life expectancy is lower than predicted due to operational behaviors not foreseen. Significantly increasing life cycle costs.	Assume not covered by warranty	2-Low	8 -High	16	1 -Very Low	2	Potential replacement of batteries or engagement of new battery supplier mid way through the project life resulting in additional costs and delays to the project	Mitigate	Ensure operational management and training programs cover the need to keep batteries at healthy state of charge. Design sufficient capacity into battery system to provide reasonable sufficient operational flexibility (for storage and unforseen delays, etc).	SBCTA	
Active	TV.7	Threat	Technical - Vehicle	Battery ZEMU - Immature technology / poor reliability	Poor reliability increases maintenance costs and spares consumption.		2-Low	4 -Moderate	8	1 -Very Low	2	Potential replacement of batteries or engagement of new battery supplier mid way through the project life resulting in additional costs and delays to the project	Mitigate	Ensure warranties are provided on all components. Maintenance training program to ensure OEM recommendations are followed.	SBCTA	

LEVEL 2 - RISK REGISTER				Project Name:	SBCTA ZEMU PROJECT - BATTERY ZEMU RISK REGISTER		Owner:	SBCTA	Project Manager	Carrie Schindler						
Risk Identification							Risk Assessment						Risk Response			
Status	ID #	Type	Category	Title	Risk Statement	Current status/assumptions	Probability	Cost Impact	Cost Score	Time Impact	Time Score	Rationale	Strategy	Response Actions	Risk Owner	Updated
Active	TV.8	Threat	Technical - Vehicle	Battery ZEMU - Supplier	Stadler has not revealed who they are partnered with to supply the battery for the ZEMU. Could result in a partnership with a less reliable battery supplier or a supplier who does not specialize in the preferred battery chemistry		2-Low	2 -Low	4	2 -Low	4	It is likely that Stadler will engage SBCTA on battery supplier. Risk is Low	Mitigate	Solicit proposal from Stadler for ZEMU vehicle once a technology decision has been made. Confirm that SBCTA will be engaged during design process and have input into the battery integration and supplier. Also suggest that the battery is standardized as much as possible to allow for flexibility with future replacements	SBCTA	
Active	TI.1	Threat	Technical - Infastructure	Wayside Charging	Final design for wayside charging infrastructure is still to be developed. ROW impacts and impacts to stations are not anticipated to be signficiant however there is a potential that the design could change		2-Low	4 -Moderate	8	2 -Low	4	Could result in design delays and increased costs should the design change significantly for power supply	Mitigate	Advance concept design for WESS early in phase 2 to identify any constraints	SBCTA	
Active	TI.2	Threat	Technical - Infastructure	Battery WESS - Battery design life over estimated	The wayside battery life expectancy is lower than predicted due to operational behaviors not foreseen. Significantly increasing life cycle costs.	Assume not covered by warranty	1-Very Low	8 -High	8	1 -Very Low	1	Wayside system will always be connected to utility supply so likelihood of energy storage state of charge impacting life is less than the OESS.	Mitigate	System to be designed to automatically manage battery health. Less dependent on operators. Pass on duty cycle requirements to supplier as part of the purchase agreement and ensure verification/validation of life predictions is provided by supplier.	SBCTA	
Active	TI.3	Threat	Technical - Infastructure	Battery WESS - Energy / Power cost savings not realised	Energy storage system does not perform like specified, causing need for higher peak power demand. Therefore higher operational costs.		1-Very Low	8 -High	8	1 -Very Low	1	Low schedule impact, but could result in significant energy costs	Mitigate	Pass on performance requirements to supplier as part of the purchase agreement and ensure verification/validation (testing) of performance predictions is provided by supplier.	SBCTA	
Active	TI.4	Opportunity	Technical - Infastructure	Battery WESS - Energy / Power cost savings underestimated	SBCTA able to negotiate more favorable power costs over time as they are able to minimize demand during on-peak hours due to energy storage capability.		3-Moderate	2 -Low	6	1 -Very Low	3		Exploit	Engage utility to provide more favorable rates based on performance.	SBCTA	
Active	IC.1	Threat	Implementation Costs	Power Supply (SCE)	Uncertainity in costs associated with obtaining necessary power to power supply (for TPSS and WESS). Should dedicated feeders be required; Southern California Edison may have signficant costs to construct new infrastructure to provide power		3-Moderate	4 -Moderate	12	4 -Moderate	12	Could result in increased costs and delays to project as a result of dealing with 3rd party provider.	Transfer	Early Engagement with Power Company (SCE) to determine any constraints for power supply in the region or requirements for providing new service. Start process early to avoid scheduling delays with SCE review/design/construction	SBCTA	
Active	IC.2	Threat	Implementation Costs	FRA Requirements	Increased implementation costs associated with specific and unforseen design elements required by FRA (safety elements, redundancy in the design etc.)		3-Moderate	2 -Low	6	4 -Moderate	12	Could result in delays and increased costs due to new infrastructure requirements	Mitigate	Early engagement with FRA to identify critical issues with regards to safety. Ensure that concept designs are discussed with FRA to identify any issues which could have signficant impact to the cost	SBCTA	
Active	IC.3	Opportunity	Implementation Costs	Cost Sharing Opportunities	Pilot project could present opportunities for cost sharing with private suppliers and companies looking to be involved in first ZEMU rail vehicle in southern california. Could result in a change in scope of project should additional partners become involved.		3-Moderate	4 -Moderate	12	1 -Very Low	3	Coordination with 3rd parties could delay schedule. Impact would be minimal	Exploit	Continue to engage with industry suppliers, vehicle suppliers etc. early to identify opportunities	SBCTA	
Active	IC.4	Threat	Implementation Costs	Operating Plan Amendments	Coordination required with existing operating company (OmniTrans) to amend operating proceedures for ZEMU Vehicles. Engagement will be required with third parties to revise emergency operating proceedures, failure recover scenarios etc. for ZEMU. Potential for delays or challenges due to conflicts with Omni Trans current operations		3-Moderate	2 -Low	6	1 -Very Low	3	Coordination with 3rd parties could delay schedule. Impact would be minimal	Share	Early coordination and engagement with Omni Trans (and other 3rd parties) during Phase 2 - Engineering	SBCTA/OmniTrans	
Active	IC.5	Threat	Implementation Costs	Maintenance Plan Amendments	Coordination required with existing operating company (OmniTrans) to amend maintenance proceedures for ZEMU Vehicles. Staff will require training to understand differences with vehicle technologies. Potential for delays or challenges due to conflicts with Omni Trans current operations		3-Moderate	2 -Low	6	1 -Very Low	3	Coordination with 3rd parties could delay schedule. Impact would be minimal	Share	Early coordination and engagement with Omni Trans during Phase 2	SBCTA/OmniTrans	
Active	IC.6	Threat	Implementation Costs	Operating Plan Amendments	Headways and runtimes of existing Arrow Service could be impacted by pilot project. it is unlikely that the ZEMU vehicle will be able to carry passengers. While vehicle is under testing, the two existing DMUs will need to operate while a 3rd vehicle is running. turn around times may be impacted by the ZEMU vehicle and charging times etc.		3-Moderate	4 -Moderate	12	4 -Moderate	12	Could impact RPRP Revenue Service	Mitigate	Complete operation modeling to determine if ZEMU will impact Arrow Service timetable	SBCTA/OmniTrans	
Active	IC.7	Threat	Implementation Costs	Operating Plan Amendments	Potential for claims related to operating delays as a result of ZEMU pilot project - depeding on operating agreements between SBCTA/OmniTrans		3-Moderate	8 -High	24	2 -Low	6	Could impact RPRP Revenue Service	Share	Early coordination and engagement with Omni Trans during Phase 2	SBCTA/OmniTrans	
Active	IC.8	Threat	Implementation Costs	Stadler Contract	Potential for change orders related to Stadler contract as a result of a) unknown FRA requirements b) delays in schedule as a result of FRA process c) uncertainties with technology and unforseen design challenges d) infrastructure delays e) testing delays f) operator and maintenace delays		4-High	8 -High	32	8 -High	32		Transfer	Risk sharing arrangement with Stadler to ensure they are incentivised to deliver but also do not overprice risk in base proposal. Ensure Stadler include all reasonable safety related design considerations in base scope. Early engagement with FRA.	SBCTA	
Active	IC.9	Threat	Implementation Costs	Future Expansion	If batteries are selected for RPRP corridor and the corridor is then expanded to the edge of SBCTA County line or LA Union Station, there will be signficant costs associated with implementing in route chargers along the corridor		4-High	16 - Very High	64	4 -Moderate	16	Signficant captial cost to expansion. Chargers will be required at every station and dwell times could also be impacted	Mitigate	Confirm if SBCTA plans to extend the corridor in the future before selecting the ZEMU Vehicle as well as the power supply	SBCTA/OmniTrans	
Active	IC.10	Threat	Implementation Costs	Future Expansion	If WESS are selected as power supply based on current Arrow Service timetables, and then time table frequency is increased in the future. TPSS would have been the preffered power supply option to serve the larger power demand		3-Moderate	2 -Low	6	2 -Low	6	Could result in inefficiencies in service	Mitigate	Confirm if SBCTA plans for longer term operations	SBCTA	

LEVEL 2 - RISK REGISTER				Project Name:	SBCTA ZEMU PROJECT - BATTERY ZEMU RISK REGISTER		Owner:	SBCTA	Project Manager	Carrie Schindler					
Risk Identification							Risk Assessment						Risk Response			
Status	ID #	Type	Category	Title	Risk Statement	Current status/assumptions	Probability	Cost Impact	Cost Score	Time Impact	Time Score	Rationale	Strategy	Response Actions	Risk Owner	Updated
Active	EV.1	Threat	Socio-Economic and Environmental	Public Support for Project	Public perception new propulsion technology and risk/safety concerns. Public could also have concerns related to additional construction for ZEMU infrastructure following opening day for Arrow Service.		1-Very Low	1 -Very Low	1	1 -Very Low	1	Low risk	Accept	Prepare and plan for public engagement process to provide information to the community on the project benefits, timelines, safety, risks and construction impacts.	SBCTA	
Active	EV.2	Opportunity	Socio-Economic and Environmental	Public Support for Project	Improvements to emissions and noise within RPRP Corridor		3-Moderate	1 -Very Low	3	1 -Very Low	3	No cost of schedule impact. Socioecomonic benets	Enhance	Use these benefits to help with Risk EV.1.	SBCTA	
Active	M.1	Threat	Market Availability	Power Supply	Prices of electricty could fluctuate throughout life of project		4-High	4 -Moderate	16	2 -Low	8	Could result in increased operating costs	Mitigate	Look at strategies to implement WESS to reduce peak power demand (if suitable) and partner with power companies to ensure surcharge on energy prices are mitigated	SBCTA	
Active	M.2	Opportunity	Market Availability	Battery Supply	Improvement to Battery design and chemistry could result in decreased operating costs over time. Also on-selling of used batteries can recuperate costs.		3-Moderate	4 -Moderate	12	2 -Low	6		Exploit	Ensure that vehicles can be modified with batteries from different suppliers. This will allow for competitive pricing when replacing batteries and end of life.	SBCTA/Stadler	
Active	M.3	Threat	Market Availability	Battery Supply	Stadler Vehicle design could result in a single battery supplier being required to provide batteries for the duration of the vehicle life. This could result in lack of competitive prices for future replacement of batteries and also opens SBCTA to an obsolescence risk if that supplier discontinues support of that product.		2-Low	4 -Moderate	8	2 -Low	4	Could result in increased replacement costs if battery supplier does not provide decreased cost to SBCTA	Avoid	If possible; specify in Stadler contract that battery integration be independent of the supplier to allow for opportunity to partner with new suppliers.	SBCTA	
Active	M.4	Threat	Market Availability	Overhead Catenary Charger	Charging infrastructure for rail vehicles in mixed use corridor is relatively new. Could be challenging to find supplier for this corridor with compeitive pricing		3-Moderate	2 -Low	6	2 -Low	6		Mitigate	Design and research should be completed early on in Phase 2 Engineering.	SBCTA	

LEVEL 2 - RISK REGISTER				Project Name:	SBCTA ZEMU PROJECT - HYDROGEN HYBRID ZEMU RISK REGISTER		Owner:	SBCTA	Project Manager	Carrie Schindler						
Risk Identification							Risk Assessment						Risk Response			
Status	**ID #**	**Type**	**Category**	**Title**	**Risk Statement**	**Current status/assumptions**	**Probability**	**Cost Impact**	**Cost Score**	**Time Impact**	**Time Score**	**Rationale**	**Strategy**	**Response Actions**	**Risk Owner**	**Updated**
Active	R.1	Threat	Regulatory	FRA Compliance	Uncertainty regarding the FRA approval process - It is not clear as to whether a Waiver or Letter of Concurrence will be required in order to operate the Hybrid FCEMU. The timeline to obtain each can vary signficantly. Our assumption is that a letter of concurrence is required. If a waiver is required, this could result in a signficiant delay to the schedule (in lieu of a Letter of Concurrence)	CNG approval (BNSF) required a Letter of Concurrence	4-High	2 -Low	8	8 -High	32	could result in 1 year delay and 25% increase in PM costs	Mitigate	Early Engagement with FRA after a technology decision has been made to develop a better understanding of the requirements and the schedule	SBCTA	
Active	R.2	Threat	Regulatory	FRA Approval Timeline	Delays in issuance of approval to operate pilot due to new propulsion technology. FRA could extend the typical timelines.	CNG approval (BNSF) required a Letter of Concurrence. This took 6 months to obtain Letter of Conurrence to pilot the vehicle	3-Moderate	1 -Very Low	3	2 -Low	6	for a letter of concurrence assume 6 months. Risk could result in 1-4 months delay	Accept	Early Engagement with FRA after a technology decision has been made to develop a better understanding of the requirements and the schedule	SBCTA	
Active	R.3	Threat	Regulatory	FRA Testing Requirements	Unknown Federal lab testing requirements for hydrogen battery hybrid technology		2-Low	1 -Very Low	2	1 -Very Low	2	Additional testing may be required for hydrogen equipment but would not result in significant costs or schedule delays	Mitigate	Early Engagement with FRA after a technology decision has been made to develop a better understanding of the requirements and ensure contract with Stadler considers all FRA requirements as best as we can	Stadler	
Active	R.4	Threat	Regulatory	FRA Restrictions on Pilot Tests	Potential for unforseen restrictions related to the use of hydrogen or batteries for operating the pilot test hybrid FCEMU on the same track as the Arrow Service		2-Low	2 -Low	4	2 -Low	4	Could limit the operating time for ZEMU	Mitigate	Engage FRA through design process and laboratory testing and test on independent track in advance of letter of concurrence	Stadler/SBCTA	
Active	R.5	Opportunity	Regulatory	FRA Rule Making	Hybrid FCEMU project could set the precedence for rule making for battery operated passenger rail vehicles. Could result in decreased time for approvals to operate with passengers		3-Moderate	4 -Moderate	12	2 -Low	6	could result in decreased timelines (<1 year) for approval to operate with passengers	Exploit	SBCTA to be involved with rule making for ZEMU rail vehicles	Stadler/SBCTA	
Active	TV.1	Threat	Technical - Vehicle	DMU Fleet Conversion to Hydrogen FCEMU	Potential for major vehicle modifications to existing DMU vehicles as a result of new wiring, addition of fuel cell tanks, etc. Design has not yet been developed by Stadler.		2-Low	8 -High	16	4 -Moderate	8	If Stadler cannot incorporate design changes into current fleet; could result in signficant delays and costs during DMU to ZEMU Conversion	Avoid	Select technology by July Board Meeting in order to allow for Stadler to incorporate necessary design changes into existing DMU fleet. Solicit proposal from Stadler for this work in July.	SBCTA	
Active	TV.2	Threat	Technical - Vehicle	DMU Fleet Conversion to Hydrogen FCEMU	Potential for lack of sufficient storage space on existing DMU vehicles for hydrogen tanks or issues related to weight/loading on vehicle axels. Design has not yet been developed by Stadler.		2-Low	8 -High	16	4 -Moderate	8	If Stadler cannot incorporate full capacity of hydrogen on current DMU design; could result in signficant delays and costs during DMU to ZEMU Conversion for a more signficiant retrofit	Mitigate	Select technology by July Board Meeting in order to allow for Stadler to begin design concept for new and converted hydrogen hybrid. Solicit proposal from Stadler for this work in July.	SBCTA	
Active	TV.3	Threat	Technical - Vehicle	Hybrid FCEMU - Delivery Risk	Stadler design and engineering takes longer than estimated. Possibly due to FRA related changes or delays or insufficient resources committed to project by Stadler.	Stadler order book is quite busy.	3-Moderate	2 -Low	6	4 -Moderate	12	See risk R.3 for FRA related risk. Stadler may not see this project as a priority if only a single vehicle is procured	Mitigate	Regular communication with Stadler and regular project milestones where project progress is statused.	SBCTA	
Active	TV.4	Threat	Technical - Vehicle	Hybrid FCEMU - Design risk	The Stadler vehicle design is heavily influenced by unforseen FRA requirements significantly influencing the vehicle / propulsion system pricing.	Assuming a risk sharing approach to SBCTA/Stadler partnership in order to minimise Stalder's cost proposal.	2-Low	8 -High	16	4 -Moderate	8	Could result in claims, or delays to design due to new requirements or unforseen challenges	Mitigate	Risk sharing arrangement with Stadler to ensure they are incentivised to deliver but also do not overprice risk in base proposal. Ensure Stadler include all reasonable safety related design considerations in base scope. Early engagement with FRA.	Stadler/SBCTA	
Active	TV.5	Threat	Technical - Vehicle	Hybrid FCEMU - Fuel Cell design life over estimated	The fuel cell life and/or battery expectancy is lower than predicted due to operational behaviors not foreseen. Significantly increasing life cycle costs.	Assume not covered by warranty	2-Low	8 -High	16	1 -Very Low	2	Potential replacement of both fuel cells and batteries. Engagement of new supplier mid way through the project life resulting in additional costs and delays to the project	Mitigate	Ensure operational management and training programs cover the need to keep batteries at healthy state of charge. Design sufficient capacity into battery system to provide reasonable sufficient operational flexibility (for storage and unforseen delays, etc).	SBCTA	
Active	TV.6	Threat	Technical - Vehicle	Hybrid FCEMU - Immature technology / poor reliability	Poor reliability increases maintenance costs and spares consumption.		2-Low	4 -Moderate	8	1 -Very Low	2	Potential replacement of both fuel cells and batteries. Engagement of new supplier mid way through the project life resulting in additional costs and delays to the project	Mitigate	Ensure warranties are provided on all components. Maintenance training program to ensure OEM recommendations are followed.	SBCTA	
Active	TI.1	Threat	Technical - Infastructure	Hydrogen Dispensing	Final design for hydrogen dispensing infrastructure (fuel tanks, fueling equipment and hydrogen production facility) is still to be developed. ROW impacts and impacts to stations are not anticipated to be signficiant however there is a potential that the design could change		2-Low	4 -Moderate	8	2 -Low	4	Could result in design delays and increased costs should the design change significantly for hydrogen and power supply for batteries	Mitigate	SBCTA to make a decision on hydrogen supply in July for pilot project and for long term applications. Advance concept design early in phase 2 to identify any constraints	SBCTA	
Active	TI.2	Threat	Technical - Infastructure	Hydrogen Production vs. Purchasing	Risks associated with design/construction of a hydrogen production facility (SMR or Electrolysis). Design still to be developed and independent risk assessment should be completed for this project to consider safety risks, and potential risk in operating costs for SBCTA to produce hydrogen.		3-Moderate	16 - Very High	48	4 -Moderate	12	Could result in design delays and increased costs should a production facility be constructed which has unforseen costs/risks that have not been considered in this register	Mitigate	SBCTA to make a decision on hydrogen supply in July for pilot project and for long term applications. Advance concept design early in phase 2 to identify any constraints. Develop risk register for Hydrogen Production and consider as separate project.	SBCTA	

LEVEL 2 - RISK REGISTER				Project Name:	SBCTA ZEMU PROJECT - HYDROGEN HYBRID ZEMU RISK REGISTER		Owner:	SBCTA	Project Manager	Carrie Schindler						
Risk Identification							Risk Assessment						Risk Response			
Status	ID #	Type	Category	Title	Risk Statement	Current status/assumptions	Probability	Cost Impact	Cost Score	Time Impact	Time Score	Rationale	Strategy	Response Actions	Risk Owner	Updated
Active	TI.3	Threat	Technical - Infastructure	Battery - Energy / Power cost savings not realised	Batteries do not perform as specified, causing need for higher demand on the fuel cell stack. Therefore a lower efficiency for the fuel cell stacks, and thus a higher hydrogen consumption rate than planned for.		1-Very Low	8 -High	8	1 -Very Low	1		Mitigate	Pass on performance requirements to supplier as part of the purchase agreement and ensure verification/validation (testing) of performance predictions is provided by supplier.	SBCTA	
Active	TI.4	Opportunity	Technical - Infastructure	Energy / Power cost savings underestimated	SBCTA able to negotiate more favorable power costs over time as they are able to minimize demand (from hydrogen production processes) during on-peak hours due to increased onsite storage, or possibly a higher rate of hydrogen production during off-peak hours	Higher rate of production would mainly be achieved through an upgrade to the H2 production equipment	3-Moderate	2 -Low	6	1 -Very Low	3		Exploit	Engage utility to provide more favorable rates based on performance.	SBCTA	
Active	IC.1	Threat	Implementation Costs	Power Supply (SCE)	Unknown costs associated with obtaining necessary power to power supply (for hydrogen production). Should dedicated feeders be required; Southern California Edison may have signficant costs to construct new infrastructure to provide power		3-Moderate	4 -Moderate	12	4 -Moderate	12	Could result in increased costs and delays to project as a result of dealing with 3rd party provider.	Transfer	Early Engagement with Power Company (SCE) to determine any constraints for power supply in the region or requirements for providing new service. Start process early to avoid scheduling delays with SCE review/design/construction	SBCTA	
Active	IC.2	Threat	Implementation Costs	FRA Requirements	Increased implementation costs associated with specific and unforseen design elements required by FRA (safety elements, redundancy in the design etc.)		3-Moderate	2 -Low	6	4 -Moderate	12	Could result in delays and increased costs due to new infrastructure requirements	Mitigate	Early engagement with FRA to identify critical issues with regards to safety. Ensure that concept designs are discussed with FRA to identify any issues which could have signficant impact to the cost	SBCTA	
Active	IC.3	Opportunity	Implementation Costs	Cost Sharing Opportunities	Pilot project could present opportunities for cost sharing with private suppliers and companies looking to be involved in first hybrid FCEMU rail vehicle in southern california. Could result in a change in scope of project should additional partners become involved.		3-Moderate	2 -Low	6	2 -Low	6	Coordination with 3rd parties could delay schedule. Impact would be minimal	Exploit	Continue to engage with industry suppliers, vehicle suppliers etc. early to identify opportunities	SBCTA	
Active	IC.4	Threat	Implementation Costs	Operating Plan Amendments	Coordination required with existing operating company (OmniTrans) to amend operating proceedures for ZEMU Vehicles. Engagement will be required with third parties to revise emergency operating proceedures, failure recover scenarios etc. for ZEMU. Potential for delays or challenges due to conflicts with Omni Trans current operations		3-Moderate	2 -Low	6	1 -Very Low	3	Coordination with 3rd parties could delay schedule. Impact would be minimal	Share	Early coordination and engagement with Omni Trans (and other 3rd parties) during Phase 2 - Engineering	SBCTA/OmniTrans	
Active	IC.5	Threat	Implementation Costs	Maintenance Plan Amendments	Coordination required with existing operating company (OmniTrans) to amend maintenance proceedures for ZEMU Vehicles. Staff will require training to understand differences with vehicle technologies. Potential for delays or challenges due to conflicts with Omni Trans current operations		3-Moderate	2 -Low	6	1 -Very Low	3	Coordination with 3rd parties could delay schedule. Impact would be minimal	Share	Early coordination and engagement with Omni Trans during Phase 2	SBCTA/OmniTrans	
Active	IC.6	Threat	Implementation Costs	Operating Plan Amendments	Headways and runtimes of existing Arrow Service could be impacted by pilot project. it is unlikely that the hydrogen FCEMU vehicle will be able to carry passengers. While vehicle is under testing, the two existing DMUs will need to operate while a 3rd vehicle is running.		3-Moderate	4 -Moderate	12	4 -Moderate	12	Could impact RPRP Revenue Service	Mitigate	Complete operation modeling to determine if ZEMU will impact Arrow Service timetable	SBCTA/OmniTrans	
Active	IC.7	Threat	Implementation Costs	Operating Plan Amendments	Potential for claims related to operating delays as a result of ZEMU pilot project - depeding on operating agreements between SBCTA/OmniTrans		3-Moderate	8 -High	24	2 -Low	6	Could impact RPRP Revenue Service	Share	Early coordination and engagement with Omni Trans during Phase 2	SBCTA/OmniTrans	
Active	IC.8	Threat	Implementation Costs	Stadler Contract	Potential for change orders related to Stadler contract as a result of a) unknown FRA requirements b) delays in schedule as a result of FRA process c) uncertainties with technology and unforseen design challenges d) infrastructure delays e) testing delays f) operator and maintenace delays		4-High	8 -High	32	8 -High	32		Transfer	Risk sharing arrangement with Stadler to ensure they are incentivised to deliver but also do not overprice risk in base proposal. Ensure Stadler include all reasonable safety related design considerations in base scope. Early engagement with FRA.	SBCTA	
Active	IC.9	Threat	Implementation Costs	Future Expansion	If hydrogen FCEMU's are selected for RPRP corridor and the corridor is then expanded to the edge of SBCTA County line or LA Union Station, there will be increased costs associated with increasing the amount of hydrogen storage and hydrogen required. This will result in increased costs to purchase or produce hydrogen and an additional hydrogen fueling station may be required.	2-Car can carry sufficent H2 to to complete 2 round trips. However increased fueling infrastructure and H2 production would be required to operate the service. Should a 4 car be implemented this will increase further	3-Moderate	4 -Moderate	12	2 -Low	6	Costs associated with extra H2 storage and fueling infrastructure for expansion	Mitigate	Confirm if SBCTA plans to extend the corridor in the future and ensure that Hydrogen production can consider future expansion	SBCTA	
Active	IC.10	Threat	Implementation Costs	Future Expansion	If ZEMUs are expanded to LA Union Station, additional vehicles will need to be added to fleet which will increase hydrogen requirements (production or purchasing of hydrogen)	hydrogen production facility should be sized appropriately to handle future expansion	3-Moderate	8 -High	24	4 -Moderate	12	Costs associated with extra H2 storage and fueling infrastructure for expansion as well as to fuel more vehicles	Mitigate	Confirm if SBCTA plans to extend the corridor in the future and ensure that Hydrogen production can consider future expansion	SBCTA	
Active	EV.1	Threat	Socio-Economic and Environmental	Public Support for Project	Public perception new propulsion technology, use of hydrogen in public environment and risk/safety concerns.		3-Moderate	4 -Moderate	12	4 -Moderate	12	H2 could require more extensive public outreach	Accept	Prepare and plan for public engagement process to provide information to the community on the project benefits, timelines, safety, risks and construction impacts.	SBCTA	
Active	EV.2	Opportunity	Socio-Economic and Environmental	Public Support for Project	Improvements to emissions and noise within RPRP Corridor		3-Moderate	1 -Very Low	3	1 -Very Low	3	No cost or schedule impact. Socioecomonic benets	Enhance	Use these benefits to help with Risk EV.1.	SBCTA	
Active	EV.3	Opportunity	Socio-Economic and Environmental	100% Renewable Hydrogen	Could look for opportunities to produce or purchase 100% Renewable hydrogen, therefore reducing the overall GHG emissions even further for the project		4-High	4 -Moderate	16	1 -Very Low	4	Cost could be impacted depending on the price for renewable electrcity. Socioecomonic benets	Enhance	Use these benefits to help with Risk EV.1.	SBCTA	
Active	M.1	Threat	Market Availability	Power Supply	Prices of electricty could fluctuate throughout life of project, which would impact the prices of the various onsite hydrogen production pathways.		4-High	4 -Moderate	16	2 -Low	8	Could result in increased operating costs	Mitigate	Look at strategies to reduce peak power demand (if suitable) and partner with power companies to ensure surcharge on energy prices are mitigated	SBCTA	

LEVEL 2 - RISK REGISTER				Project Name:	SBCTA ZEMU PROJECT - HYDROGEN HYBRID ZEMU RISK REGISTER		Owner:	SBCTA	Project Manager	Carrie Schindler								
Risk Identification							Risk Assessment							Risk Response				
Status	ID #	Type	Category	Title	Risk Statement	Current status/assumptions	Probability	Cost Impact	Cost Score	Time Impact	Time Score	Rationale	Strategy	Response Actions	Risk Owner	Updated
Active	M.2	Threat	Market Availability	Hydrogen Supply	Should SBCTA initially purchase the hydrogen (rather then produce), prices of H2 could fluctuate throughout life of project, which would impact the overall operating cost to SBCTA. If operating costs are so signficiant and there are no funds to construct a production facility, the ZEMU operation could be terminated or put on hold.		4-High	8 -High	32	1 -Very Low	4	Could result in signficant increase operating costs.	Mitigate	Look at strategies to partner with supply companies to ensure surcharge and fluctuation on fuel prices are mitigated as best as possible. Ultimately look to construct a hydrogen production facility	SBCTA	
Active	M.3	Opportunity	Market Availability	Fuel Cell Supply	Improvement to fuel cell design could result in decreased capital costs (and possibly maintenance costs) over time		3-Moderate	4 -Moderate	12	2 -Low	6		Exploit	Ensure that vehicles can be modified with batteries from different suppliers. This will allow for competitive pricing when replacing batteries and end of life.	Stadler/SBCTA	
Active	M.4	Threat	Market Availability	Fuel Cell Supply	Stadler Vehicle design could result in a single fuel cell supplier being required to provide fuel cells for the duration of the vehicle life. This could result in lack of competitive prices for future replacement of fuel cell stacks and also opens SBCTA to an obsolescence risk if that supplier discontinues support of that product.		2-Low	4 -Moderate	8	2 -Low	4	Could result in increased replacement costs if battery or fuel cell supplier does not provide decreased cost to SBCTA	Avoid	If possible; specify in Stadler contract that fuel cell and battery integration be independent of the supplier to allow for opportunities in the future for new suppliers	SBCTA	
Active	M.5	Threat	Market Availability	Hydrogen Storage Tanks	Hydrogen storage tanks for atop rail vehicles is relatively new. Could be challenging to find supplier with compeitive pricing for tanks designed to be put atop a multiple unit vehicle		3-Moderate	2 -Low	6	2 -Low	6		Mitigate	Design and research should be completed early on in Phase 2 Engineering.	SBCTA	

L. Battery and Hydrogen Fuel Cell Hybrid Evaluation Matrix

Technology Alternatives for Vehicle Power				**Lithium Ion Battery (LIB)**	**Hydrogen FC Hybrid**
General Description of Technology				**A battery is a device that converts chemical energy into electrical energy to provide onboard power. In Lithium Ion type configurations, lithium ions move from the negative electrode (anode) to the positive electrode (cathode) during discharge and in the opposite direction during charging. Different chemistries are combined to form the cathode and anode of a LIB, which result in many different specific configurations of LIBs.**	**Chemical reaction between hydogren fuel and oxygen across cellular membrane produces electricity to power vehicle and emits water as exhaust. Combined system of HFCs and battery packs. The HFCs provide the average power while batteries provide peak power and capability to regenerate energy.**
Specific Types				**Lithium Titanate (LTO)**	**Proton Exchange Membrane (PEM) / LTO**
Description				Modified LIB which utilizes lithum titanate nano-crystals for the anode.	
Suppliers (Vehicle or *Technology Specific)				*Centum Adetel, *ABB	
Evaluation Criteria					
	Weighting		***Weighting***		
Cost	**0.25**	Cost - Capital	0.10	Total capital cost depends on fleet size. Per vehicle may be approximately 20% extra on top of an equivalent DMU cost. Requires capital for charging stations which for longer network mileage could be significant. However, research shows LTOs to cost the most of LIB at an average $1000/kWh	Total capital cost depends on fleet size. Per vehicle may be approximately 20-30% extra on top of an equivalent DMU cost. Requires capital for fuel stations, several hydrogen production options are available. This rating is based on Electrolysis as it is the best emission option but also most Capital cost. SMR would be cheaper.
		Cost - Operations (fuel cost / energy efficiency)	0.08	Electricity supplied by grid. Slightly worse efficiency than OSC due to losses in charging cycles, however can store regenerated power from braking. LTO has the highest charging efficiency of the LIB chemistries.	Electrolysis is similar fuel cost to diesel, hydrogen production by SMR would be approx 40% of the cost. HFC hybrid provides a roughly 50% energy consumption reduction from operations (on-vehicle) compared to diesel.
		Cost - Life Cycle (maintenance)	0.08	Replace batteries after approximately 7 years, however they may have residual re-sale value. Minimal preventative maintenance required (less than diesel engine). Significant cost reductions are anticipated over the life of vehicle but not considered in assessment.	Routine maintenance costs of the HFC are lower than diesel due to fewer moving parts, but capital replacement mean whole LCC more. Significant cost reductions are anticipated over the life of vehicle but not considered in assessment.
Infrastructure	**0.10**	Additional ROW or land acquisition required	0.02	Potentially needed for multiple substations	Production and storage equipment needs to be installed at the MSF.
		Catenary Free (When vehicle is in movement)	0.04	Yes	Yes
		Charging/Fueling Infrastructure Required	0.03	Overhead or under vehicle charging. Can be contact or wireless (inductive) system. Either requires substation(s) to step up/stepdown voltages/currents or wayside energy storage. Generally, voltages at utility distrubution level (13kV or 4kV AC, 3 phase) would be stepped down to 600V-1500V AC then rectified to 600V-1500V DC for charging. Need a footprint of up to 1000 ft2 for TPSS/WESS plus the vehicle interface infrastructure.	An electrolysis station and on-site storage and dispensing is required at the MSF. This will require a approx 1,300 ft2, plus the vehicle interface infrastructure.
		Utility/Fuel Availability	0.02	Supplied from electrical grid, requires a substation to either provide high charging power intermittently or deliver low power to a wayside energy storage.	For electrolysis option, electricity and water nedds to be supplied to the production facility. Other options are available so the operator can react to market changes. This is even an advantage over diesel services.

Technology Alternatives for Vehicle Power				**Lithium Ion Battery (LIB)**	**Hydrogen FC Hybrid**
Environmental Considerations	**0.15**	Land use compatibility	0.01	No emissions are expected during operations, therefore have no impact on sensitive land use receptors in the area. Charging infrastructure may add additional structures within ROW/station area which is also zoned for transportation purposes.	No emissions are expected during operations, therefore have no impact on sensitive land use receptors in the area. The infrastructure will be contained in the MSF which is zoned for industrial purposes.
		Point-of-use / Operations (GHG and regulated emissions)	0.05	Zero Emissions	Zero emissions
		Well-to-Wheel Emissions (GHG and regulated emissions)	0.03	Assuming current California electricity mix, still near zero emissions with potential for true zero if 100% renewables supply electricity	Assuming current California electricity mix, still near zero emissions with potential for true zero if 100% renewables supply electricity. Rated lower than battery because of higher energy consumption than Battery system so higher emission at current California mix.
		Recyclability of components	0.02	The battery cells can be recycled to retreive certain metals, however the applications and commercial viability can be limited. There may be options to on-sell batteries as LIB's do not suffer 'sudden death' failure but rather gradual reduced performance, typically a reduction in capacity of 20-30%. This state is too low for rail vehicle application but could be utilised for other applications, e.g. stationary storage.	Most of the fuel cell is recycleable/re-useable. Only the electrolytic membrane, and some smaller component (valves, etc) will need replacing at overhaul. The carbon fibre hydrogen storage tanks are more complext to be recycled. Some batteries are on-board and will be same characteristics as the battery option.
		High voltage / hazard clearance requirements	0.01	Only at charging points	Potential exclusions while connecting electrolyser, otherwise no high voltages. Hydrogen storage hazards due to pressure and flammability similar to diesel precautions,
		Socio-economic impacts of ZEMU vehicles and infrastructure	0.02	Technology anticipated to be zero emissions which will alleviate some of the pollution as experienced by disadvantaged communities as defined by SB 535. New propulsion technology has potential to create new supporting job opportunities for the local community.	Technology anticipated to be zero emissions which will alleviate some of the pollution as experienced by disadvantaged communities as defined by SB 535. New propulsion technology has potential to create new supporting job opportunities for the local community.
		Aesthetics	0.02	Good	Good
		Noise	0.02	Some noise will be emitted from cooling system fans, but expect the system will be quieter than the equivalent DMU.	Some noise will be emitted from cooling system fans, but expect the system will be quieter than the equivalent DMU.

Technology Alternatives for Vehicle Power				Lithium Ion Battery (LIB)	Hydrogen FC Hybrid
Operations	**0.30**	Range	0.09	Longer range travel will require larger battery pack or more charging points. Note, on average the energy density of LTO batteries is lower than most LIB due to smaller cell voltages.	Most reliable catenary free option for emission free long range travel. Leads to a comparable range to diesel vehicles. Refueling times are also similar to diesel.
		Energy Density (Wh/L)	0.00	170 - 230 Wh/L @ Cell Level	Hydrogen tanks have significantly lower energy density than diesel, but significantly higher than batteries.
		Specific Energy (Wh/kg)	0.00	90 - 130 Wh/kg @ Cell Level	Hydrogen tanks have significantly lower energy density than diesel, but significantly higher than batteries.
		Performance (acceleration / top speed)	0.06	Utilizing LTOs would likely require a larger battery configuration to achieve the requireed power for train performance due to lower power density than LFPs. However, they are also an optimal choice due to higher achievable C-rates. LTO C-Rates: Up to 10C Continuous, 60C Pulse	Fuel cells are comparable to a diesel engine for power to space/weight efficiency, however the full system (including balance of plant and hydrogen tanks) will take much more volume on-board the vehicle. A hybrid system will be able to deliver equivalent performance to diesels by utilizing batteries in addition to the fuel cells.
		Power Density (W/L)	0.00	< 400 W/L @ at nominal C-Rate, but can operate safely at much higher C-Rates	Fuel cells are comparable to a diesel engine for power to space efficiency.
		Specific Power (W/kg)	0.00	< 200 W/kg @ at nominal C-Rate, but can operate safely at much higher C-Rates	Fuel cells are comparable to a diesel engine for power to weight efficiency.
		Energy Recovery from Regenerative Braking	0.02	LTOs have highest C-rates available today, making them the most optimum to accept high amounts of regenerated power. For this ZEMU application, they are considered equivalent in performance to supercapacitors.	a HFC hybrid with LTO batteries will be able to accept the regenerative braking power due to high C-rate capability
		Operational Compatibility	0.02	A battery ZEMU will require operational management of charge levels, while charging infrastructure needs to be designed for compatibility with other network users (i.e. freight and locomotive hauled coaches).	No impact to the ROW or compatibility with mixed traffic networks
		Life span (before replacement)	0.03	3000-8000 charge/discharge cycles	Manafacturers warrant 20,000+ hours of operation for fuel cell stacks. Balance of plant is warranted for 50,000+ hours. N bus operations over 30,000 hours have been demonstrated, and is still on-going without overhaul.
		Frequency of Major Overhauls	0.02	Replace after approximately 7-10 years if managed properly.	For fuel cell systems similar timeframe to batteries, however the tanks and balance of plant would typically last 12-15 years between overhauls.
		Reliability	0.03	A complicated battery and thermal management system is required to achieve reliability. LTO is the most robust and stable chemistry for high charging rates and cycles, and thermal loads.	Appropriate power and thermal management is required for a reliable service. The reliability performance of HFCs to date has been driven by the balance of plant, more than the fuel cells themselves. Battery reliability is similar to comments for LTOs.
		Scalability	0.05	The limitation to scalability is primarily the charging infrastructure required at terminals and en-route for mid-to-long routes.	As their range is much greater without infrastructure support, HFC vehicles allow greater scaling of services than a battery vehicle. For example, a hydrogen train designed to operate the Arrow service, would also be capable of service to LAUS and back (twice) without modification.

Technology Alternatives for Vehicle Power				Lithium Ion Battery (LIB)	Hydrogen FC Hybrid
Regulatory Compliance	**0.05**	FRA, NFPA, Electrical Codes etc.	0.05	Currently, no specific power source standards for rail industry. However, some direction is provided by examples of regulator approval in Europe and the UK. Of the LIB family, the LTO is best placed to pass approvals based on its specific thermal safety characteristics and redunancy of energy capacity. Battery light rail vehicles are in operation in the US.	No current Hydrogen rail operations in the US. Direction of regulator approval process can be taken from a natural gas project. Direction on design detail regulatory acceptance can be taken from Germany (rail), and automotive and buses in the US.
Implementaion Schedule	**0.05**	Time for Planning, Design, Construction Phases	0.05	3 - 4 years for development and delivery of the first vehicle.	4 - 5 years for delivery of first vehicle. Design and regulatory approval for pilot may be 6 to 12 months longer than battery.
Risk Analysis	**0.10**	Availability of Warranty	0.03	Typical warranty would be 2 years leaving a significant risk with SBCTA regarding battery life. Suppliers may be open to extended warranties, however there will be costs involved. SBCTA should discuss with supplier the optimum operating conditions to maintain battery life and warranty.	Manafacturers warrant 20,000+ hours of operation for fuel cell stacks. Balance of plant is warranted for 50,000+ hours. N bus operations over 30,000 hours have been demonstrated, and is still on-going without overhaul.
		Maturity of technology	0.03	First introducted to market in 2008, but not as prevalent as NMC or LFP. Development/implementation is growing and is most suited to rail vehicle applications.	Regional train operating in Germany, light rail in the Middle East and China. Several cars and bus operations in the US. This type of technology has been in service in road applications since the mid 2000's.
		Technology related health, safety & environment risk	0.05	Batteries cannot be completely discharged and therefore remain an inherent hazard that needs to be managed for maintenance and storage. LTO specifically are designed to mitigate overcharge and thermal runaway risks.	Hydrogen facilities require sufficient ventilation and leak detection but are overall a similar hazard to manage as diesel. Similar battery related mitigation measures are required.
Total Weighted Scores	**1.00**		**1.00**	**3.66**	**3.67**

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