ATTACHMENT B

METROLINK

ZERO EMISSIONS TECHNICAL ANALYSIS

prepared for: Metrolink

prepared by: Hatch LTK, STV Inc.

Cambridge Systematics, Inc.

JUNE 2023

TABLE OF CONTENTS

TABLE OF CONTENTS

4. FINDINGS FOR THE PILOT

5. ZERO EMISSIONS PILOT

6. CONCLUSIONS

APPENDICES

FIGURES

FIGURES

TABLES

1 INTRODUCTION

1. INTRODUCTION

The Zero Emissions Technical Analysis (Analysis) evaluates and rates the available zero emission propulsion systems, vehicle types, operational and infrastructure impacts, project cost, safety considerations, and regulatory considerations. This Analysis advances the Southern California Regional Rail Authority's (Metrolink) vision laid out in the Strategic Business Plan (SBP) and Climate Action Plan. Metrolink's Strategic Business Plan approved in January 2021, envisions further reduction of greenhouse gases (GHG), accelerated efforts to a zero emissions fleet between 2026 and 2030, and a transition to a full zero emissions fleet between 2030 and 2050, in alignment with the State of California's goals. In March 2021, Metrolink's Board of Directors also approved the Metrolink Climate Action Plan (CAP). CAP is the agency's first, formal environmentally focused plan, which anchors to the commitments set forth in the SBP.

A key goal of this Analysis is to advance planning for the zero emissions pilot that included as part of the Transit and Intercity Rail Capital Program (TIRCP) Metrolink Antelope Valley Line (AVL) Capital and Service Improvements Project grant received in 2020. Metrolink, in partnership with its member agency, Los Angeles Metropolitan Transit Authority (Metro), was awarded $10 million in Network Integration funding to assess the feasibility of a rail multiple unit (RMU) and zero emissions propulsion service through a pilot project on the Metrolink AVL.

The AVL is the only line that runs in one county, Los Angeles County, and connects riders along a 76-mile corridor from Lancaster in North Los Angeles County to Los Angeles Union Station in Downtown Los Angeles, as shown in Figure 1. It crosses rural, suburban, and urban regions of the county and offers opportunities for land use and transportation to support sustainable communities. However, the terrain of the AVL is challenging especially for zero emission equipment with an elevation gain of nearly 3000 feet.

There are a few ZE alternatives that can be implemented on the AVL. Other than full-scale electrification using overhead catenary, practical ZE rail rolling stock solutions are still in early stages of development, and no "off the shelf" ZE solution is available that would meet Metrolink's needs. Metrolink is thus faced with a complex decision on how to best utilize the available funding to advance its long-term goals as described in CAP and Rail Fleet Management Plan Update. As a result of these decisions and activities, Metrolink initiated an Analysis to develop a rational approach to the ZE pilot and a preferred strategy that appropriately maximizes the potential benefits to Metrolink while mitigating the risks.

The goal of a pilot will be to evaluate the chosen propulsion technology holistically by considering its performance, reliability, maintainability, infrastructure requirements, constraints imposed on operations, and capital and operating costs in revenue service-like operations. The knowledge and experience gained at the end of pilot implementation will be used to develop the master plan for a zero emissions fleet and attain the end goal of having a zero emissions fleet as shown in Figure 2.

The project was conducted in two phases: The first phase consisted of a Gap Analysis, which identified areas where Metrolink required additional information to support an informed decision, along with associated action items (see Appendix A) to address each gap. This created a concise and defined method for selecting a path to completion of a zero emission pilot program and transition to a zero emissions fleet. The second phase entailed development of the Analysis, which includes findings for a technology and vehicle type for pilot program execution using the TIRCP funding (see Appendix H for funding information). This Analysis is supported by technical, financial, and strategic analyses to facilitate decision making.

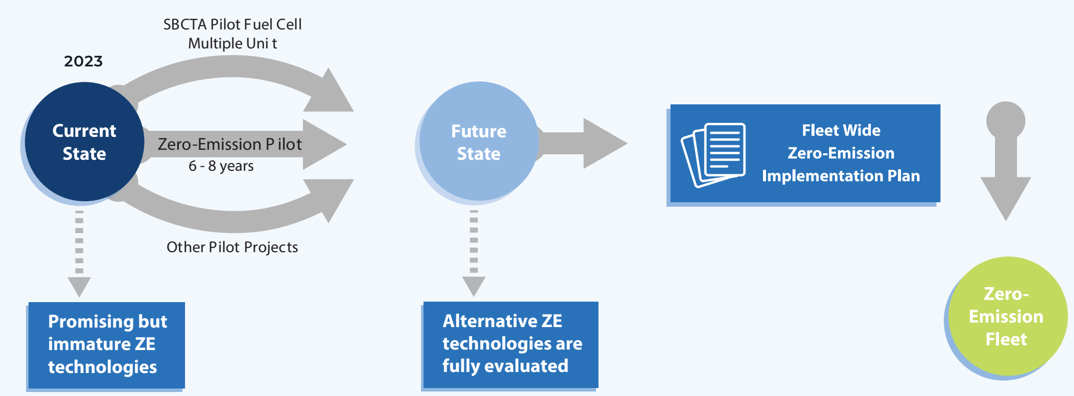
Presently, the most promising propulsion technologies that offer potential for zero emissions are:

- Battery Electric
- Hydrogen Fuel Cell - Battery Hybrid
- Overhead Catenary Electric

Among the zero emission propulsion technologies, full overhead catenary electric propulsion technology was not examined for a pilot as it is already proven but has high capital costs. However, in the strategic assessment sections of the Plan, it is considered as an enabler technology that can complement battery propulsion technology. The Analysis focuses on promising, but immature, battery electric and fuel cell propulsion technologies that have the potential of leading Metrolink to a zero emissions fleet and operations in the long term.

FIGURE 1: ANTELOPE VALLEY LINE ROUTE

FIGURE 2: THE PURPOSE OF ZERO EMISSIONS TECHNICAL ANALYSIS



In addition to propulsion technology, the Analysis provides findings for the type of vehicle that should be utilized for the pilot. For this purpose, the following vehicle types were evaluated:

Vehicle Type / Propulsion Type	New Locomotive	Rebuilt Locomotive	Rail Multiple Unit
Battery Electric	Option 1	Option 2	Option 3
Fuel Cell Battery Hybrid	Option 4	Option 5	Option 6

TABLE 1: OPTIONS FOR ANALYSIS

- Rebuilt Locomotive (Conversion)
- New Locomotive
- Rail Multiple Unit (RMU)

The Analysis benchmarks these technologies and selects one of the options shown in Table 1.

2 PROPULSION TECHNOLOGY BENCHMARK

2. PROPULSION TECHNOLOGY BENCHMARK

During the evaluation of emerging propulsion technologies with many technical and operating unknowns, deploying such technologies for fleet-wide usage is a daunting and risky process and requires a holistic evaluation.

Within this Analysis, propulsion technologies are benchmarked according to various criteria that will identify the advantages and challenges of each.

The technology benchmark results are summarized below:

- Battery electric propulsion is superior to fuel cell battery hybrid propulsion in terms of system efficiency, well-to-wheels GHGs, technology maturity, hardware/software complexity, vehicle cost, and synergistic opportunity with other propulsion technologies (diesel engine and overhead catenary).

- Fuel cell battery hybrid propulsion is superior to battery electric propulsion in terms of range and refueling time.

- Neither fuel cell battery hybrid propulsion nor battery electric propulsion matches the range and refueling time capabilities of diesel propulsion.

- Neither fuel cell battery hybrid propulsion nor battery electric propulsion meets Metrolink's current operational requirements.

2.0 Technology Summary and Possible Implementation Scenarios

Battery Electric Propulsion

With battery electric propulsion, batteries provide the energy required to propel a train through a driver circuitry that controls traction motors as shown in Figure 3. As a result, the interface components between traction motors and batteries are minimal. Once depleted, the batteries need to be charged. Charging can be accomplished by different means such as a pantograph system or plug-in charger. Pantograph systems charge the batteries by an external charger, and plug-in systems use a charger plug connected to the vehicle. In both cases, charger circuitry converts utility- supplied alternating current power to the desired DC voltage level to efficiently charge the batteries in a controlled fashion.

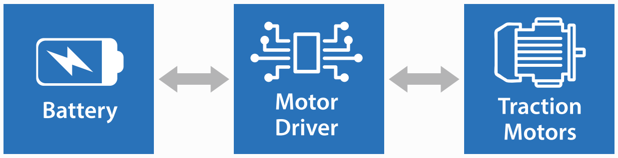


FIGURE 3: BATTERY ELECTRIC PROPULSION

To meet the performance requirements, batteries can be charged flexibly at various locations:

- Passenger stations with pantograph type chargers
- Layover facilities with pantograph type chargers
- Train yards with pantograph or plug-in type chargers

Battery electric propulsion can be designed in a modular structure to increase on-board energy storage capacity, where battery tender cars complement the main propulsion vehicle with on-board batteries.

Fuel Cell Battery Hybrid Propulsion

With fuel cell battery hybrid propulsion, the propulsion system consists of fuel cells and batteries. Fuel cells convert hydrogen gas to DC electrical energy using oxygen available in air while batteries complement the fuel cell's output power and capture regenerative braking energy. Due to the availability of two energy sources, fuel cells and battery need to be isolated through a DC-DC converter as shown in Figure 4.

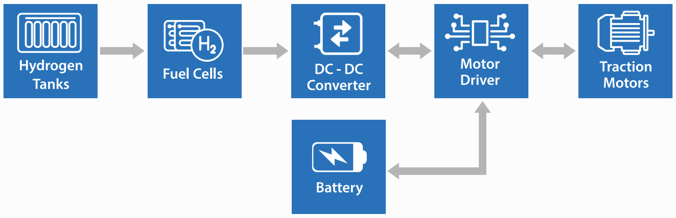


FIGURE 4: FUEL CELL BATTERY HYBRID PROPULSION

Charging the batteries is generally handled by the fuel cell and DC-DC converter system. Therefore, wayside battery charger and related infrastructure are not needed. However, the infrastructure to deliver the required hydrogen is needed in fuel cell applications.

2.1 System Efficiency

Criterion	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
System Efficiency	Very Good	Good

System efficiency is defined as the ratio of the energy delivered to the traction motor driver and the energy content of the fuel supplied to the vehicle (electricity and hydrogen). The losses in traction motor driver and traction motor are not included in the system efficiency calculations since these losses would be the same for both battery electric and fuel cell battery hybrid propulsion systems.

With battery electric propulsion, charger and battery to traction motor driver efficiencies are approximately 95% and 98%, respectively, which results in a system efficiency of 93%.

With fuel cell battery hybrid propulsion, fuel cell and DC-DC converter efficiencies are approximately 45% and 95%, respectively, which results in a system efficiency of 43%.

Battery Electric Efficiency is more than twice that of Fuel Cell Battery Hybrid Efficiency

As a result, battery electric propulsion is much more efficient than fuel cell battery hybrid propulsion in terms of overall vehicle system efficiency as shown in Figure 5.

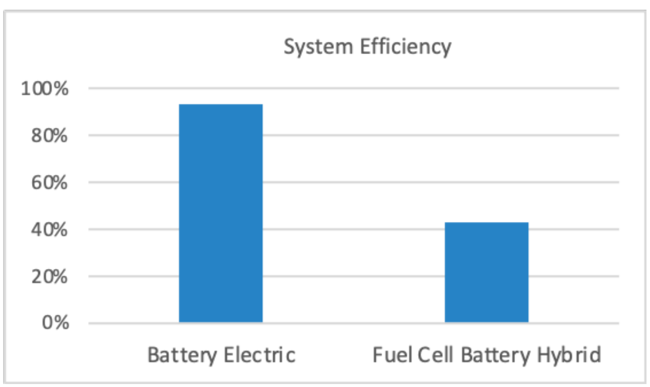


FIGURE 5: SYSTEM EFFICIENCY (ENERGY SOURCE TO TRACTION MOTOR INVERTER) COMPARISON OF BATTERY ELECTRIC PROPULSION AND FUEL CELL BATTERY HYBRID PROPULSION

2.2 GHG Emissions (Well-to-Wheel)

Criterion	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
Well-to-Wheel GHG Emissions	Very Good	Good

Well-to-Wheel emissions are defined as all the emissions emitted as the result of fuel or electricity production, distribution, and use. According to the California Energy Commission, 33% of California's total power mix was renewable energy in 2020, which places California in the top 10 states in the U.S. in terms of highest renewable energy generation. If Metrolink uses renewable electricity in its future battery electric train operations, the "well-to-wheel" GHG emissions would be close to zero.

The energy source for fuel cell systems is hydrogen. Presently, the most common method of generating hydrogen with zero emissions is through a water electrolysis process that uses renewable electricity. However, since average conversion efficiency of the electrolysis process is 70%, more electric energy is consumed in creating the energy source for a fuel cell propulsion system. Moreover, the tap water consumption of the electrolysis process (11-15 liters of water per 1 kg of hydrogen produced) would have a negative impact on California's water shortage problem.

If hydrogen is produced through steam methane reforming (SMR), which is the most widely used method for hydrogen generation, 9 kg of CO2 is emitted for each kg of grey hydrogen worth 33.3 kWh[1].

If clean hydrogen is transported to Metrolink hydrogen fueling stations instead of on-site hydrogen production, GHG emissions of hydrogen delivery trucks would have a negative impact on the environment and overall efficiencies of the system.

According to the U.S. Energy Information Administration, electric utilities in California emitted 0.177 kg CO2 per kWh generated in 2020. Using this rate, CO2 emissions due to 100 kWh energy consumption by a traction electric motor driver in a rail vehicle are calculated to benchmark the emissions for a battery electric vehicle, fuel cell battery hybrid vehicle using hydrogen generated on-site through electrolysis, and steam methane reforming, as shown in Figure 6.

Moreover, fuel cell propulsion has the potential of having a negative impact on global warming. The extremely small molecular size of hydrogen results in significant leakage into the atmosphere throughout its lifecycle. Recent research findings indicate its potency as an indirect contributor to climate change by retarding the breakdown of GHG methane in the atmosphere.

[1] Criteria Air Pollutants and Greenhouse Gas Emissions from Hydrogen Production in U.S. Steam Methane Reforming Facilities," Pingping Sun et al., Environ. Sci. Technol. 2019, 53, 12, 7103–7113.

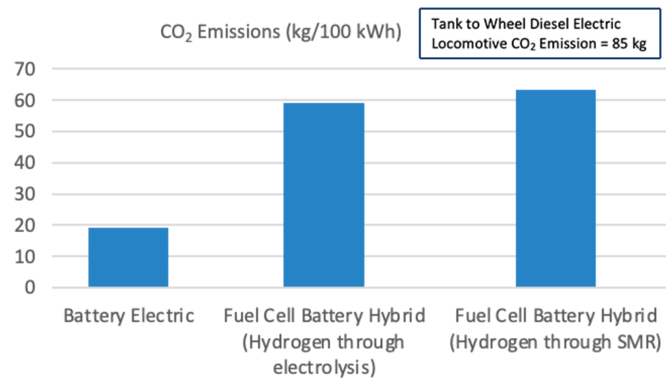


FIGURE 6: AVERAGE CO2 EMISSIONS PER 100 KWH TRACTION ENERGY CONSUMED

2.3 Range

Criterion	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
Range	Deficient	Unsatisfactory

In the “Metrolink Fleet Modernization Alternate Propulsion Study” prepared by Hatch LTK and submitted to Metrolink (Summarized in Appendix E), train simulations were performed for both battery electric and fuel cell battery hybrid propulsion systems on selected Metrolink routes (See Appendix E). Based on the results from these analyses, the range of a battery electric locomotive is estimated to be between 50% and 60% of a comparable fuel cell battery hybrid locomotive. Both are far shy of the existing 500+ mile range of Metrolink’s existing diesel electric fleet.

2.4 Charge/Refuel Time

Criterion	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
Charge/Refuel Time	Deficient	Unsatisfactory

The “Metrolink Fleet Modernization Study” evaluated charging times for battery electric locomotives and hydrogen fueling times for fuel cell battery hybrid locomotives. Battery electric locomotives can be fully charged between 60 and 90 minutes. Similarly, the hydrogen tanks of a fuel cell locomotive can be filled between 55 and 90 minutes. However, hydrogen fueling time can be shortened via simultaneous use of multiple fueling nozzles or higher pressures with pre-cooling upstream of the dispensing point.

2.5 Required Infrastructure and Cost

Criterion	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
Infrastructure Cost	Unsatisfactory	Unsatisfactory

With battery electric propulsion, required infrastructure includes charging equipment and electric grid capacity to support the total desired battery charge power. Typical unit cost for a pantograph charging device is $1,000/kW, equating to $700,000 for a 700kW charger and $1.5M for a 1.5 MW charger. Additional work is required for new electric utility service, new switchgear and transformer, and miscellaneous civil work such as concrete pads and bollards.

A pantograph-style charging station is becoming standard for most electric transit buses and is recommended for use in the pilot vehicle evaluation because of its compact configuration that avoids the use of excessive cables. The construction cost of a 1.5 MW pantograph charger at Metrolink Central Maintenance Facility (CMF), including the required civil work and grid capacity upgrades, is estimated to be $4.24M. Construction cost for a second 1.5 MW charger at an outlying layover point (e.g., Lancaster) is estimated at $4.15M.

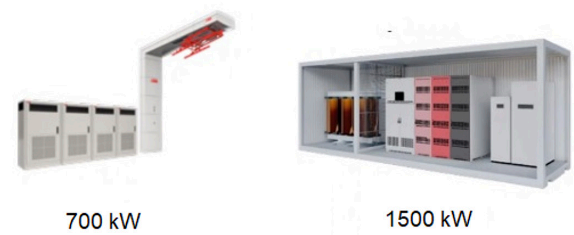


FIGURE 7: WAYSIDE CHARGING STATION

Upgrading CMF for five 1.5 MW pantograph charging stations has an estimated total construction cost of $25 million, including owner costs and contingency. With the use of charge management software and interim equipment moves, it should be feasible to charge two or three battery locomotives or battery EMUs with one charging station (approximately 15 trains with five chargers) during overnight layover. Five charging stations would also serve approximately 30 trains during the revenue service time. Moreover, individual charging stations can continue to be added over time as funding becomes available and more battery units are phased in, provided that DWP is able to continue upgrading the utility feed and there is sufficient trackside space for the footprint of the charging stations.

At the point of charging half or more of the locomotives at CMF, it may be necessary to consider an overhead catenary system (OCS) for the yard (including substation), which will maximize charging flexibility because a locomotive can be charged anywhere underneath the wire. Another consideration is that, with OCS, the locomotive (or RMU) will need to be equipped with its own pantograph, whereas a stand-alone charging station would be equipped with a pantograph that lowers to the contact shoe on the vehicle roof.

Hydrogen fuel cell propulsion and fuel cell battery hybrid technologies require a reliable supply of hydrogen in either gaseous or liquid form. The chart below shows the typical ‘break points’ for various supply options:

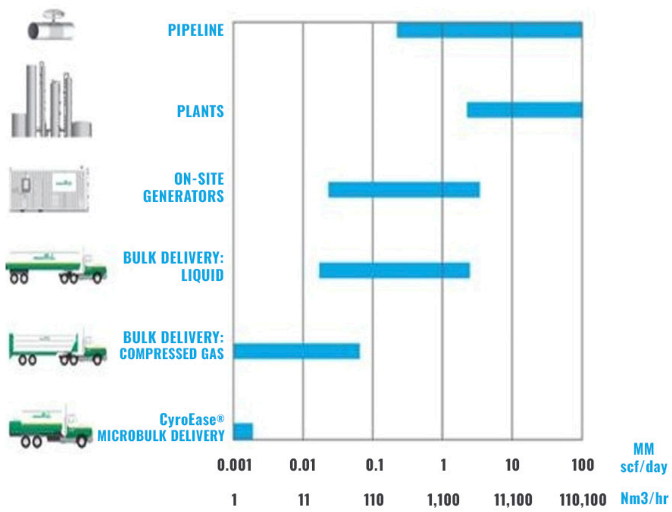


FIGURE 8: HYDROGEN SUPPLY OPTIONS

For the pilot project with a single vehicle, it is feasible to rely on bulk delivery by a gaseous tanker truck, with product potentially sourced from Torrance, CA. To improve supply stability, Metrolink can utilize a "trailer swap-out" program in which one or more full trailers are left onsite and changed out regularly as needed.[2] A standard 53-ft trailer holds 500 kg of H2 in gaseous form and can refuel at 5,000 psi (approx. 350 bar). The Stadler and Alstom Fuel Cell Battery Hybrid Multiple Units are designed to fuel at the 5,000 psi (350 bar) level, which eliminates the need for pre-cooling. Fueling would be accomplished by connecting the trailer to an adjacent package dispenser unit, which could be purchased or leased. For the full 500 kg of hydrogen at 5,000 psi the refueling time is approximately 2 hours (or about 70 minutes for 300 kg), which is considerably longer than diesel fueling,[3] but slightly less than typical battery recharging time. Moreover, cooling can decrease the amount of time needed for refueling but requires more infrastructure.

For gaseous tube-trailer delivery, the price varies based upon volume and distance but is estimated to be $9.50/kg and $8/kg at 450 kg/day and 1,000 kg/day stations, respectively (US DOE, 2020). Liquid tanker delivery is recommended for delivery volume over 1,000 kg/day with a projected delivery cost of $8/kg. One advantage of the liquid tanker is that it can carry four times as much hydrogen as the gaseous tanker. For the pilot project it is recommended that "gray" hydrogen be considered for cost savings unless "green" hydrogen is a requirement of grant funding or provides a non-tangible but important project benefit.

As an alternative to truck delivery, a small (1 MW) electrolyzer system with storage tank, producing 450 kg of hydrogen per day (18.75 kg/hr.), could be used. The estimated unit cost for a 1 MW unit is $1.5 million, plus $1.15 million for storage tank and associated civil/electrical upgrades and $1.58 million for soft costs soft costs (staff time, contingency, design, DSDC and CM) with total estimated construction cost of $4.23 million.[4] For the pilot project, it is recommended that construction costs of permanent infrastructure be minimized, and to rely either on tanker deliveries with a leased dispenser, or a leased electrolyzer station with leased dispenser.

FIGURE 9: TYPICAL HYDROGEN DISPENSING UNIT (BUS EXAMPLE)

[2] Typical hydrogen delivery package would consist of a monthly service charge (includes 24-hr remote monitoring), plus fuel cost and delivery charges (includes disconnecting empty trailer from dispenser, re-connecting new trailer); start-up and employee training.

[3] 15-20 minutes, assuming 80-100 gpm flow rate at the nozzle and a 1,500-gallon locomotive tank.

[4] This cost is based on a PEM electrolyzer unit cost of $7,600 per standard cubic meter of hydrogen produced in one hour. 1 kg H2 = 11.126 cubic meters, thus the capital unit cost = $84,557/kg H2 produced per hour.

For fleet growth beyond a single pilot vehicle, it is recommended to consider onsite production of hydrogen due to the delivered cost of hydrogen, large number of truck deliveries per day, and the carbon footprint associated with these truck deliveries. Of the various methods of hydrogen production, the two most viable ones for onsite production are Steam Methane Reforming (SMR) and Proton Exchange Membrane (PEM) water electrolysis. SMR is the most widely used process for generating hydrogen and has a slightly higher hydrogen yield efficiency (69% for small scale stations and up to 76% at large production facilities); however, it requires a large supply of natural gas and produces CO2 as a byproduct.

Hydrogen electrolyzer requires electrical upgrades comparable to those for battery charging stations plus the cost of the electrolyzer unit

PEM electrolysis produces hydrogen by means of an electrolyzer station that uses electricity to split water into hydrogen and oxygen, as shown in Figure 10. PEM electrolysis is well-suited for fueling stations as it is relatively easy to modularize and scale up for production. The primary drawback of PEM electrolysis, especially in arid California, is the large volume of treated water required. Estimated electricity consumption is 54 kWh per kg of H2. Water consumption can be derived from the chemical equations shown below; however, this is based on using purified water. The process of purification involves softening and demineralization (e.g., reverse osmosis), which produces a stream of higher mineral content "reject" water. Thus, the overall water usage is in the range of 11-15 kg per kg of hydrogen produced. Given the natural gas supply requirement, and production of CO2 associated with SMR, PEM electrolysis is the recommended method if onsite hydrogen production is to be utilized.

The critical inputs to the PEM process are electricity and treated water. For the resulting hydrogen to be considered "green hydrogen," the electricity must be from a renewable source such as solar. Because the water supply at CMF is fairly hard (high mineral content, typical for the Los Angeles basin), demineralizing will be required. The electrolyzer station will also require a storage tank for the hydrogen produced.

The production and storage capacities are determined by the projected fueling requirements, which would entail one level during a hypothetical transition phase (while both zero emission rail multiple unit and conventional diesel locomotives are in use), and another level when a full transition to zero emission vehicles is complete.

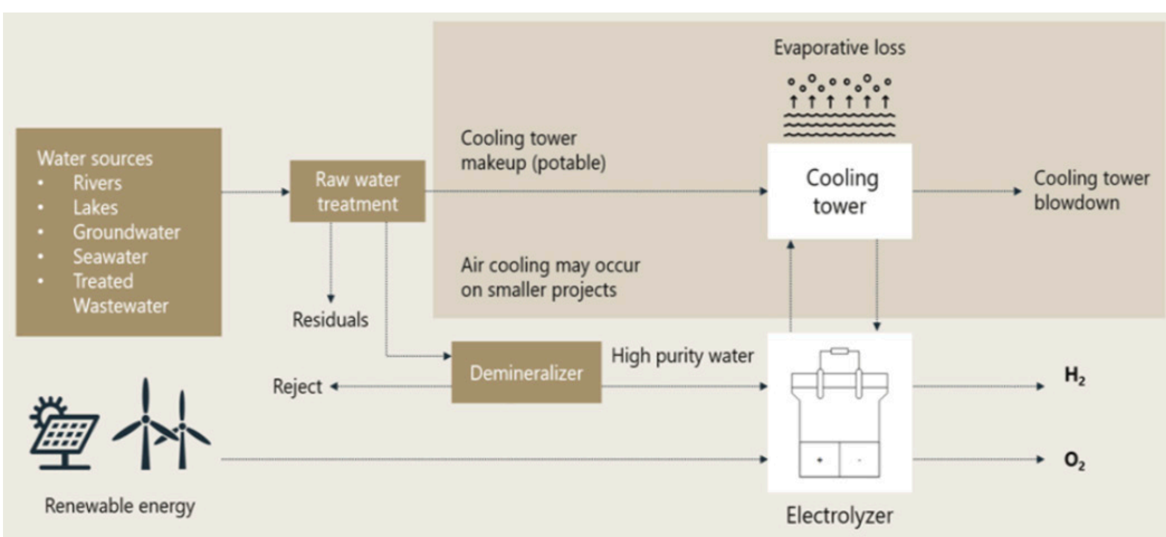


FIGURE 10: HYDROGEN ELECTROLYSIS PROCESS

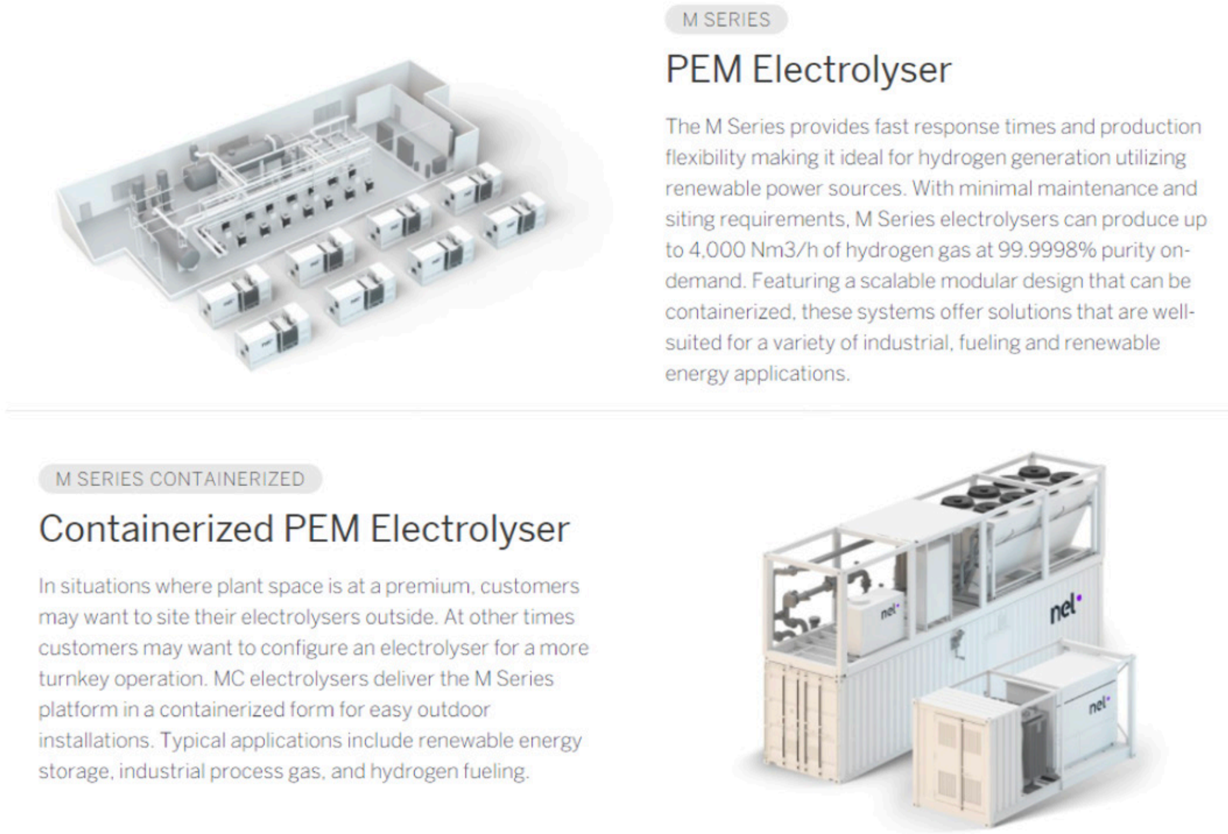


FIGURE 11: CONTAINERIZED PEM ELECTROLYZER SOLUTION

For example, a 5 MW electrolyzer station during fleet growth/transition could produce 2,250 kg of hydrogen per day and be scaled up as the fleet increases. The simulation results in the “Metrolink Fleet Modernization Alternate Propulsion Study” demonstrated that 2,250 kg hydrogen would be equivalent to the hydrogen consumption of 8 round trips on the San Gabriel Line. Such a system would have an associated 3,000 – 5,000 kg storage tank, which would be a Type 3 (composite) tank with no pre-cooling required. The capital cost of the electrolyzer station is estimated at $7.5 million, plus $3.3 million for storage tanks and associated civil/electrical upgrades, and $6.4 million in soft costs, for a total estimated cost of $17.2 million. Ongoing hydrogen production costs are estimated at $6/kg. This cost depends upon future costs for electricity and water.

20-MW electrolyzer would meet the hydrogen demand of approximately 50% of Metrolink’s daily operations.

The electrolyzer station that meets the hydrogen demand of 50% of Metrolink’s daily operations would require at least a 20 MW capacity for production of 10,000 kg+ of hydrogen per day and have a correspondingly larger storage tank. To allow for faster refueling times (due to the larger number of fuel cell/hybrid vehicles), a Type 4 (plastic with composite wrap) tank with pre-cooling would be required. Due to site constraints at CMF (both space constraints, and surrounding neighborhood concerns about H2 production and storage), a large electrolyzer station and associated electrical substation would likely need to be placed at an off-site location owned or leased by Metrolink, and the product brought to CMF by truck. One of the largest PEM Electrolyzer plants currently in design is a 10 MW plant in Germany (concept view shown in Figure 12), which requires a five-year duration for design, construction, and testing. This plant will have a building size of approximately 80 ft x 80 ft, with additional perimeter space required for exterior chiller units, for a total footprint of about 8,000 SF, with additional footprint required for electrical equipment and H2 storage tanks. The capital cost of the electrolyzer station is estimated at $30 million, plus $11.7 million for storage tanks, associated civil/electrical upgrades and $24.8 million in soft costs, for a total estimated cost of $66.5 million. Ongoing hydrogen production costs are estimated at $5/kg - $6/kg, plus trucking costs if made offsite from CMF.

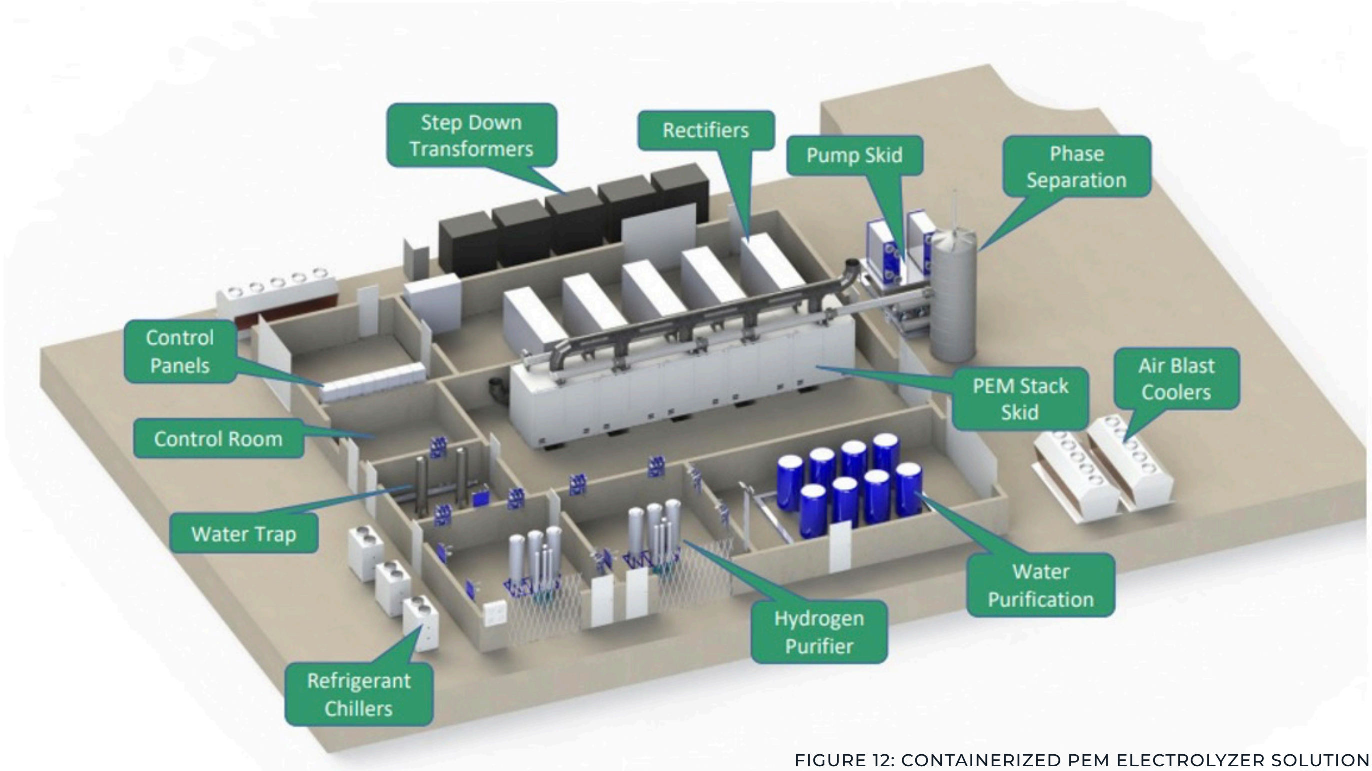


FIGURE 12: CONTAINERIZED PEM ELECTROLYZER SOLUTION

In both the above electrolyzer station scenarios, the electrolyzer unit itself could be provided under a leasing arrangement with a supplier that would design, build, and install the electrolyzer unit, which Metrolink would pay a unit price for the hydrogen plus a service charge. The supplier would also provide maintenance support of the system as part of the leasing arrangement. This would significantly reduce capital costs and reduce the risk of technological advances making a purchased electrolyzer unit prematurely obsolete.

2.6 Hardware/Control Software Complexity

Criterion	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
Hardware/Software Complexity	Good	Unsatisfactory

The system architecture and controls are straight-forward with battery electric propulsion. However, fuel cell battery hybrid systems and their controls are much more complicated due to the sophisticated control software needed to make decisions about which independent energy source (fuel cell or battery) needs to be used and at what capacity. As a result, the development efforts for a fuel cell propulsion system would be expected to be more than for a battery electric propulsion system.

2.7 Technology Maturity and Future Potential

Criterion	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
Technology Maturity	Unsatisfactory	Deficient

Except for the latest cutting-edge battery chemistry developments, battery electric propulsion has been a field proven technology in the automotive industry. It has also started spreading rapidly in the electric bus industry, and with certain limitations, in streetcar service. In rail, Wabtec, Progress Rail, Alstom, Stadler, and Siemens are developing battery electric locomotives or multiple unit vehicles. Moreover, the bus and rail industries are leveraging the results of significant R&D investments made by automotive Original Equipment Manufacturers (OEMs) and suppliers on battery technology developments. Past energy density improvements indicate that at least 3% energy capacity increases annually in Li-Ion battery technology can be expected.[5] Moreover, solid state Li-Ion battery technology is a promising path that can result in up to 30-50% energy density (Wh/kg) increases in the next 10 years.

Although there are some efforts in the bus and rail modes of transportation, fuel cell propulsion is a newer emerging technology than battery electric and needs further evaluation and improvements regarding operating life, application history in transportation, hydrogen storage, delivery, and technologies to mass-produce green hydrogen.

[5] "Re-examining Rates of Lithium-Ion Battery Technology Improvement and Cost Decline," Micah S. Ziegler et al., Energy Environ. Sci., 2021, 14, 1635.

2.8 Technology Cost

Criterion	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
Vehicle Cost	Unsatisfactory	Deficient

According to the cost study performed for this overall project the cost of a new locomotive with battery electric propulsion would be 48% lower than a comparable fuel cell battery hybrid locomotive. The overall usage cost of using fuel cell propulsion would increase significantly with the inclusion of hydrogen delivery or production and fueling infrastructure investments.

In rough order of magnitude (ROM) terms, the capital cost for a pantograph charging solution is $1,000 per kW, while the capital cost for hydrogen production is $1,550 per kW. These capital costs do not include soft costs such as contingency, Metrolink staff time, and construction support. As described in section 2.5, hydrogen capital costs can be mitigated by utilizing truck delivery or leasing of production equipment, although this will increase operational costs.

For a sample pilot project involving two round trips per day, and hydrogen delivered by gaseous tanker truck, the following are estimated fuel costs, with diesel included as a 'baseline' comparison:

Mode	Cost per Weekday (Pilot)	Annual (120 days)	Assumptions
Diesel	$3,705	$444,660	120 miles per round trip, @ 3.19 gal/mile for F125 diesel, $4.84/gal
Electric Charging	$3,201	$384,183	Two round trips per weekday, electricity @ $.362 per kWh, 5 MW over 4-hr charge cycle = 4,422 kWh/trip, two charge cycles
Hydrogen (delivery)	$5,360	$643,000	Two round trips per weekday, @ 282 kg/trip and $9.50/kg

TABLE 2: ESTIMATED VEHICLE ENERGY CONSUMPTION COSTS

Electricity cost is based on rates during mid-day low peak rate as published by Los Angeles Department of Water and Power Electric Rate Summary.[6]

2.9 Meeting Metrolink's Operational Requirements

Criterion	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
Meeting Metrolink's Operational Requirements	Deficient	Unsatisfactory

According to Metrolink's pre-COVID train assignment information or cycle, each locomotive travels between 125 and 465 miles per day. In some consecutive trips layover duration does not exceed 30 minutes. According to the simulation results performed during the Metrolink Fleet Modernization Study, the range of a fuel cell locomotive varies between 120 and 175 miles, depending on the terrain and speed profile, whereas a battery locomotive's range is between 72 and 93 miles. As a result, at the present state of technology, neither of the zero emission propulsion technologies can meet the range capability of a standard diesel electric locomotive. Therefore, the introduction of a zero emissions fleet requires operational changes (more frequent trips to the maintenance facilities for refueling/recharging, longer wait times at final stations to allow for charging, etc.) and fleet size changes to meet Metrolink's current operation plan. Moreover, supplementing the current service with shorter trips may not actually lower Metrolink's overall impact on GHG emissions because Metrolink would likely express through some stations that are covered by these shorter trips and then service more of the corridor with its existing fleet. One possible technical solution to overcome the range issue of zero emission vehicles is to complement a battery electric locomotive with a battery tender car, or a fuel cell locomotive with a hydrogen storage car to increase the overall range of a consist.

Neither Battery Electric nor Fuel Cell Battery Hybrid Propulsion matches the range of a conventional diesel electric propulsion.

Criterion	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
Hybrid Operations with Other Zero Emission Technologies	Good	Unsatisfactory

2.10 Potential of Hybrid Implementation with Other Propulsion Technologies

Many of the limitations of zero emission propulsion technologies can be addressed through the use of multiple zero emission technologies simultaneously. Battery electric propulsion can be operated as a complementary technology to an overhead catenary system with a pantograph on the vehicle. The segments of Metrolink's system, which cannot be converted economically to use an OCS, may be covered through battery electric propulsion. While the train is traveling under OCS, the consumed battery energy during "off-wire" operations (non-OCS territory) can be replenished (batteries charged) through excess available OCS energy. The optimal hybrid operations of battery electric propulsion technology coupled with OCS may eliminate the range issues, and a phased implementation of OCS could progressively extend the range of battery electric to cover more and more of Metrolink's needs.

[6] https://rates.ladwp.com/UserFiles/Rate%20Summaries/Electric%20Rate%20Summary%20(effective%207-1-2019).pdf

Another alternative is to facilitate “opportunity charging” of vehicle batteries for short durations at frequent intervals through a pantograph system located at train passenger stations. This alternative would not result in a dramatic improvement of the range of a battery electric train due to the short wait times of a commuter train at passenger stations minimizing charging time availability.

Based on current information, there is uncertainty in the interoperability of fuel cell propulsion systems with OCS due to safety concerns that arise from potential sparks generated through the pantograph and OCS interface. Fuel-powered trains (e.g. diesel or fuel cell if safe) could operate without burning their fuel while under OCS, but would not have the recharging benefit that battery electric would, so the extension of their range would be less.

2.11 Completed and In-Process Zero Emission Pilot Rail Projects

During the last two decades, numerous rail vehicle pilot programs have announced and in some cases tested hydrogen and battery electric propulsion technologies. Table 3 summarizes these programs and detailed descriptions are provided in Appendix B.

Project Name	Agency/Location	Battery Electric	Hydrogen Fuel Cell
Multiple Units			
NE Train KuMoYa E995FC	JR East/Japan	X	X
EV-E301 series	JR East/Japan	X	
EV-E801 series	JR East/Japan	X	
FV 991	JR East/Japan		X
BEC819 series	JR Kyushu/Japan	X	
Class 379 Electrostar	Network Rail/UK	X	
Class 777	LCRCA	X	
Class 230	Vivarail/UK	X	
Alstom Hydrogen Fuel Cell Coradia iLint MU	Various agencies/Austria, Sweden, Netherland, France		X
Stadler Flirt	SBCTA/USA		X
Bombardier AGC	SNCF/France	X	
Alstom BEMU	LIRR/USA	X	
Siemens Desiro ML Cityjet Eco	S-Bahn/Austria	X	X
Streetcars			
Brookville Liberty	Various Locations/USA	X	
CAF Urbos 3	NSW/Australia	X	
CRRC TRC Tram	China		X
Locomotives			
PEMFC switcher locomotive	BNSF/USA		X
Wabtec FLX	BNSF/USA	X	
Progress Rail EMD Joule	UP,LIRR & PHL/USA	X	
Wabtec FLX	UP/USA	X	
F40 Battery Locomotive	METRA (Chicago USA)	X	
CRRC Battery Locomotive	OBB/Austria	X	

TABLE 3: SUMMARY OF RAIL VEHICLE PILOT PROGRAMS

The Wabtec Battery Electric locomotive has been tested by BNSF and now Class I railroads have placed several orders for the locomotive.

FIGURE 13: WABTEC BATTERY ELECTRIC FREIGHT LOCOMOTIVE
*Photo Courtesy of Wabtec

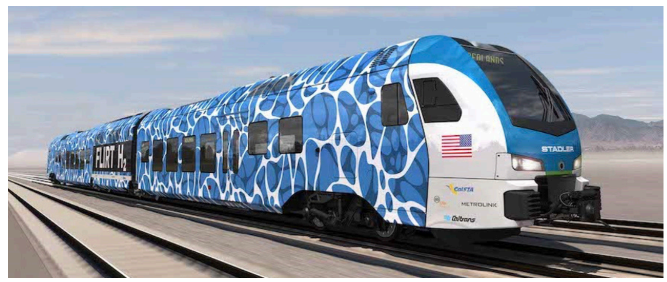


FIGURE 14: SBCTA STADLER ZERO EMISSION MULTIPLE UNIT
*Photo Courtesy of SBCTA

FIGURE 15: ALSTOM CORADIA ILINT TRAINSET
*Photo Courtesy of Alstom

The Alstom vehicle has been successfully tested in several countries in Europe and with orders being placed. The battery electric two car MU vehicle in Japan on the JR East is shown in figure 16 during testing.

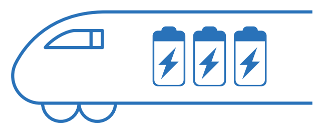
FIGURE 16: BATTERY ELECTRIC MULTIPLE UNIT ECV-E801

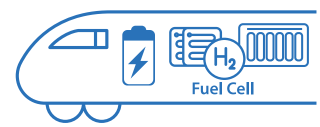
2.12 Summary, Strategic Perspectives, SWOT Analysis, and Conclusions

In the preceding sections, potential zero emission propulsion technologies were benchmarked comprehensively considering various categories. This information is summarized in this section, and strategic perspectives are defined that will be followed for the recommended technology for further pilot implementation.

Table 4 summarizes the benchmark results of fuel cell and battery propulsion technologies by providing "+" and "–" symbols representing ratings to each provided category. For example, if a propulsion technology is deemed to be superior to diesel electric propulsion for a particular category, it is noted by one or two + symbols, with two symbols representing a larger benefit. If a propulsion technology is deemed to be inferior when compared to diesel electric propulsion, one or two – symbols are used to signify the severity of its deficiency. A total of these rankings (a single + representing 1, a double ++ representing 2, a single - representing -1, and a double - - representing -2) is included to generalize each technology, considering the overall combination of criteria. If a propulsion technology's performance in a criterion is comparable to the diesel electric propulsion, 0 is assigned for that criterion.

According to this evaluation method, battery electric propulsion has fewer negatives compared to fuel cell battery hybrid propulsion (-7 vs. -9). However, fuel cell battery hybrid is superior to battery electric in two important criteria, which are range and charge/refueling time. Having negative scores for zero emission propulsion technologies indicates the inability of these technologies to match the performance of a conventional diesel electric propulsion.





CRITERIA	Battery Electric Propulsion	Fuel Cell Battery Hybrid Propulsion
Zero Emissions	++	+
Range	- -	-
Charge/Refuel Time	- -	-
Hardware/Software Complexity	+	-
Technology Maturity	-	- -
Vehicle Cost	-	- -
Infrastructure Cost	--	-
Hybrid Operations with Other Zero Emission Technologies	0	-
Meeting Metrolink's Operational Requirements	- -	-
Total	-7	-9

TABLE 4: BENCHMARK BETWEEN BATTERY ELECTRIC AND FUEL CELL BATTERY HYBRID PROPULSION TECHNOLOGIES

2.12.1 Strategic Perspectives

All zero emission propulsion technologies have some disadvantages and challenges that need to be evaluated and resolved in the field. None of these alternatives are definitively superior. Each transit agency or railroad is encouraged to not confront these challenges independently but join efforts with vehicle builders and peer operators to uncover and address as many unknowns as possible about each potential technology instead of investing in the same or similar technology while not considering some others. Figure 17 shows the potential solution map for a zero emission fleet implementation with the unknown areas identified that need to be evaluated and decoded with pilot implementation programs. In this figure, the diameter of each red circle represents the extent of the unknowns about the respective technology, with a larger diameter equating to more unknowns and risks. The fuel cell technology without batteries (signified by diagonal blue stripes) is not considered as an alternative technology in the transportation industry due to its inability to capture regenerative braking energy and poor transient response.

The unknowns for a fuel cell battery hybrid propulsion system (represented by circle number 2) in Figure 17 recommended for evaluation during a pilot implementation program are:

- Fuel cell power, battery capacity, and hydrogen carrying capacity on the target vehicle for the target routes
- Range of the train on the target routes during actual operating conditions
- Facility and infrastructure related issues
- Hydrogen delivery and production issues and operating costs
- Reliability of the propulsion system and fueling system
- Maintenance practices and cost
- Performance under different weather conditions

Fuel cell technology, especially when coupled with green hydrogen production, is a less mature technology compared to battery and charging technologies. As stated in the U.S. Department of Energy Hydrogen Program, a comprehensive set of R&D activities are required to solve technical problems on multiple fronts (hydrogen production including access to sufficient clean water, delivery, storage, fuel cells, safety, systems integration, etc.) for a sustainable hydrogen economy.[7] Therefore, it would be beneficial for Metrolink to wait for the results of these separate and critical R&D activities before making any substantial investments in fuel cell technology.

San Bernardino County Transit Authority (SBCTA) has already invested in the pilot testing of a fuel cell battery hybrid multiple unit and it is expected that some of the unknowns and risks associated with fuel cell propulsion will be uncovered during that project. If Metrolink leverages the results and lessons learned from this pilot project and explores the viability of other alternative propulsion technologies, the large number 1 and 2 red circles in Figure 17 would shrink and Metrolink could achieve the transition to the fleet-wide zero emissions implementation whether battery, fuel cell or some combination with fewer unknowns and risks.

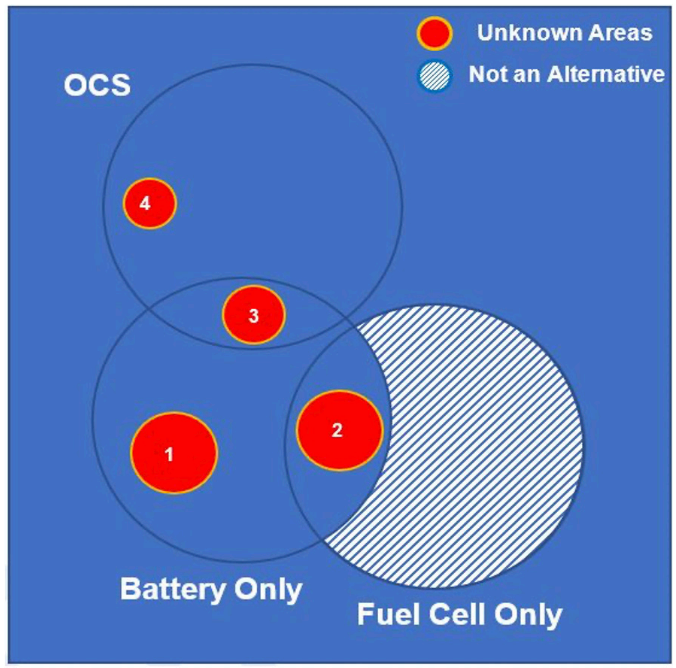


FIGURE 17: POSSIBLE ZERO EMISSIONS FLEET SOLUTIONS WITH UNKNOWN AREAS

The unknowns for a battery only propulsion system that need to be evaluated during any pilot implementation program are:

- Battery capacity on the target vehicle for the target routes
- Range of the train on the target routes during actual operating conditions
- Alternative battery charging methods
- Infrastructure limitations on the charging system
- Reliability of the propulsion system and charging system
- Battery aging
- Electricity cost
- Maintenance practices and cost
- Performance under different weather conditions

[7] https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office
https://www.energy.gov/eere/fuelcells/articles/hydrogen-and-fuel-cell-technologies-office-multi-year-research-development

Despite some limitations, battery only electric propulsion has considerable potential because of the intensive R&D efforts of the highway motor vehicle industry and the variety of promising battery chemistries. Range limitations can be mitigated with complementary solutions in commuter rail such as battery tender cars and dual mode operations with catenary systems. Transit agencies should study the unknowns in battery-only electric propulsion under realistic, real-world operational conditions before considering the fleet-wide implementation of any zero emission technology.

Battery electric propulsion systems can have a useful synergy with a complementary OCS system. In combined operations, while some track sections are electrified, battery energy is used on the remaining non-electrified route segments. An accurate technical and financial evaluation cannot be performed without first assessing the technical capabilities of a battery propulsion system in realistic operating conditions. The pilot implementation effort of a battery electric propulsion system, and the resulting lessons learned, may lead to a feasible catenary-battery hybrid operations for fleet wide implementation. The viability of such a solution would be supported by the following two factors:

1. California High Speed Rail Plan
2. Metrolink Climate Action Plan

According to the latest available plan documents, California High Speed Rail will share some of Metrolink's corridors (Lancaster - Palmdale, Burbank Airport - LA Union Station, and LA Union Station to Anaheim). This sharing of infrastructure might lead to the possibility of electrifying some of Metrolink's route segments more cost effectively.

Metrolink's Climate Action Plan targets the use of locomotives with dual operation (diesel and catenary) capabilities. The battery and catenary dual operations would be an extension to this target, and hence, a battery electric propulsion pilot would be the first crucial step. As a result, a battery electric propulsion pilot implementation program would help decoding and solving the unknowns in both number 1 and number 3 red circles in Figure 17.

2.12.2 SWOT Analysis

A strengths, weaknesses, opportunities, and threats (SWOT) analysis has been performed to summarize findings of the battery electric and fuel cell propulsion technologies. Table 5 shows the SWOT analysis performed for the battery electric propulsion.

Strengths	Weaknesses
• The most efficient propulsion technology • Less complicated hardware/software • Direct use of grid electricity without any transportation losses and conversion losses • Higher technical maturity level than fuel cell technology • Less expensive than fuel cell technology • Fewer safety concerns than fuel cell technology • More R&D efforts and available funding than any other technology • On-going investments by U.S. locomotive manufacturers • Competitive battery supplier base	• Range (energy density): This issue can be minimized with novel train consist concepts (one battery electric locomotive and one battery tender car) or hybrid operations (catenary + battery electric). Battery energy densities have increased consistently over the last 25 years (3% annually) and this trend is projected to continue in the next 10 years with the advances in the battery chemistry like solid state batteries, silicon anode and lithium metal batteries. • Charge Time: The power rating of chargers and the charge acceptance rate of batteries keep increasing. Novel charging concepts like parallel charging of each battery string in a battery pack are possible • The environmental impact of the mining for battery minerals
Opportunities	**Threats**
• Technical progress in the battery technology (gradual energy density increases, solid-state battery developments, possible step changes in energy density for the medium term) • Possible cost reductions in the future due to the wide adoption of battery electric vehicle technologies • Transfer of know-how from the automotive light-duty and heavy-duty industries to the rail industry • Transitional low emission propulsion technologies like diesel battery hybrid and diesel electric + catenary would lead to the adoption of battery electric propulsion • Hybrid implementation with a partial catenary system (battery in the city, catenary in the outskirts) • Leverage the catenary infrastructure that will be built for California High Speed Rail System (shared corridors between Lancaster - Palmdale, Burbank Airport - LA US, LA US - Anaheim) • Complementary to the prospective learnings from the pilot projects of other agencies (technology, infrastructure, maintenance, fuel/energy supply, reliability)	• Widespread adoption of hydrogen technology in the rail industry: Since pilot battery electric train does not require high capital investments on the infrastructure, hydrogen technology can be adopted at a later stage if this threat becomes true. • The knowledge gained from battery electric can be transferred to hydrogen trains as fuel cell trains would also use the same batteries in their system. Electrical grid capacity increases due to the charger requirements can be utilized to power electrolyzers for on-site hydrogen production if that technology prevails. Fuel cell experience from the Redlands Branch would be easily transferred to Metrolink's other lines for an aggressive rollout plan. • Battery supply shortages due to demand: Investments in battery technology development and manufacturing continue to meet the demand. • No progress in battery capacity and durability: Current battery technology can be seamlessly integrated with a catenary and fuel cell system or battery tender cars.

TABLE 5: SWOT ANALYSIS FOR BATTERY ELECTRIC PROPULSION

Strengths	Weaknesses
• Longer range compared to battery electric propulsion • Shorter fueling time compared to battery electric propulsion • Green hydrogen can be produced via on-site electrolysis during periods of low electricity rate and higher green power mix.	• Range: Limited to the size and quantity of on-board hydrogen tanks compared to diesel electric propulsion. This weakness can be eliminated through novel train consist concepts like hydrogen tender cars. But this concept has not been implemented yet. • Hydrogen Availability: At present, there is no scalable green hydrogen technology and virtually all U.S. hydrogen is produced from natural gas. Therefore, the lower cost option for hydrogen supply is hydrogen produced from natural gas and delivered by trucks. This option has negative environmental impact. The green hydrogen solution is on-site hydrogen production through an electrolyzer. But it is an energy-inefficient process with massive water consumption. • Cost: Vehicle cost is higher than battery electric propulsion. • Low well to wheels conversion efficiency • Complicated hardware and software • Unknowns in the U.S. hydrogen strategy and future developments in the hydrogen economy and technologies • Uncertainty in the interoperability of fuel cell propulsion with catenary system due to safety concerns • Limited fuel cell supplier base
Opportunities	**Threats**
• Leverage lessons learned from fuel cell heavy duty vehicle operators • Technology advancements from clean hydrogen R&D activities • California can be one of the regional clean hydrogen hubs that help solve supply and cost issues of clean hydrogen	• Regulatory agencies may determine additional safety requirements after prototype or hydrogen production related technology advancements may make the pilot infrastructure investments obsolete. • Easy-to-leak and flammable gas • Battery developments may surpass the pace of improvements in fuel cell and green hydrogen production and make the pilot infrastructure investments obsolete.

TABLE 6: SWOT ANALYSIS FOR FUEL CELL PROPULSION

2.13 Alternatives to Battery Electric and Fuel Cell Battery Hybrid Propulsions

Neither battery electric nor fuel cell battery hybrid propulsion technologies have been developed sufficiently to allow for a direct replacement of diesel electric propulsion for use in either a locomotive or RMU. Furthermore, the emerging zero emissions rolling stock will be more costly than a comparable vehicle using diesel electric power. If Metrolink could consider the evaluation of low emission instead of zero emission propulsion technologies in the pilot implementation project under a modest budget, the most viable option would be diesel battery hybrid propulsion that does not require wayside battery charger equipment. According to the results of the simulation completed in Metrolink's Fleet Modernization Project, 20% fuel savings can be achieved with diesel battery hybrid propulsion and the battery can propel the train and provide hotel electric power (HEP), which is used to provide climate control, lighting and communications for the rail cars, for a limited time and distance without the necessity to use the diesel engine (see Appendix G).

2.13.1 Reducing Fuel Consumption with Alternative Propulsion

Multiple units are smaller, lighter vehicles which consume less fuel in comparison with locomotives and bi-level cars. Another alternative to reduce diesel fuel consumption is to operate diesel battery hybrid locomotive trainsets can help to reduce diesel fuel consumption by operating with a battery locomotive in the trainset. An existing diesel locomotive could be run in conjunction with the full battery electric locomotive reducing fuel consumption per trip.

Fuel savings of diesel battery hybrid equipment as well as other new and legacy equipment can be increased by a few more percentage points by implementing a trip optimization algorithm that identifies upcoming speed limits, train stations, and terrain, and then optimizes the acceleration, deceleration, and auxiliary power consumption of the train for lower fuel consumption. Not all are available for a passenger operation, but some could be implemented to train the operators how to use less fuel by modeling a train route.

3 VEHICLE TYPE FOR THE ZERO EMISSIONS PILOT

3. VEHICLE TYPE FOR THE ZERO EMISSIONS PILOT

Based on a detailed review of the industry and evaluation of feasible emerging technologies, there are three viable candidates for the zero emission pilot vehicle:

- Rebuilt Locomotive
- New Locomotive
- Rail Multiple Unit (RMU)

3.1 Rebuilt Locomotive

If this option is utilized, one of Metrolink's retired Tier 0 locomotives will be converted to a zero emission locomotive. The conversion process will include the removal of the already decommissioned diesel electric propulsion system, replacement of DC traction motors with AC traction motors, installation of selected zero emission propulsion systems with the required cooling system, electrification of auxiliary subsystems that are originally driven by the diesel engine, and other items.

According to the Metrolink Rail Fleet Management Plan Update for FY2020-FY2040, one of the retired F59PHI locomotives built in 2001 will be the best candidate vehicle for the conversion. An alternative candidate for the conversion is one of the MP36PH-3C Tier 2 locomotives that are due for mid-life overhaul in 2023. The advantage of using an MP36PH-3C over the F59PHI is its length (9.5 feet longer) that would enable more battery energy and hydrogen carrying capacity to use. The disadvantage, however, is that the MP36PH-3C's are currently needed for planned service growth and could not be spared for this purpose unless they can be replaced with new Tier 4 locomotives.

3.1.1 Vehicle Cost for Pilot

Pilot rebuilt battery electric locomotive has lower acquisition cost than fuel cell locomotive diesel electric propulsion.

For the pilot project, it is assumed that Metrolink would use existing spare trailer coaches and a cab car. Therefore, the pilot vehicle cost includes only the locomotive related items.

Table 7 shows the estimated unit price of a rebuilt locomotive with battery electric and fuel cell battery hybrid propulsion systems for a pilot project. The table also includes non-recurring engineering (NRE) expenses and contingency.

To analyze how the fleet implementation affects the unit cost, a separate study has been also conducted for fifteen (15) rebuilt zero emissions locomotives . For the fleet implementation, it is assumed that Metrolink would rehabilitate the aged trailer coaches and cab cars to use with the zero emission locomotives. Therefore, the fleet cost includes both locomotive related items and rehabilitation cost of trailer and cab cars. According to this analysis, unit cost drops to $15,300,000 and $15,920,000 for a 4-car consist with a rebuilt battery locomotive and a 4-car consist with a rebuilt fuel cell locomotive, respectively. In the fleet implementation case, the unit price difference between rebuilt battery locomotive and rebuilt fuel cell locomotive narrows down since higher NRE cost of fuel cell locomotive is spread out in the fleet implementation.

Technology	Units	NRE	Contingency	Price
Rebuilt Battery Locomotive	1	$13,050,000	$5,880,000	$30,910,000
Rebuilt Fuel Cell Locomotive	1	$29,800,000	$10,980,000	$56,390,000

TABLE 7: REBUILT LOCOMOTIVE WITH BATTERY AND FUEL CELL PROPULSION PILOT IMPLEMENTATION

3.1.2 Facilities Cost

The CMF locomotive shop is already equipped to service conventional diesel-electric locomotives with equipment such as a 30-ton bridge crane, drop table, and roof-level platforms for roof access. Required shop facility upgrades are expected to be minimal to accommodate a locomotive rebuilt using battery, and slightly higher for fuel cell battery hybrid propulsion. Primary cost impacts will be due to hydrogen gas leak detection upgrades for a fuel cell battery hybrid locomotive. The yard facility requirements are related to battery charging or hydrogen refueling, and Table 8 shows the estimated facility capital costs for Pilot Implementation for a rebuilt locomotive (does not include operating costs for electricity or delivered/produced hydrogen).

	Shop Costs	Yard and Layover Costs
Rebuilt Battery Locomotive with Two High Power Chargers	$16,000	$8,400,000
Rebuilt Battery Locomotive with One High Power Charger	$16,000	$2,620,000
Rebuilt Fuel Cell Battery Hybrid Locomotive – H2 delivered	$215,000	$180,000
Rebuilt Fuel Cell Battery Hybrid Locomotive – H2 produced	$215,000	$4,210,000

TABLE 8: REBUILT LOCOMOTIVE FACILITY COSTS

3.1.3 Life Cycle Cost for Pilot

Pilot rebuilt battery electric locomotive has lower life cycle cost than fuel cell locomotive.

Table 9 shows the estimated life cycle cost of one rebuilt locomotive with battery electric and fuel cell battery hybrid propulsion systems in a pilot project for a 5-year operating period. The life cycle cost includes NRE cost, contingency, non-vehicle and vehicle capital cost, fuel/electricity, and maintenance cost of both locomotive and trailer and cab cars.

To analyze how the fleet implementation affects the life cycle cost, a separate life cycle cost study has also been conducted for 15 rebuilt zero emission locomotives for a period of 20 years. According to this analysis, the life cycle cost ratio of rebuilt battery locomotive over rebuilt fuel cell locomotive increases from 52% for the pilot implementation to 70% for the fleet implementation.

Technology	Units	5 Year Period
Rebuilt Battery Locomotive	1	$30,680,000
Rebuilt Fuel Cell Locomotive	1	$58,470,000

TABLE 9: LIFE CYCLE COST FOR PILOT IMPLEMENTATION

3.1.4 Summary

Based on estimated vehicle cost and life cycle cost analyses for the pilot implementation, the following conclusions are noted:

- The vehicle procurement cost of one pilot battery locomotive would be 55% of a fuel cell battery hybrid locomotive.
- The major cost driver for a fuel cell battery hybrid locomotive relative to a battery electric locomotive would be non-recurring engineering expenses.
- 5-year life cycle cost of a rebuilt battery locomotive would be about 52% of a rebuilt fuel cell battery hybrid locomotive.

3.2 New Locomotive

For this option, Metrolink would prepare technical specifications for the zero emission locomotive and potential builders would bid based on their own locomotive and propulsion system designs.

3.2.1 Financial Evaluation

3.2.1.1 Vehicle Cost for Pilot

Pilot new battery electric locomotive has lower acquisition cost than new fuel cell locomotive.

For the pilot project, it is assumed that Metrolink would use existing spare trailer coaches and a cab car. Therefore, the pilot vehicle cost includes only the locomotive related items. Table 10 shows the estimated unit price of a new locomotive with battery electric and fuel cell battery hybrid propulsion systems for a pilot project. The table also includes recurring and non-recurring engineering expenses and contingency amount.

To analyze how the fleet implementation affects the unit cost, a separate study has been also conducted for fifteen (15) new zero emission locomotives. For the fleet implementation, it is assumed that Metrolink would rehabilitate the aged trailer coaches and cab cars to use with the zero emission locomotives. Therefore, the fleet cost includes both locomotive related items and rehabilitation cost of trailer and cab cars. According to this analysis, unit cost drops to $16,580,000 and $17,280,000 for a 4-car consist with a new battery locomotive and a 4-car consist with a new fuel cell locomotive, respectively. In the fleet implementation case, the unit price difference between new battery locomotive and new fuel cell locomotive narrows down since higher NRE cost of fuel cell locomotive is spread out in the fleet implementation.

Technology	Units	NRE	Contingency	Price
New Battery Locomotive	1	$11,920,000	$5,880,000	$30,880,000
New Fuel Cell Locomotive	1	$32,940,000	$12,250,000	$62,770,000

TABLE 10: NEW LOCOMOTIVE WITH BATTERY AND FUEL CELL PROPULSIONS FOR PILOT IMPLEMENTATION

3.2.1.2 Facilities Cost

Table 11 shows the estimated facility capital costs for Pilot Implementation of a new battery or fuel cell locomotive (does not include operating costs for electricity or delivered/produced hydrogen). They are estimated to be the same as for a rebuilt locomotive in terms of shop equipment needs, and charging/hydrogen fueling equipment needs.

	Shop Costs	Yard and Layover Costs
New Battery Locomotive with Two High Power Chargers	$16,000	$ 8,400,000
New Battery Locomotive with One High Power Charger	$16,000	$2,620,000
New Fuel Cell Battery Hybrid Locomotive – H2 delivered	$215,000	$180,000
New Fuel Cell Battery Hybrid Locomotive – H2 produced	$215,000	$4,210,000

TABLE 11: NEW LOCOMOTIVE FACILITY ESTIMATED COSTS

3.2.1.3 Life Cycle Cost for Pilot

Pilot new battery electric locomotive has lower life cycle cost than fuel cell locomotive.

of one new locomotive with battery electric and fuel cell battery hybrid propulsion systems in a pilot project for a 5-year operating period. The life cycle cost includes NRE cost, contingency, non-vehicle and vehicle capital cost, fuel/electricity, and maintenance cost of both locomotive and trailer and cab cars.

To analyze how the fleet implementation affects the life cycle cost, a separate life cycle cost study has also been conducted for 15 new zero emission locomotives for a period of 20 years. According to this analysis, the life cycle cost ratio of new battery locomotive over new fuel cell locomotive increases from 48% for the pilot implementation to 74% for the fleet implementation.

Technology	Units	5 Year Period
New Battery Locomotive	1	$30,720,000
New Fuel Cell Locomotive	1	$64,310,000

TABLE 12: ESTIMATED LIFE CYCLE COST OF NEW LOCOMOTIVES FOR PILOT IMPLEMENTATION

3.2.1.4 Summary

Conclusions from the vehicle cost and life cycle cost analyses for the pilot implementation are:

- The estimated vehicle procurement cost of one pilot new battery locomotive would be 49% of a fuel cell battery hybrid locomotive.
- The major cost driver for a new fuel cell battery hybrid locomotive relative to a battery electric locomotive would be non-recurring engineering expenses.
- 5-year estimated life cycle cost of a new battery locomotive would be about 48% of a new fuel cell battery hybrid locomotive.

3.3 Rail Multiple Unit (RMU)

Zero emission propulsion technology can be evaluated on a rail multiple unit (RMU). Metrolink currently operates with locomotives and coaches and will begin operating RMUs later this year on a limited segment of its network. The evaluation of RMUs requires detailed analysis that would involve technical, financial, and strategic evaluations.

3.3 Rail Multiple Unit (RMU)

3.3.1 Vehicle Cost for Pilot Implementation

Pilot battery electric RMU has lower acquisition cost than fuel cell RMU.

Table 13 shows the estimated unit price of an RMU with battery electric and fuel cell battery hybrid propulsion systems for a pilot project. The table also includes non-recurring engineering expenses and contingency amount.

To analyze how the fleet implementation affects the unit cost, a separate study has been also conducted for 30 zero emission RMUs. Since the seating capacity of a 4-car RMU trainset is approximately half that of the trains Metrolink currently operates, it is assumed that the number of RMUs in the fleet would be twice the number of zero emission locomotives. According to this analysis, unit cost drops to $15,230,000 and $16,330,000 for a battery RMU and a fuel cell RMU, respectively.

Technology	Units	NRE	Contingency	Price
New Battery MU	1	$17,410,000	$8,820,000	$45,590,000
New Fuel Cell MU	1	$16,340,000	$8,660,000	$44,810,000

TABLE 13: RMU WITH BATTERY ELECTRIC AND FUEL CELL BATTERY HYBRID PROPULSIONS FOR PILOT IMPLEMENTATION

3.3.2 Facilities Cost

Table 14 shows the estimated facility capital costs for Pilot Implementation of a new battery or fuel cell RMU (does not include operating costs for electricity or delivered/produced hydrogen). The primary driver for the shop costs is a set of synchronized jacks for truck replacements, plus new concrete pads in the Progressive Maintenance (PM) Track area, as described in Section 3.4.8. A scaffold system will be required for roof access to the RMU. Based on Stadler and Alstom RMUs on the market, the power car components are modularized and can be removed via forklift. Yard/layover costs for charging or H2 fueling are the same as for a battery or fuel cell locomotive. One significant factor is the shop was built to maintain locomotives and cars. The cars can be uncoupled from each other and the locomotive and repaired in shop or outside. The shop is nearly at capacity with the existing fleet size.

	Shop Costs	Yard and Layover Costs
New Battery MU with Two High Power Chargers	$1,860,000	$ 8,400,000
New Battery MU with One High Power Charger	$1,860,000	$2,620,000
New Fuel Cell Battery Hybrid MU – H2 delivered	$2,140,000	$180,000
New Fuel Cell Battery Hybrid MU – H2 produced	$2,140,000	$4,210,000

TABLE 14: FACILITY COST OF RMU (PILOT)

3.3.3 Life Cycle Cost for Pilot

Pilot battery electric RMU has lower life cycle cost than fuel cell RMU.

Table 15 shows the estimated life cycle cost of one RMU with battery electric and fuel cell battery hybrid propulsion systems in a pilot project for a 5-year operating period. The life cycle cost includes NRE cost, contingency, non-vehicle and vehicle capital cost, fuel/electricity, and maintenance cost.

To analyze how the fleet implementation affects the life cycle cost, a separate life cycle cost study has been also conducted for 30 zero emission RMUs for a period of 20 years. According to this analysis, the life cycle cost ratio of battery RMUs over fuel cell RMUs decreases from 95% for the pilot implementation to 68% for the fleet implementation.

Technology	Units	5 Year Period
New Battery MU	1	$45,750,000
New Fuel Cell MU	1	$47,930,000

TABLE 15: ESTIMATED LIFE CYCLE COST OF RMUS FOR PILOT IMPLEMENTATION

3.3.4 Summary

Conclusions from the vehicle cost and life cycle cost analyses for the pilot implementation are:

- The estimated procurement cost of one pilot fuel cell battery hybrid RMU would be 98% of a battery RMU.

- The estimated life cycle cost of a battery RMU would be 95% of a fuel cell battery hybrid RMU.

3.4 Technical Evaluation

In this section RMUs are benchmarked against locomotives in terms of seating capacity, shunting performance, platform length, and height criteria.

3.4.1 Seating Capacity

According to Metrolink's pre-COVID train cycles, 45% of Metrolink's cycles are operated with four multilevel coaches, whereas 33% of the cycles are operated with six multilevel coaches. The remaining cycles (22%) are performed with five multilevel coaches. The seating capacity of four-coach and six-coach trains are approximately 532 and 810, respectively. RMU maximum seating capacity is approximately 510 if two extended units are coupled to make an eight-car set. Higher capacity RMUs to rival five-car locomotive sets would require even longer consists or multiple-level MUs – technically possible but generally not economical except in places that are fully electrified with OCS.

An extended eight-car RMU can match the seating capacity of a four-coach train. However, empty weight (AW0) per one seated passenger (AW0 weight/seating capacity) is 768 kg/passenger for an RMU and 683 kg/passenger for a locomotive driven four-coach train. As a result, a four-coach train is more efficient in terms of the required weight to carry one passenger. Figure 19 shows how the train weight per passenger varies according to the seating capacities of different locomotive hauled train consists and RMUs.

FIGURE 18: SEATING CAPACITY COMPARISON BETWEEN TRAIN TYPES

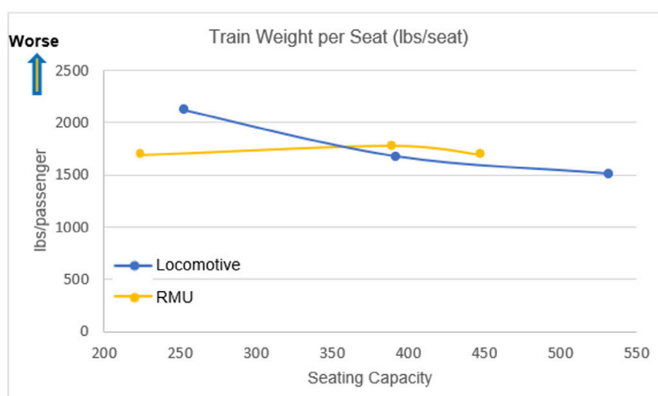


FIGURE 19: TRAIN WEIGHT PER PASSENGER FOR DIFFERENT LOCOMOTIVE BASED CONSISTS AND RMUS

Five-car RMU units (4 passenger cars and one non-passenger power car) that are currently manufactured and certified in the U.S. may not have the capability of being coupled with another four-five car unit due to the lack of crashworthiness certification. Under this constraint, an RMU can consist of a maximum four cars, have the seating capacity of a two-coach train. RMUs in the U.S. market cannot match the seating capacities of Metrolink's current locomotive push-pull trains, based on possible RMU configurations.

3.4.2 Zero Emissions Range

As explained in the previous section, RMUs are lighter than locomotive hauled trains for the seating capacity less than 350 passengers. Therefore, it can be expected that RMUs have a longer range than locomotives for low seating capacities. The validation of this hypothesis has been explored in the Metrolink Fleet Modernization Alternate Propulsion Study. In that study, the range of a locomotive hauled train has been benchmarked to the range of an RMU with a comparable seating capacity on the Antelope Valley Line. According to that study, a locomotive hauled train has longer range than an RMU for both battery and fuel cell battery hybrid propulsion systems as shown in Table 16 despite a locomotive hauled train's higher weight because locomotives have more volume and weight capacity for the placement of batteries and hydrogen tanks. As shown in that table, a fuel cell battery hybrid locomotive with two bi-level cars has the highest range whereas a battery RMU with four single level cars has the lowest range. This report also provides the feasible battery energy capacity, fuel cell power, and hydrogen storage capacity that can be fit into a locomotive and an RMU (shown in Appendix F). In conclusion, locomotive hauled trains are more advantageous than RMUs in terms of zero emission range.

	Battery Locomotive with Two Cars	Fuel Cell Locomotive with Two Cars	Battery RMU	Fuel Cell Battery RMU
One-Way Trip Feasibility	✓	✓	✓	✓
One Round-Trip Feasibility	✓	✓	✕	✓
One and a Half Round-Trips Feasibility	✕	✓	✕	✕

TABLE 16: RANGE COMPARISON OF LOCOMOTIVE-HAULED TRAINS AND RMUS

3.4.3 Shunting Issue

The current railway signal systems used by Metrolink use track circuits to detect the presence of a train or other track occupancy. Track circuits interpret the condition wherein electrical current is being directed away from the relay/receiver as the presence of a train, or a track occupancy. This track occupancy information allows the signal system to control train permissions and activate crossing warning systems in a manner that results in safe and efficient railroad operation. The locomotives on Metrolink provide a path (shunt) for a low voltage circuit and low current through the wheels of the locomotive. The weight of the locomotive and number of axles throughout the entire train are key factors to ensure that the desired wheel-to-rail contact condition is provided. Historically, Metrolink locomotive hauled coaches have experienced occasional shunting issues. To mitigate this risk, Metrolink has a scheduled rail brushing program that scrubs sections of the San Gabriel, Shortway, Perris, and Orange Subdivisions to provide a clean running rail surface. This rail brushing program, in conjunction with monitoring and periodic signal equipment upgrades, has proven successful at mitigating shunting issues related to Metrolink locomotive hauled coaches.

Several other railroads which operate RMU type trains have observed periodic issues with consistent and reliable shunting. RMU operators have reported intermittent erratic shunting performance with certain types of track circuits. To mitigate this risk, systems designed for RMU operation must be configured differently than those systems currently used throughout the Metrolink system. Additionally, the wide variety of causes and influencing factors means that the shunting performance of a new RMU operated on Metrolink will not be known until the pilot/test vehicle has been operated and monitored on the specific tracks under examination. This testing and monitoring must be conducted after known system changes to accommodate RMU operation have occurred.

3.4.4 Risks Associated with Erratic Shunting

The ability of a train to shunt track circuits reliably and continuously is a fundamental requirement for the safe and reliable operation of the existing Positive Train Control (PTC), signaling and grade crossing warning systems.

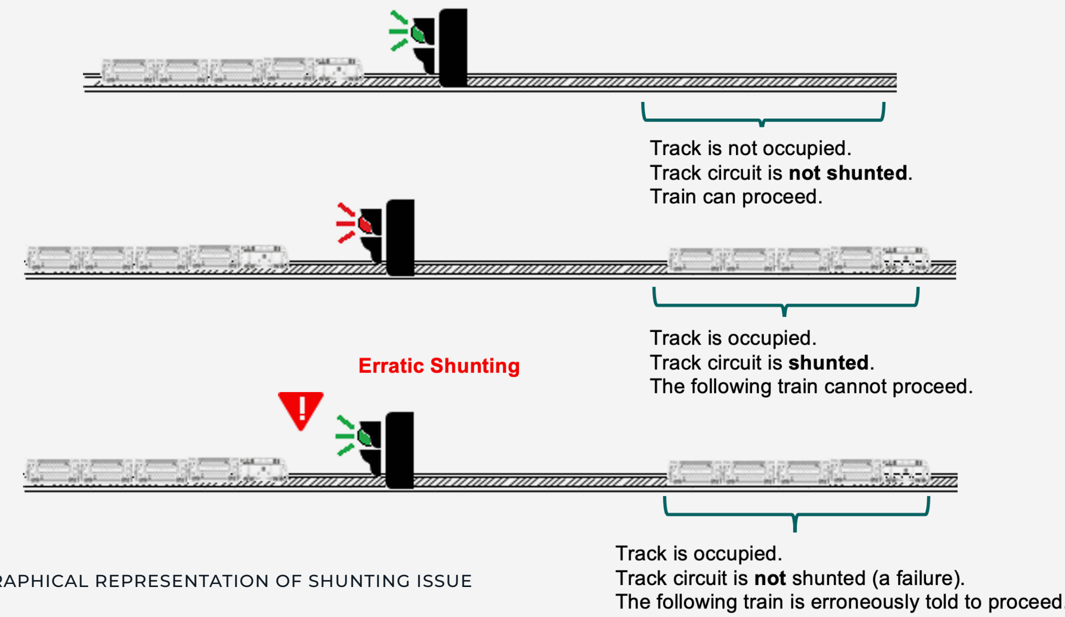


FIGURE 20: GRAPHICAL REPRESENTATION OF SHUNTING ISSUE

Inconsistent or erratic shunting performance can have several negative impacts to the signal system such as:

- Erratic train tracking or loss of display in the CAD/dispatch system

- Flashing of signal aspects if approach lighting is used

While not reported by the other RMU operators, a sustained loss of shunt would have much more severe impacts:

- Upgraded speed commands to a following train (violation of safe braking distance requirements)

- Unlocking of switches under a train

Crossing Warning systems, particularly predictor or constant-warning-time type systems, which are used throughout the Metrolink system, are particularly sensitive to erratic shunting, including:

- On approach to a crossing, an intermittent shunt could cause long (early) warning or pre-emption activation, lowering gates and stopping traffic signals considerably earlier than intended, particularly for slower moving trains

- As a train is passing a crossing, intermittent shunt could cause long (late) release of the warning or pre-emption signals, holding the crossing down for an extended period after the train clears

- An intermittent failure to shunt could lead to an activation failure or a late activation, wherein the gates are not down for an appropriate amount of time prior to train arrival.

3.4.5 Causes of Poor Shunting

The potential poor shunting performance associated with RMUs is based on a wide array of contributing factors, none of which are singularly responsible for the observed issues.

The main factor causing poor shunting is higher electrical resistance between the rail and wheel, typically due to contamination of the running rail surface. This contamination is usually oxidation/rusting of the running rail, which can, even when very thin, act as an insulating layer. Heavy, frequent train traffic with numerous axles will break down this layer and keep the railhead clean. RMUs are typically lighter (overall and per-axle) than locomotive hauled coach-sets and have fewer axles within a trainset. This can reduce the ability of the wheels to “break through” any railhead contaminants and reduces the number of contact points for conduction of the track signals from rail-to-rail. RMUs may also impart a different wheel tread to rail head contact patch when compared to other trains which run on the same track. In this case, while part of the railhead may have a good, clean surface, the RMU contact patch may be through a less used part of the running rail. This increases the likelihood of a loss of shunt occurring.

While rail condition and vehicle weight are drivers for shunt performance, certain track side equipment and track circuits are more susceptible. Shunt reliability becomes worse as the carrier frequency of the track circuit is lowered. A high audio-frequency track circuit (e.g., 3,240 Hz overlay, as applied on the Redlands Passenger Rail Project) will more effectively shunt under the same conditions than a low frequency predictor (e.g., XP4 operating at 86 Hz) since it has been noted that higher frequencies can more readily penetrate contamination between the wheel and rail. In this sense, the rail contamination can be considered a dielectric material, similar to a capacitor. DC coded track circuits, such as E-Code or ElectroCode, may also be susceptible due to their slow shunting reaction time and lower operating frequency. However, non-coded DC track circuits can be more reliable since they can be set up with a higher sensitivity and react faster to train occupancy.

Erratic shunting performance can be further influenced by environmental factors or other dynamic factors. Rail head oxidation can be expected to worsen immediately following rainfall or during particularly humid weather and can be affected by the nearby presence of bodies of water, especially saltwater. The buildup of contamination on the rail can be affected by the amount of train traffic on the tracks in question. Frequent, heavy freight train traffic is likely to keep the running rail surface cleaner than in areas with very limited train activity. Metrolink's estimation of mixed freight rail traffic in 2025 is shown in Table 17. This freight traffic may not all be through trains. Some freight trains depart from a yard (e.g., BNSF San Bernardino) and operate on a particular subdivision, such as the San Gabriel, while switching industry sites along the line and return in the same direction back to the yard.

Predicted Freight Traffic 2025	
Subdivision	**Frequency/Weekday**
Valley	8 trains
San Gabriel	21 trains
Perris Valley	1 train
Orange	11 trains
San Bernardino (BNSF)	35 trains
River	43 trains
Olive	6 trains
Ventura	13 trains

TABLE 17: PREDICTED FREIGHT TRAFFIC 2025

3.4.6 Potential Mitigations

Metrolink will require baseline system changes to accommodate RMU operations. These baseline changes will include grade crossing system frequency modifications and reconfiguration of signal block track circuits. Included within these baseline system changes, Metrolink will likely have to expand its current rail brushing program to include areas of the system not currently being scrubbed. If, after the baseline system changes have occurred, Metrolink observes shunting concerns when testing the new RMU vehicle, there are several mitigating actions that can be pursued, tested, and evaluated. Other railroads have shown that there is no one-size-fits-all solution to RMU erratic shunting and typically have applied multiple control methods.

Vehicle centric mitigations include modifications to wheel profiles, wheel tread scrubbers, wheel shunts, and onboard shunt enhancers, such as:

- Onboard shunt enhancers are electrical devices mounted to the car or bogie, which (through various means) induce a high frequency AC voltage difference across the rails. This induced signal is effectively a "whetting" or "biasing" signal which helps to initiate a conducting path for the track circuit signal. This can be understood similarly to biasing a transistor or modulating a signal on a carrier wave. These enhancers should be considered highly experimental and have no service proven history in the US. Many of the non-US demonstrations have little direct information and evidence that they resolve shunting performance concerns.

- Wheel profiles can be adjusted to match other trains running on the same trackage which can improve the likelihood that the RMU wheel contact patch is on the same portion of the rail head as other passenger or freights cars. This allows its shunt performance to benefit from the "cleaning" effect of other rail traffic.

- On-board vehicle wheel tread scrubbers are routinely used with RMUs to keep wheel treads clean to maximize the wheel-to-rail interface.

Wayside signal equipment modifications can also be performed primarily focused on making the signal system more tolerant of erratic shunting. The last bullet in this section applies to grade crossings, while the remainder are applicable for signals only:

- Track circuits can be changed to use uncoded-DC track circuits in place of ElectroCode. DC tracks may shunt more reliably. Elimination of the coded circuits would necessitate the addition of vital fiber optic line circuits between interlockings.
  - This was done on the Redlands Passenger Rail Project.
  - A vital line was installed for the signal system for Sonoma Marin Area Rail Transit (SMART)
  - A vital line was installed for the signal systems for North County Transit District Sprinter service
- Overlay track circuits can be used alongside the existing coded track circuits. These overlays can provide a redundant method of detecting trains.
- Loss-of-shunt timers can be applied to track circuits, which exhibit shunting issues. A loss-of-shunt timer is traditionally used only in interlocking/over-switch track circuits to maintain locking; however, the same concept could be applied to block track circuits. This timer would require a track to detect unoccupied condition for a pre-determined time period, prior to indicating unoccupancy.
- Predictor track circuits can be changed to higher frequencies. Higher frequency AC tracks have been shown to improve shunting performance. However, predictor track circuits at higher frequencies have shorter maximum lengths. Crossing systems will need to be assessed as baseline improvement to understand where frequencies can be changed without negatively impacting the operation of the crossing.
- Wireless Crossing Activation System technology can be pursued and deployed. This system has been recently deployed by the Denver Regional Transportation District. This system eliminates the need for track circuit-based train detection systems used at grade crossings by leveraging the existing Positive Train Control (PTC) system. By eliminating the track circuit-based train detection systems, the concern with erratic shunting for grade crossings is mitigated.

Infrastructure or maintenance improvements that can be used to help improve shunt performance:

- Rail Scrubbing is used by several U.S. RMU operators, as well as by Metrolink. Scrubbing or brushing of the railhead is a mitigation factor to improve its surface by removing corrosion and improving conductivity A high-rail or work train, equipped with powered brush equipment, (Figure 21), is used to scrub the railhead on a regular basis (daily, weekly, depending upon the needed frequency).
  - Texas DMU operators have established a set scrubbing schedule
  - SMART has established a routine scrubbing schedule
  - Metrolink performs scrubbing on an as-needed basis on certain lines
- Top-of-Rail Friction Modifiers, which are primarily for reducing wear on the rails, have been shown to be successful at improving shunting performance as well. The lubricant seems to serve as a protective layer on the rail head, preventing the build-up of rust/oxidation. However, detailed studies are warranted to ensure that braking performance is not adversely affected.

FIGURE 21: EXAMPLE OF RAIL SCRUBBING EQUIPMENT

Due to the unknown performance of any new RMU on Metrolink tracks, significant time and financial resources during the pilot project should be allocated, after baseline system changes have occurred, to identify outstanding problematic track circuit segments. The planning and conducting of vehicle tests, collecting data recorder logs from grade crossing predictors, and testing alternate solutions, will require much staff time from Metrolink. Staff will be coordinating all these activities without disrupting their passenger operations before starting any zero emission vehicle test.

3.4.7 Cost of Mitigating Shunting Issue

It is difficult to estimate the costs related to the mitigation of shunting. The problem can be either determined through testing on each subdivision or by testing at known problem locations. The severity of shunting issues detected would determine what would be needed to mitigate it.

The expectation is that a crew would have to run the locomotive or RMU over a series of weeks to test and capture the event or collect data. For example, a crew would be operating a train for a few months with flagmen at the crossings. The estimated cost to Metrolink would be approximately $3.5M-$8.2M, which reflects operating crew and flagging crew costs since a majority of the investigation is by testing. Additionally, the cost to upgrade wayside equipment is estimated at $25.6M, but could be more. The table shown below is a rough order estimate of test and implementation costs to mitigate shunting issues. The sweeping activity could be required through the pilot and possibly after wayside systems are installed. The track sweeping/scrubbing activity is a very low speed activity, requiring frequent brush changes and dedicated track time to complete.

Level	Subdivision	Activity	Description	Time Period	Total
Testing	Valley	Testing	Pilot Testing - Operating Crew	16 weeks	$152,000
	Valley	Testing	Test Crews and Subject Matter Expert Evaluation (5) persons	16 weeks	$3,635,200
	Valley	Flagging	Flagging crossing as needed (10) persons	8 weeks	$4,480,000
	Valley	Test Scrubbing	Cleaning rail head - Vehicle and Operator	A/R from testing	
Regular Scrubbing	Valley	Scrubbing	Cleaning rail head - Vehicle and Operator	2 days/ Week	$7000/ Week
	Subdivision	Activity	Description	Distance	Total
Baseline Wayside Upgrades	Valley	Track Circuit	Frequency Overlay - Signal Block Track Circuits	76 miles	$17.1M*
	Subdivision	Activity	Description	Crossings	Total
Baseline Crossing Modifications	Valley	Constant Warning Systems	Crossing Warning Systems Modification	55	$8.25M*

TABLE 18: ESTIMATED SHUNTING MITIGATION PREVENTION

Note * - Estimate to be further revised after findings from testing

Metrolink recently completed a section upgrade on the San Gabriel Subdivision that included a simple overlay circuit for the signal block track circuits of the 1.4 miles to the Redlands branch to mitigate the shunting issue. The cost for that section upgrade was approximately $315,000.

Crossing modifications are also needed to mitigate the shunting issue. These modifications include frequency changes and upgrades to account for new track circuit repeater locations and are estimated as $150,000 per crossing.

As a result, the estimation for baseline upgrades for track circuit for the AVL was calculated as:

$315,000/1.4 Miles = $225,000/Mile

$225,000/Mile x 76 Miles = $17.1 Million

$150,000/Crossing (CWD) x 55 CWD = $8.25 Million

Scrubbing the railhead requires the scrubbing vehicle to operate on the rails at a speed of 5 mph and sometimes requires brush replacement while in operation. The cost in Table 18 is listed as a weekly activity that includes the maintenance vehicle, the operator, fuel, and brush replacement cost. This may go on continually until crossing warning and signal systems are improved. The shunting mitigation may eventually be reduced and limited to certain segments, reducing the needed time to dispatch brushing maintenance.

3.4.8 Platform Length

The approximate length of an extended RMU that will have the equivalent seating capacity of a four-coach train would be approximately 565 feet (depending on manufacturer), comparable to the length of a 6-coach train. The lengths of station platforms on the Antelope Valley Line, where the pilot train will operate, vary between 1,000 feet and 495 feet. Three stations (Sylmar/San Fernando, Newhall, and Palmdale) are shorter than an RMU's length and three stations slightly exceed an RMU's length. Therefore, if a zero emission RMU operates on the target route, some of the cars will not be able to open their doors and the passengers would have to walk through to the adjacent cars to exit. This is a problem experienced by some longer trainsets today.

3.4.9 Platform Height

The current Metrolink standard for station platform height is 8 inches above the top of the adjacent rail, and the platform edge must be 5 feet 4 inches from the centerline of the track, to meet freight minimum clearance requirements per California Public Utilities Commission (CPUC) General Order 26-D. To meet ADA requirements, each platform is also equipped with a Mini-High platform that is 1'-9" above Top of Rail (TOR), and set back 2'-7" from the edge of platform, per below excerpt from Metrolink standard drawing ES3101-01, Section A. The mini-high platform is centered 60 feet from the station end for stations with a single mini-high. For stations with a mini-high at both ends, they shall be placed at opposing ends of the platform per Metrolink design standards.

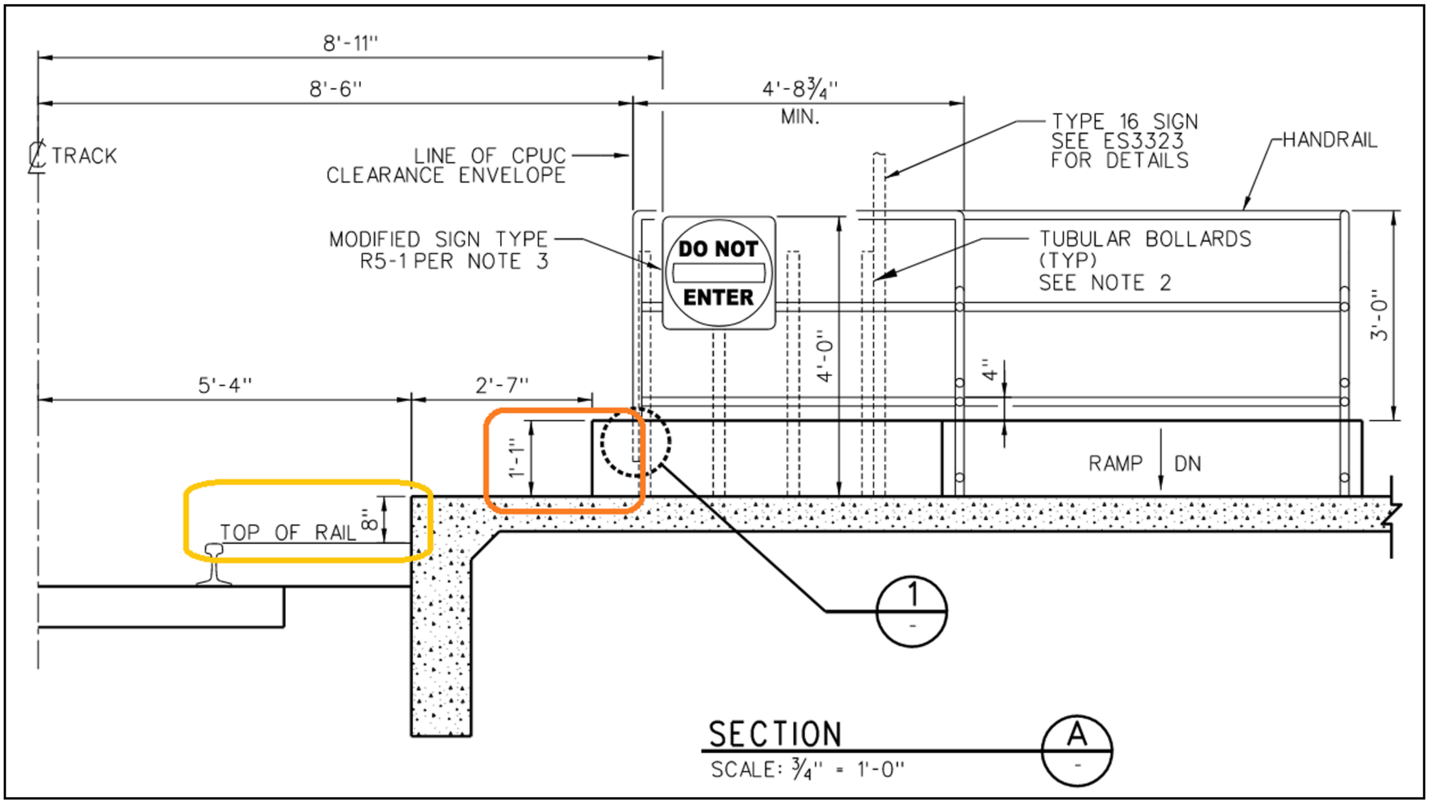


FIGURE 22: MINI-HIGH PLATFORM DIMENSIONAL REQUIREMENTS (METROLINK STANDARDS)

The mini-high platform is primarily intended for passengers in wheelchairs, and typically has two ramps, though at some stations there is only one ramp due to space constraints. The floor height of the Bombardier and Rotem bi-level coaches is 25" above TOR, and each coach is equipped with a bridge plate that is manually deployed by the conductor if needed. The bridge plate accommodates the height difference between the mini-high platform (21") and coach floor (25"), while meeting the 1:12 slope requirement of ADA.

The station platform shown below has a mini-high platform with dual ramps, with its leading edge set back from the track to the right. The top of the ramp is indicated by the blue arrow.

FIGURE 23: EXAMPLE OF MINI-HIGH RAMP

For a pilot program, the existing Metrolink mini-high platform set-up could be compatible with an RMU such as the Stadler Flirt utilized on the new San Bernardino ARROW service. The RMU must be configured in a manner that allows correct positioning of the accessible car with the mini-high platforms. The Stadler vehicle has a floor height of 24" above TOR, and can be equipped with a manually-deployed bridge plate. Also, it can be equipped with a step just below the threshold to board the car from Metrolink standard height platform (Note that the platforms for the ARROW service are higher at 23.5", to allow for level boarding at all train doors.) This would allow use of existing platforms on the Antelope Valley line by both existing bi-level coaches as well as a pilot program zero emission RMU.

Whether the existing platform design will be suitable for a pilot program without adaptation to allow all-door level boarding may be subject to review and approval from the FRA or FTA (see excerpt below from code of federal regulations).

CFR 49 § 38.91 General (c) 1, "Commuter rail cars shall comply with §§ 38.93(d) and 38.109 of this part for level boarding unless structurally or operationally impracticable."

The meaning of "operationally impracticable" is vague; however, given the short-time nature of a pilot it is reasonable to argue that all-door boarding would be impractical and thus not required.

Following completion of the pilot program, the long-term introduction of a new vehicle type may trigger a requirement from FRA or FTA for level boarding at every door of the vehicle, and thus may require an level board alternate compliance through FTA as stated in the Metrolink Design Criteria Manual (Section 7.7).[8] This request was done successfully for the Perris Valley Line (PVL) extension in 2012. Riverside County Transportation Commission (RCTC) submitted a "Request for Determination of Alternate Method of Compliance regarding Level-Boarding for the Perris Valley Line Commuter Rail Extension Project" to FTA in October 2010, which included analysis in a Level Boarding Report. An RCTC follow-up was sent in March 2011, and FTA finally granted approval in Feb 2012.

There are two key issues with use of the mini-high platforms:

- They often put a person with a disability out of the general public way, at the far end of the platform, sometimes out in the rain

- Because the ADA requires that all cars be accessible, they can require the use of "re-spotting" the train one or more times. Each re-spotting can take several minutes with the boarding/deboarding and can have a serious operational impact on the timetable.

The primary justifications for the use of mini-high platforms are the incompatibility of high platforms with freight traffic, and the high cost of alternative solutions such as movable platform edges or gauntlet tracks. Gauntlet tracks at station platforms are utilized, for example, by Northern Indiana Commuter Transportation District (NICTD) which operates the South Shore Line and by Sonoma–Marin Area Rail Transit (SMART). Retractable station platform edges have been utilized by New Jersey Transit (NJT).

Portable station lifts are utilized by Amtrak, and avoid the re-spotting issue, but are not recommended for Metrolink due to numerous problems associated with their use, including mechanical failures, risk of theft or vandalism, and a variety of human errors in their use as reported by the National Disability Rights Network.

Another potential solution considered was the use of multiple mini-high platforms (e.g., four of them for a standard 4-door ZEMU). This would avoid the re-spotting issue, while allowing regular boarding with legacy bi-level cars. However, this approach was not approved for the Caltrain system, and it is assumed that it would not be approved for the Metrolink system.

If the current Bombardier or Rotem bi-level passenger coaches from the Metrolink fleet are used with a pilot zero emission locomotive, no station platform changes would be required.[9]

---

[8] "For new or altered stations serving local communities, commuter, intercity, or high-speed rail lines or systems, in which track passing through the station and adjacent to platforms is shared with existing freight rail operations and the railroad proposes to use a means other than level-entry boarding, the railroad is required to meet the following requirements:

Perform a comparison of the costs (capital, operating, and life-cycle costs) of car-borne lifts and the means chosen by the railroad operator, as well as a comparison of the relative ability of each of these alternatives to provide service to individuals with disabilities in an integrated, safe, timely, and reliable manner.

Submit a plan to FRA and/or FTA, describing its proposed means to meet the performance standard at that station. The plan shall demonstrate how boarding equipment or platforms would be deployed, maintained, and operated; and how personnel would be trained and deployed to ensure that service to individuals with disabilities is provided in an integrated, safe, timely, and reliable manner.

Obtain approval or a waiver from the FTA (for commuter rail systems) or the FRA (for intercity rail systems). The agencies will evaluate the proposed plan and may approve, disapprove, or modify it. The FTA and the FRA may make this determination jointly in any situation in which both a commuter rail system and intercity or high-speed rail system use the tracks serving the platform." Metrolink Design Criteria Manual, 7.7

[9] For a more extensive and/or longer-term implementation of RMUs or acquisition of any new rail cars, Metrolink will need to address the issue of level boarding access from all doors in a consist. With the range of platform and vehicle entry heights currently being used in mainline rail service in California, effectively addressing this issue transcends Metrolink's operation, and may best be dealt with on a more systematic statewide basis.

3.4.9 Platform Height

For any Metrolink lines that might be selected for future conversion to zero emission RMUs, there are various options to consider for modification of station platforms:

Option 1 – Status Quo (Single Mini-High Platform):
No further changes to the platforms, and passengers would continue to step up into the RMU vehicle from the 8" platform, as is currently done with the bi-level coaches. This assumes that the existing single mini-high platform would serve both the bi-level coach fleet and RMUs in meeting minimum ADA requirements. However, the introduction of a new vehicle could trigger an FTA requirement for level boarding at all vehicle doors, which is the preferred ADA scenario. Again, a request for determination of alternate compliance regarding level-boarding to FTA would be the best option. Case studies for the Metrolink Perris Valley Line (PVL) extension and peer Authorities (Caltrain) have been successful in this approach. In the case of PVL, the request was granted in 2012 on the basis of preserving compatibility with freight traffic, and because PVL had to be compatible with the existing service using existing vehicles; in the case of Caltrain, it is more appropriate example as it was a new vehicle in mixed consists on existing line/stations. Study references are included in Appendix I. If the request were to be denied by the FTA, Metrolink would be required to move to an alternate approach with the associated costs.

A variation on this approach is to utilize a mini-high platform but deploy the ramp from the vehicle. This adds more cost to the vehicle design and could be slower to deploy. A powered mechanism improves ergonomics for the conductor but adds the risk of a mechanical failure and train delay.

Option 2 – Vehicle-Borne Lift:
Provide a boarding lift mechanism at all vehicle doors. This will require the use of a swing-out lift deployed from the vehicle, and such a requirement will need to be included in the RMU vehicle specification. Without the need to link up with a mini-high platform location, this will simplify spotting the vehicle on the platform and will not require "re-spotting."

The lift mechanism would be located in a pocket at the door entrance. The lift would be deployed to Metrolink's current platform height, and a disabled passenger can board. The lift would typically be power-operated and would add approximately $25-$30K per door location to the vehicle cost for the lift itself, plus potential re-design work to a standard vehicle without such lift mechanisms. Retrofitting a powered lift could require significant design work for the structural model and calculations, depending upon how much the carbody structure has to be modified. Moreover, powered lifts, whether car-or platform-based, tend to increase boarding times, and are subject to mechanical failures. The lift mechanism must be designed with the utmost simplicity and reliability, as a lift failure in the open position can significantly delay the train. In U.S. rail operations, an in-door wheelchair lift mechanism is utilized in train cars for Amtrak's San Joaquin service (see Figure 24).

Vehicle-borne lifts are not a recommended solution, particularly for a pilot vehicle, for the following reasons:

- Complexity and cost of retrofitting a mechanism to each door of a standard RMU
- Increased maintenance cost due to repair and testing of lift mechanisms
- Increased time for pre-departure checks, due to need to verify proper operation of all lifts
- Risk of train delay due to failure of a lift mechanism in the open position

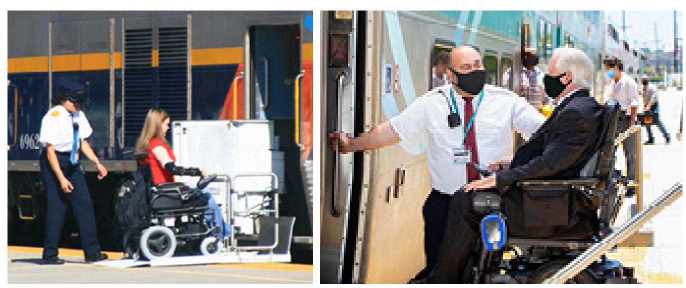


FIGURE 24: BOARDING LIFT MECHANISM FULLY DEPLOYED

FIGURE 25: BOARDING LIFT MECHANISMS IN DOOR ENTRANCE

Option 3 – Full-Height Platforms with Gauntlet Track
Using a phased approach over several years, convert platforms to full-height and, where feasible, build new platforms with a full-height level boarding option (e.g., one side of a center platform, or partial length). Where required to accommodate freight traffic, install a gauntlet track (an offset track parallel to the main track that allows a train to pass a fixed object, such as a high-level boarding platform). This approach assumes the gradual retirement of the bi-level coach fleet, or modification of the bi-level door entrances with steel plates to eliminate the steps. This is the most expensive option to implement, because it requires a turnout at each end of the station, as well as signal system modifications and installation of new rails (and possibly new crossties). In addition, if the end of the station is close to a grade crossing, the grade crossing would also require modification to include the gauntlet track. Increasing the height of the platform will also require modifications to stairs and ADA ramps, as well as relocation of amenities such as lighting, canopies, benches, and sign boards.

A variation on the phasing approach is to lengthen station platforms, with the new portion being at full height for level boarding with RMUs, while the original platform services the bi-level coaches. This is only feasible at station locations with sufficient space that is already owned by Metrolink or available for purchase. This approach could slightly reduce the cost of gauntlet track, but the main benefit is avoiding much of the disruption of modifying the platform while in active use. Metrolink could also elect to temporarily take the station out of service and provide a bus bridge.

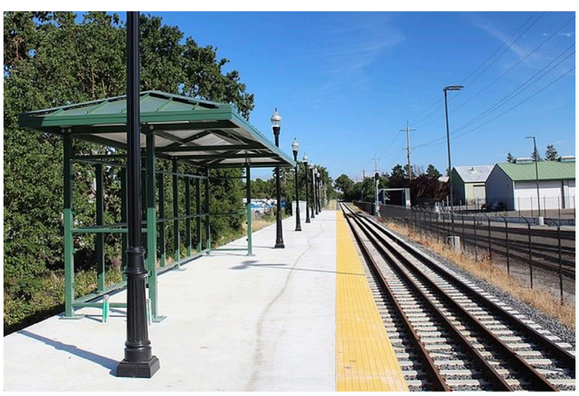


FIGURE 26: GAUNTLET TRACK AT SMART AIRPORT STATION

3.4.10 Facility Issues

Charging/Fueling:
It is assumed that a battery locomotive or RMU will be charged during overnight and mid-day layovers. Further upgrades may include other points along the route to permit OCS for opportunity charging. The pilot project will require charging infrastructure at both the CMF and an outlying facility (e.g., the EMF for a San Bernardino route) or layover track (e.g., Lancaster for an Antelope Valley route). The challenge for battery charging is the need for additional utility service, which at CMF would likely be brought in from San Fernando Road and have to cross below several tracks. Charging several locomotives would require a new substation, along with OCS in the yard, to provide maximum flexibility for charging at any storage spot.

FIGURE 27: OVERVIEW OF CENTRAL MAINTENANCE FACILITY

Based on simulations, a hydrogen fuel cell locomotive or RMU will have sufficient capacity to make one round trip. Thus, H2 refueling will need to be provided at the CMF only, on a single dedicated track. The primary challenge for hydrogen refueling during the Pilot program is the requirement to locate storage and dispensing that is near a track as well a paved roadway for deliveries. If a small PEM electrolyzer unit is to be utilized instead of delivery/trailer swap, then there is also the need to locate the electrolyzer unit itself, as well as providing the necessary 480 VAC power and water supplies. The power requirement for a 1.5 MW electrolyzer is comparable to that of a battery charging station, which thus means an additional utility feed from San Fernando Road.

Maintenance of Locomotives:
Hydrogen fuel cell or battery electric locomotives will dimensionally be very similar to diesel-electric units in the current fleet, and have similar axle-loading, given that they will have to meet clearance and loading requirements over Metrolink routes. Thus, no upgrades to shop pedestal track or platforms should be necessary. Inside the maintenance shop at the CMF, which is already at capacity, special components such as batteries, tanks, and fuel cells, will be modularized and removed vertically by means of the existing bridge crane, or from the side via forklift. Trucks can be removed using the existing drop table.

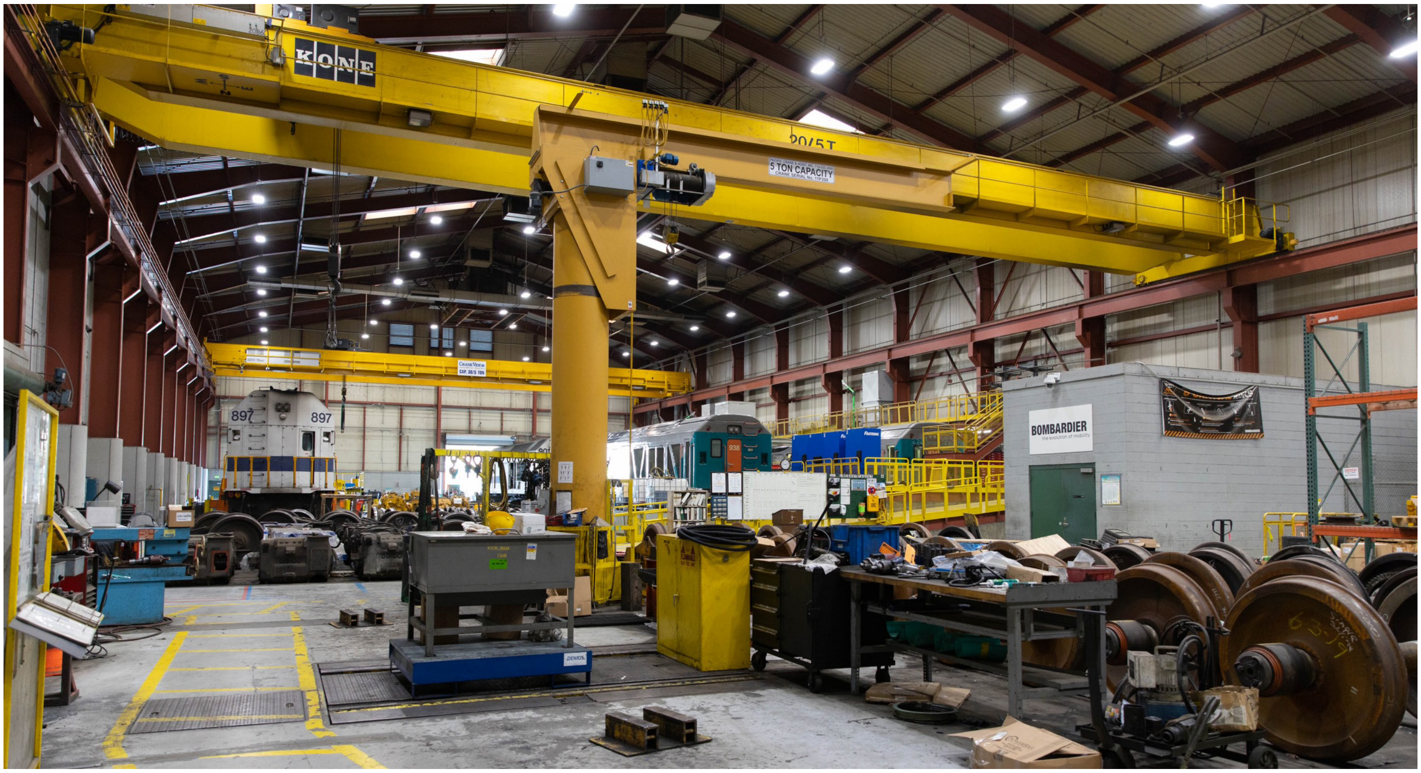


FIGURE 28: CMF LOCOMOTIVE SHOP INTERIOR VIEW

A hydrogen fuel cell hybrid locomotive will require a leak detection system at the CMF. Because hydrogen is lighter than air (like CNG), this necessitates the addition of ceiling level detectors and a wall-mounted alarm indication panel. This system will interface with the exhaust fans to turn them on automatically in the event of detection of hydrogen above a certain threshold. Exhaust fans may need to be upgraded to non-sparking type.

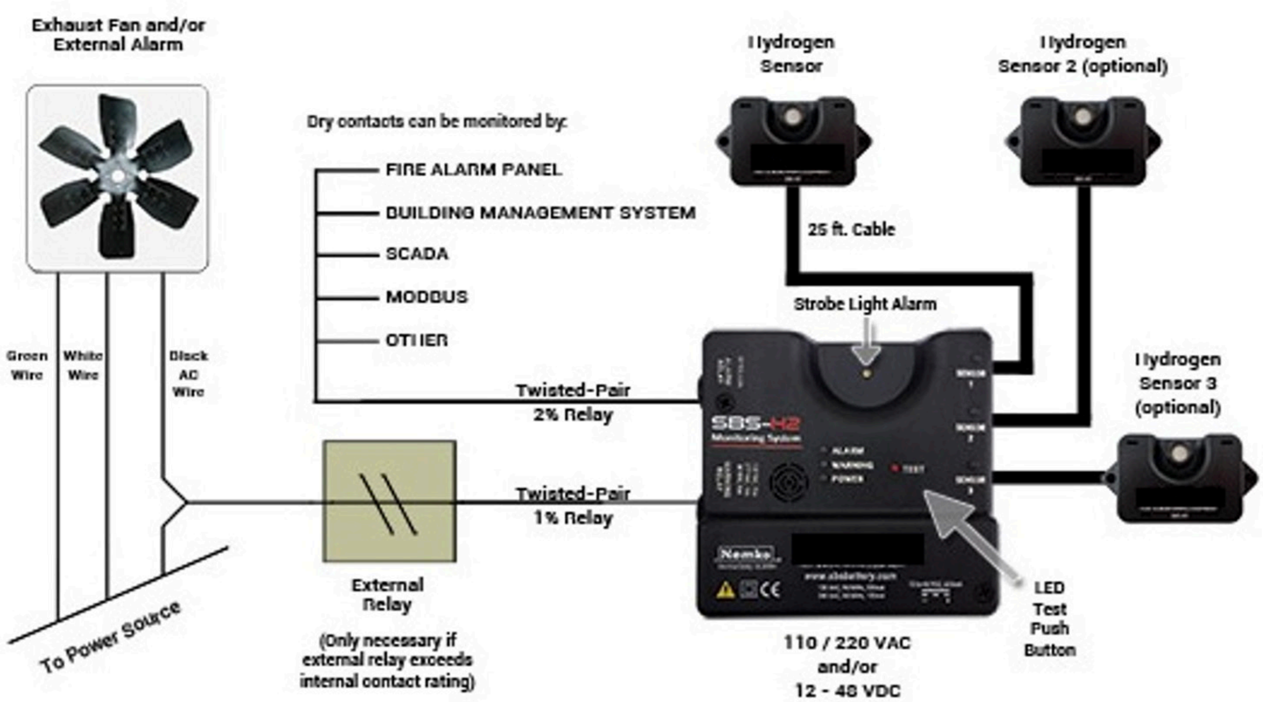


FIGURE 29: TYPICAL HYDROGEN DETECTION SYSTEM

Maintenance of RMUs:

Zero Emission RMU vehicles (ZEMUs) with battery and hydrogen fuel cell variants are currently in production by Stadler and Alstom. Both are semi-permanently coupled consists with a ‘power car’ in the middle of the consist (though Alstom also offers a variant with distributed battery power). The battery RMU can be equipped with a roof-mounted pantograph for opportunity charging under OCS to extend the vehicle’s range.

Many of the required maintenance activities are similar to those needed for Metrolink’s existing fleet, e.g., couplers, brakes, HVAC, windows and windshield wipers, doors, signage, etc., and can be accommodated in existing CMF shop areas with pit tracks, small work platforms/scissor lifts on flat floor areas, and a bridge crane, as found in the Car Shop (flat floor / center pit with bridge crane) and Progressive Tracks (pedestal track pit, no crane).

Power Car:

Like the DMU currently planned for the Arrow Service in San Bernardino, component removal is from the side of the power car and can be performed from either side. However, unlike the DMU, the battery and hydrogen fuel cell systems are modularized, which simplifies removal because the modular components are much smaller and lighter than for the DMU’s diesel engine. On the Stadler vehicle, for example, the modular components weigh no more than 250 kg (550 lbs.), which allows for removal by a typical forklift in any flat floor area (or even outdoor track) with sufficient maneuvering room for the forklift.

The primary issues with maintaining a ZEMU at CMF are as follows:

- CMF is already operating at capacity, and a ZEMU - due to its considerably greater length as compared to a locomotive - creates greater space constraint issues inside the shop and in the Yard

- Will require the purchase of specialized vehicle lift equipment to enable truck removals from the vehicle.

Trucks:

The 4-car RMU consist from Stadler, for example, has an overall length of 272 ft. and utilizes a shared truck between car segments. In a typical locomotive shop, truck removals can be accomplished using either a drop table or a set of synchronized jacks.

The CMF drop table is located on a stub-end track in the Locomotive Shop from the centerline of the drop table to the end of the stub track is 73 feet. This does not provide sufficient room, as explained below, to allow placement of every truck over the drop table service top, even if the RMU were to be turned. A secondary consideration is that, due to the shared truck configuration, each car end needs to be supported (two sets of body supports are required); however, the CMF drop table has only one set of supports.

FIGURE 30: CMF LOCOMOTIVE SHOP, WITH DROP TABLE

Because the RMU is a semi-permanently coupled consist, with shared trucks, the process of uncoupling a particular car segment is complex and is best accomplished inside a shop with an overhead crane and dummy trucks to support the end of the car segment. As a result, it would not be feasible to routinely uncouple the consist for truck replacements over the existing CMF drop table.

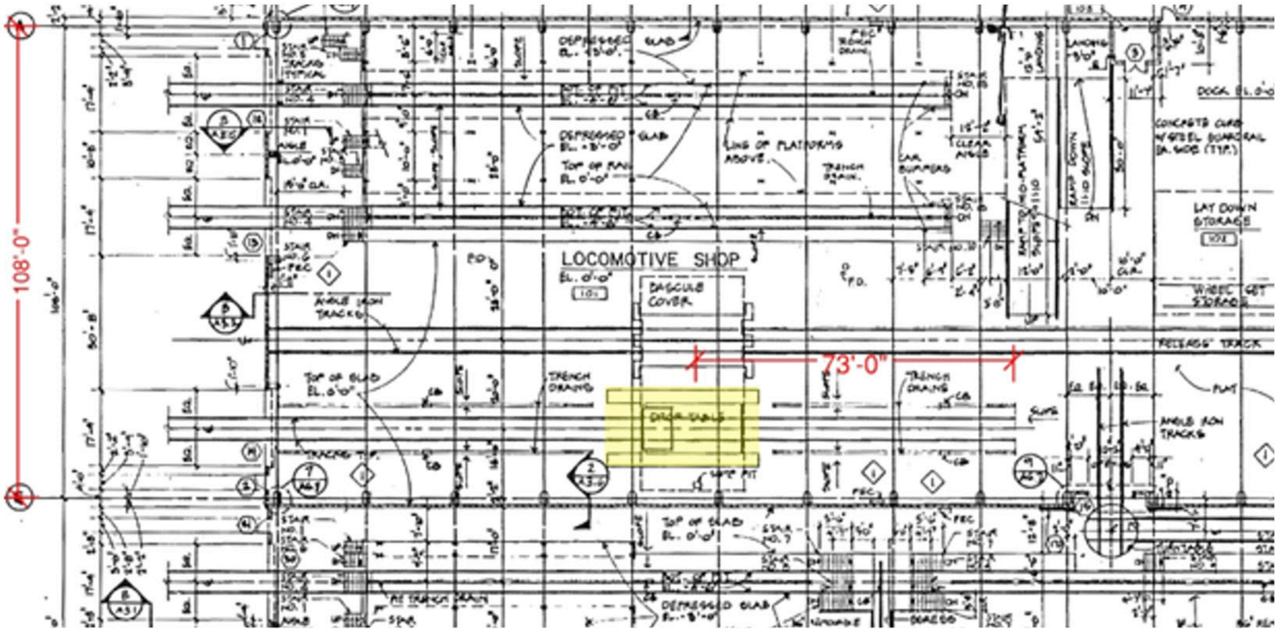


FIGURE 31: CMF LOCOMOTIVE SHOP,
WITH DROP TABLE HIGHLIGHTED IN YELLOW

The second method for truck removal is to utilize a set of synchronized column lifts (mechanical screw jacks) to raise the entire consist, as shown in Figure 31. For a 4-car RMU consist, this would require a set of 20 jacks, with 10 on each side. The 4-car RMU from Stadler, for example, has an empty weight of approximately 380,000 lbs. Thus, the capacity for each jack must be at least 20 tons.

For removal of a particular truck, it is disconnected from the car body (including all power, signal, and air lines) before the consist is raised. Then the consist is raised and the truck is rolled out to one end of the consist. On a flat floor with embedded track, intermediate turntables can be used to redirect the truck without having to go all the way to the end. An overhead crane is utilized to place the truck on a flatbed for transport off-site for repair or overhaul. The process is reversed for the replacement truck.

FIGURE 32: EMU RAISED ON SYNCHRONIZED JACKS
*Photo Courtesy of Stadler

Synchronization of the jacks can be done via a daisy-chain of shielded cables, or wirelessly. Each jack requires a 480 VAC connection for power. At a new facility, these outlet boxes can be set into the floor with conduit under the slab. At an existing facility such as the CMF, power cables would run to wall outlets. To protect the cables, heavy-duty rubber cable protectors could be utilized, or trenches could be sawcut in the slab, and provided with steel cover plates.

With the length of the 4-car RMU consist at 272 ft, the lifting process requires an equivalent length of level tangent track. The track typically would be embedded rail in a flat floor, or have a center (gauge) pit, with a thickened slab to accommodate the point load from each jack.

At the CMF, there are three possible locations for lifting an RMU consist on jacks, and each has some challenges:

- Car shop track
- Progressive track
- Outside track

FIGURE 33: CMF CAR SHOP

Option 1:

In the CMF Car Shop, the entire bay is 220 ft long, and the gauge pit portion is 180 ft long, as compared to a consist length of 272 ft. Therefore, a portion of the consist would be outside the building on the concrete apron. This would require positioning at least two jacks outside on the apron. The Car Shop is equipped with a bridge crane, which facilitates handling of trucks. Because the consist would be passing through the train door opening, overhead clearance is an issue. The door opening is 18'-0" per the original design drawings. The RMU height is approximately 14'-1", leaving less than 4 ft of lifting room at the doorway.

Required upgrades for RMU would include the following:

Description	Cost
Increase the height of the doorway opening to a minimum of 21 ft; install new roll-up train door	$35,000
Add a truck turntable and embedded rails to enable a truck to be rolled out from beneath the vehicle for bridge crane handling	$75,000
Movable scaffold for roof access	$30,000
Upgrade six jacks for outdoor usage and provide removable covers	$15,000
Electrical upgrades to provide 480V/3ph power to all synchronized jacks (including six outdoor on apron)	$26,000
Synchronized jacks for truck replacements; miscellaneous tools and equipment	$1,010,000
Staff time (10%); Contingency (35%); Design / DSDC / CM (10%)	$708,000
Total estimated shop upgrades construction cost (battery RMU)	**$1,900,000**
Hydrogen leak detection and ventilation upgrades	$125,000
Staff time (10%); Contingency (35%); Design / DSDC / CM (10%)	$74,000
Total estimated shop upgrades construction cost (fuel cell battery hybrid RMU)	**$2,099,000**

TABLE 19: ESTIMATED FACILITY COST FOR SHOP MODIFICATIONS – OPTION 1

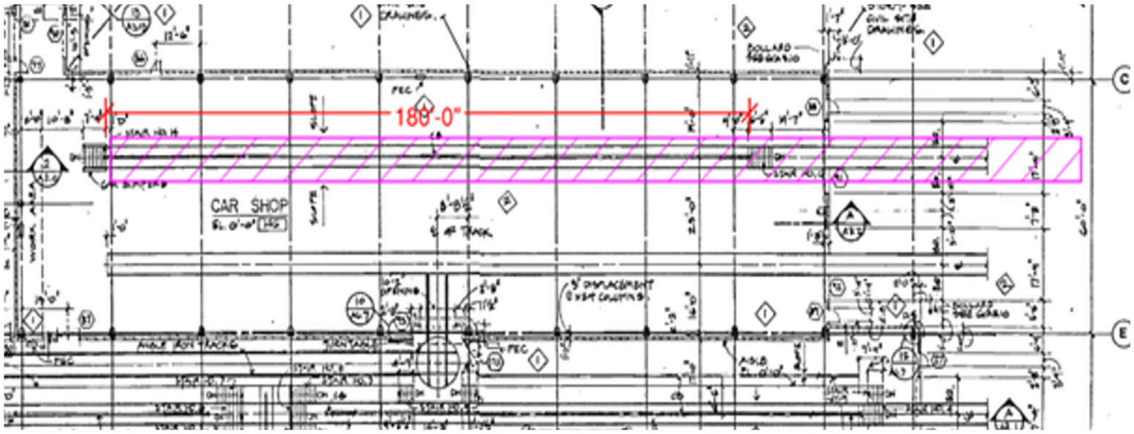


FIGURE 34: CMF CAR SHOP LAYOUT WITH RMU LENGTH OVERLAY

FIGURE 28: CMF LOCOMOTIVE SHOP INTERIOR VIEW

<u>Option 2:</u>

The Progressive Tracks have sufficient length and overhead clearance to accommodate the RMU but have two disadvantages: (1) pedestal track with side pits, and (2) lack of an overhead crane. Due to the presence of side pits, one of three modifications would need to be made to allow the use of jacks:

1. Jacks could be customized with longer support arms, which increases the overturning moment and would necessitate a much larger base and/or a restraining device at the back of the lifting jack.

2. It may be possible to locate the jacks in the side pit, which would mean a customized jack with a longer screw jack. However, the pit floor thickness would need to be sufficient to accommodate the load of a jack while it is supporting a vehicle.

3. Add reinforced concrete plinths in the side pit, to enable positioning the jacks closer to the consist. The top of the plinth would match the top of rail/finish floor. This would likely be the least expensive option but would create permanent obstacles in the side pits.

Option 2 is recommended for the facility upgrades in the Technical Analysis. But it should be noted that the proposed area may be impacted by the California High Speed Rail alignment between Burbank and Los Angeles.

Required upgrades for RMU maintenance under Option 2 would include the following costs for battery and fuel cell battery hybrid vehicles, as well as a low-cost scenario that does not include synchronized jacks (requires truck replacement offsite):

Description	Cost
Add a truck turntable and embedded rails to enable a truck to be rolled out from beneath the vehicle for bridge crane handling	$75,000
Movable scaffold for roof access	$30,000
Form and pour new jacking pads along the PM Track	$28,000
Electrical upgrades to provide 480V/3ph power to all synchronized jacks	$25,000
Synchronized jacks for truck replacements; miscellaneous tools and equipment	$1,010,000
Staff time (10%); Contingency (35%); Design / DSDC / CM (10%)	$695,000
Total estimated shop upgrades construction cost (Battery RMU)	**$1,860,000**
Hydrogen leak detection and ventilation upgrades	$175,000
Staff time (10%); Contingency (35%); Design / DSDC / CM (10%)	$104,000
Total estimated shop upgrades construction cost (Fuel cell battery hybrid RMU)	**$2,142,000**
Low Cost Scenario: Battery RMU shop upgrades w/o synchronized jacks	**$64,000**
Low Cost Scenario: Fuel cell battery hybrid RMU shop upgrades w/o synchronized jacks	**$343,000**

TABLE 20: ESTIMATED FACILITY COST FOR SHOP MODIFICATIONS – OPTION 2

Option 3:

Utilize an outside track for truck removals. This option would be the lowest cost but is not recommended. The jacks could be weatherized for an exterior location, and perhaps provided with covers when not in use; however, it is likely that their service life would be degraded. 480 VAC outlets and conduit would need to be added to this track area. The location must also ensure that the jacks do not foul an adjacent track. Truck replacements in adverse weather such as high winds or rain would be challenging or not feasible. Another drawback would be the requirement to rent a truck crane to load a removed RMU truck, and unload replacement one. The estimated $5,000/day crane rental would be a recurring operating expense.

Required upgrades for battery RMU would include the following:

Description	Cost
Movable scaffold for roof access	$30,000
Outdoor rating and removable covers for synchronized jacks	$50,000
Electrical upgrades to provide exterior 480V/3ph power to all synchronized jacks	$35,000
Synchronized jacks for truck replacements; miscellaneous tools and equipment	$1,010,000
Staff time (10%); Contingency (35%); Design / DSDC / CM (10%)	$670,000
Total estimated shop upgrades construction cost (Battery RMU)	**$1,795,000**

TABLE 21: ESTIMATED FACILITY COST FOR SHOP MODIFICATIONS – OPTION 3

Because it assumes use of an outdoor track location, RMU option 3 would not require hydrogen leak detection and ventilation upgrades for a hydrogen fuel cell battery hybrid RMU.

Summary:

Due to the cost and configuration challenges at the CMF, a battery or fuel cell hybrid locomotive would require significantly less cost for constructing facility upgrades as compared to an RMU. The locomotive would remain as a push-pull operation identical to existing operating train sets. Of the locomotive options, a battery electric locomotive would have the lowest cost impact on shop facilities. CMF upgrade construction costs are summarized in the table below:

Vehicle	Battery Electric	Hydrogen Fuel Cell / Hybrid
Locomotive	$16,000	$215,000
RMU – Option 1 (Car Shop Mods)	$1,900,000	$2,099,000
RMU – Option 2 (Progressive Track Mods)	$1,860,000	$2,142,000
RMU – Option 3 (Exterior Mods)	$1,795,000	$1,795,000

TABLE 22: ESTIMATED FACILITY COST FOR SHOP MODIFICATIONS – SUMMARY

3.5 Financial Benchmark

Rebuilt and new battery locomotives have the lowest total cost in a pilot implementation.

Rebuilt and new battery locomotives have the lowest life cycle costs in a pilot implementation.

Rebuilt locomotives, new locomotives, and RMUs for pilot implementation are financially benchmarked by considering all related cost items as shown in Table 24. According to this table, rebuilt and new battery locomotives have the lowest overall cost while rebuilt and new fuel cell battery hybrid locomotives have the highest cost. Moreover, in the financial analyses - except the one for a fuel cell battery hybrid RMU - it was assumed that all non-recurring engineering costs are reflected in the cost of a single pilot vehicle. It should be noted that recent prospective battery locomotive and RMU procurements by Metra and MBTA may result in reduced NRE costs for battery propulsion options. Although battery propulsion has the highest yard and layover cost mainly due to the required grid upgrades for high power charging, it is advantageous in the other cost items. Fuel cell battery hybrid RMU option is estimated to be less expensive than battery RMU and fuel cell battery hybrid locomotive options due to the SBCTA vehicle procurement of European fuel cell battery hybrid MU designs that are already in development. Moreover, as described in the previous sections, rebuilt and new battery locomotives have the lowest life cycle cost.

In the cost projections, it is assumed that Metrolink would use existing spare trailer and cab cars for the locomotive pilot implementation in a consist with one trailer car and one cab car. If Metrolink cannot accommodate these cars for the pilot due to the full utilization of the existing fleet, it may be required to acquire one trailer car and one cab car by leasing or purchasing them. If the cost of these cars is included in the cost projections, the total cost of the pilot locomotive options would increase by approximately $8,400,000 and the total cost of rebuilt and new battery locomotive options would be closer to the cost of the fuel cell battery hybrid RMU option.

		Battery Electric			Fuel Cell Battery Hybrid		
		Locomotive		RMU	Locomotive		RMU
		Rebuilt	New	New	Rebuilt	New	New
Acquisition	Non-recurring Engineering	$13,050,000	$11,920,000	$17,410,000	$29,800,000	$32,940,000	$16,340,000
	Material + Labor	$6,560,000	$7,670,000	$11,980,000	$6,790,000	$7,900,000	$12,530,000
	Spare Parts	$1,500,000	$1,500,000	$1,500,000	$1,500,000	$1,500,000	$1,500,000
	Contingency	$5,880,000	$5,880,000	$8,820,000	$10,980,000	$12,250,000	$8,660,000
	Metrolink + Consultant Engineering/Testing Labor	$3,920,000	$3,920,000	$5,880,000	$7,320,000	$8,170,000	$5,770,000
	Acquisition Cost Total	**$30,910,000**	**$30,890,000**	**$45,590,000**	**$56,390,000**	**$62,760,000**	**$44,800,000**
Operational	Maintenance during Pilot Testing	$130,000	$130,000	$100,000	$140,000	$140,000	$120,000
	Energy Cost during Pilot Testing	$560,000	$560,000	$450,000	$970,000	$970,000	$850,000
	Additional Rail Brushing during Pilot Testing	$0	$0	$730,000	$0	$0	$730,000
	Operational Cost Total	**$690,000**	**$690,000**	**$1,280,000**	**$1,110,000**	**$1,110,000**	**$1,700,000**
Facilities	Facility - Shop Cost	$16,000	$16,000	$1,860,000	$215,000	$215,000	$2,140,000
	Facility - Yard and Layover Cost	$8,400,000	$8,400,000	$8,400,000	$4,210,000	$4,210,000	$4,210,000
	Facilities Cost Total	**$8,416,000**	**$8,416,000**	**$10,260,000**	**$4,425,000**	**$4,425,000**	**$6,350,000**
Shunting	Testing	$0	$0	$8,270,000	$0	$0	$8,270,000
	Wayside Upgrades	$0	$0	$25,350,000	$0	$0	$25,350,000
	Shunting Cost Total	**$0**	**$0**	**$33,620,000**	**$0**	**$0**	**$33,620,000**
	Total	**$40,016,000**	**$39,996,000**	**$90,750,000**	**$61,925,000**	**$68,295,000**	**$86,470,000**

TABLE 23: ESTIMATED FINANCIAL BENCHMARK OF OPTIONS FOR PILOT ANTELOPE VALLEY LINE IMPLEMENTATION

One of the main goals of the Analysis is to take a holistic approach and evaluate all aspects of the chosen zero emissions technology during the pilot phase. If this goal is traded off for a lower pilot cost, one of two high power overhead chargers for the pilot propulsion, on-site hydrogen production for the fuel cell battery hybrid propulsion and synchronized jacks (and associated upgrades) for RMU can be removed from the Analysis.

4 FINDINGS FOR THE PILOT

4. FINDINGS FOR THE PILOT IMPLEMENTATION

Propulsion Type \ Vehicle Type	New Locomotive	Rebuilt Locomotive	Rail Multiple Unit
Battery Electric	Option 1	Option 2	Option 3
Fuel Cell Battery Hybrid	Option 4	Option 5	Option 6

TABLE 24: OPTIONS FOR PILOT IMPLEMENTATION

4.1 Propulsion Technology and Vehicle Type

In this section, the findings for the pilot vehicle type and propulsion technology will be made using the information presented in the previous sections. Both battery and hydrogen technologies are promising and both may play a role in Metrolink's long term transition strategy. For the sake of completeness, all the available options for the pilot project are redisplayed in Table 24.

All zero emission propulsion technologies have some disadvantages and challenges that need to be evaluated and resolved in the field. Each transit agency or railroad should not confront these challenges independently but join efforts with peer operators to uncover and address as many unknowns as possible about each potential technology instead of investing in the same or similar technology while not considering some others. With this vision, Metrolink is advised to work on advancing a different type of zero emission technology from SBCTA's fuel cell battery hybrid RMU and minimize the unknowns about zero emission technologies before committing to any fleet-wide decision.

For the propulsion technology findings, funding availability is the most critical parameter because zero emissions vehicle implementation at pilot and fleet level would have significant cost implications for Metrolink. Transit and Intercity Rail Capital Program's (TIRCP) funding of $10 million is currently available to advance a zero emissions pilot on the Antelope Valley Line.

4.2 Findings for Zero Emissions Vehicle Pilot on the Antelope Valley Line

This Analysis recommends that Metrolink continue to explore partnership opportunities with Caltrans for a comprehensive research and development program and use the funding from the TIRCP to support additional study and zero emissions pilot vehicle testing. This approach will allow Metrolink to test at least one zero emissions vehicle, without bearing the procurement risk of purchasing untested technology.

The approach is consistent with this Analysis' technical findings on compatibility, financial effectiveness, and strategic alignment with the Metrolink program and mission.

Any testing arrangement would need to meet Metrolink's operational, financial, safety and regulatory requirements. Depending on the vehicle type selected by Caltrans, the required funding for the testing and infrastructure upgrades may exceed the $10 million available from the Transit and Intercity Rail Capital Program (TIRCP) funded Metrolink Antelope Valley Line (AVL) Capital and Service Improvements Project and additional grant funds would need to be identified to support the test. The findings from the Pilot project, along with the projects lead by SBCTA and other passenger rail agencies, will help advance the eventual transition of Metrolink's core fleet to zero emissions.

- This Analysis concludes that testing battery electric technology will be less costly and technologically complex to integrate into Metrolink's existing fleet and facilities for a single vehicle demonstration. Battery electric propulsion has great potential because of the intensive research and development (R&D) efforts of the light-duty vehicle industry and the variety of promising battery chemistries. This Analysis recommends that Caltrans, as part of their Zero Emission Research and Development Program (Caltrans ZE R&D Program) highly consider testing battery electric propulsion technology as part of the Caltrans ZE R&D Program.
    - Battery electric propulsion systems offer a useful synergy with a complementary overhead catenary system. In combined operations, while some track sections are electrified, battery energy is used on the remaining non-electrified route segments. Overhead catenary systems are costly. The level of investments depends on the restricted clearances on overpasses, right-of-way clearances.

  - A battery electric locomotive will use existing coaches and cab cars in a push-pull operation identical to the train consist currently in use. The train consist can be interchanged with a diesel electric locomotive or coupled directly to the pilot battery electric. The zero emissions locomotive is less of a burden to CMF activity and space constraints.

  - The range disadvantage may be overcome with novel train consist concepts such as battery tender car and dual mode operation with an overhead catenary system. Moreover, Li-Ion battery technology has the potential of 30-40% energy density increase in the next 5-10 years that would close the range gap with the fuel cell technology.

  - To limit the project budget, the battery could be charged with the existing 480 VAC capacity at CMF and layover stations. Such a solution would meet 60% of the initial goals set for a pilot battery electric locomotive.

- Fuel cell technology provides attractive range advantages. Ideally if funding is available over the next decade, Metrolink will ultimately test a variety of zero emissions vehicle types and technologies.

  - Fuel cell technology has a greater level of technical complexity in comparison with batteries and has not been service proven to the same extent. Maintenance facilities would need to be modified for hydrogen gas leak detection and enhanced ventilation systems and possible rail tunnel ventilation improvement costs may also be required. Fuel cell technology, especially coupled with green hydrogen production and supply, is a less mature technology compared to battery and charging technologies.

  - San Bernardino County Transit Authority (SBCTA), one of Metrolink's member agencies, is already procuring a fuel cell battery hybrid multiple unit with delivery expected in 2023, which will be the first of its kind operating in the United States. It is expected that some of the unknowns and risks associated with fuel cell propulsion will be addressed during the deployment. Metrolink can take advantage of lessons learned.

  - At InnoTrans in September 2022, CalSTA and Caltrans signed an MOU with Stadler, a vehicle manufacturer, for four zero emissions FLIRT trains to be deployed in California. These vehicles will be a longer version of the vehicle than SBCTA is procuring and there are purchase options expected.

- This Analysis also concludes that testing a locomotive is less capital intensive and technologically complex. There are additional complexities with integrating rail multiple units into Metrolink's system. The complexities are highlighted below. As part of the TIRCP grant, it is recommended that funding be set aside to develop a plan to delve more deeply into the costs and activities required to operate multiple units on the AVL.

  - Significant capital costs are required to mitigate the signal system shunting issues anticipated with a smaller, lighter rail vehicle. A loss of shunt could result in delay or no activation of crossing gates or a loss of track occupancy detection in dispatch. Increased operational costs are also expected for mitigation measures such as frequent track brushing.

  - RMUs have lower seating capacity (approximately half that of a comparable length bi-level consist).

  - A locomotive could utilize existing coach cars, potentially avoiding the need to procure additional passenger-carrying cars. Any new car (locomotive-hauled or multiple unit) would need to be compatible with existing platforms. This is currently understood to involve steps and the use of mini-highs for ADA purposes, but changes in ADA regulation or enforcement may occur. If platforms needed to be upgraded, this would represent a significant expense. Project timeline may be accelerated to make significant platform improvements to address level boarding requirement triggered by the procurement of a new vehicle type like an RMU. These platform modifications are a significant cost for which Metrolink does not yet have funding.

  - Significant maintenance facility upgrade costs would be required, primarily due to the need for synchronized lifting jacks to perform maintenance such as truck replacements.

- The space constraint issues at CMF (which is already at capacity) would have a greater impact on the RMU implementation due to longer length of the RMU.

- RMU related knowledge base will be expanded through maturity of the Arrow service. Since RMU issues are independent from the propulsion technology, the scope of collaboration can be flexible and may be performed with diesel electric RMUs as well.

- Ultimately, these issues could represent a significant portion of the pilot implementation project budget and effort and would introduce additional time, money, and risk to the project. Since none of these issues are related to the evaluation of a zero emission propulsion technology, the efforts performed to resolve these issues would not contribute to the elimination of the unknowns in zero emission propulsion technologies.

RMU pilot would necessitate the allocation of a significant portion of the pilot project budget to exploring and solving RMU issues unrelated to zero emission propulsion technologies.

Worst-case Scenario Analysis:
In any strategy development, a what-if analysis needs to be conducted. In the best-case scenario, the propulsion system Metrolink will evaluate in the pilot project becomes the mainstream propulsion technology in the U.S. commuter train sector. Again, this is simply the best case; risk analysis assessment is not needed.

However, in the worst-case scenario, the propulsion system Metrolink has chosen for the pilot implementation may not achieve the expected technical progress and adoption in the industry. These worst-case scenarios will be evaluated for both battery electric and fuel cell battery hybrid propulsion systems.

Scenario 1:
Metrolink acquires and deploys a fuel cell battery hybrid vehicle for the pilot implementation and invests in the green hydrogen production or delivery and hydrogen fueling infrastructure.

- The technologies related to fuel cell modules, high volume green hydrogen, storage, and supply and hydrogen cost do not improve as projected.

- Battery technology improves in terms of cost and energy density and novel train architectures are validated successfully in the rail industry.

In this scenario, reverting the decision from fuel cell battery hybrid to battery electric would be costly because hydrogen storage and fueling related investments would have been made. Yard modifications for hydrogen fuel would have been completed. Moreover, the pilot fuel cell battery hybrid vehicle would not be integrated into the existing revenue service and would be disposed after the end of the pilot project.

Metrolink would then have to initiate another pilot project for the evaluation of battery electric propulsion and possibly a dual mode operation with an overhead catenary system.

Scenario 2:
Metrolink acquires and deploys a battery electric vehicle for the pilot implementation and invests in the charging infrastructure.

- Battery technology does not improve in terms of cost and energy density and battery electric propulsion does not become the mainstream zero emission technology in the rail industry.

- The technologies related to fuel cell modules, green hydrogen volume production, storage, and supply improve and become widely available in the rail industry. Green hydrogen cost decreases as well.

In this scenario, reverting the decision from battery electric propulsion to fuel cell battery hybrid would not be as costly as the Scenario 1 for the following reasons:

- Battery electric propulsion does not require significant yard or infrastructure changes.

- Investments in electric grid capacity would be leveraged to power the green hydrogen production facility.

- Battery electric propulsion can still be feasible with the dual mode operation with a partial overhead catenary system especially after California High Speed Rail Plan is completed to a certain degree.

- Transition to a fuel cell battery hybrid fleet would be seamless by leveraging the lessons learned in the SBCTA's Redlands line about fuel cell technology and hydrogen fuel supply.

- The pilot battery electric vehicle can be still used in revenue service after the pilot project is completed as a tandem to a diesel electric locomotive to provide fuel savings through capturing regenerative braking energy and zero emissions operation in certain segments of a route.

4.3 Summary of Benchmark Results

Table 25 summarizes all the findings in a condensed form to compare the available options according to various criteria categorized under Technical, Financial, and Strategic groups. The evaluations are performed according to the color codes. Green, yellow, orange, and red show sequentially the degree of the advantage, where green and yellow colors mean superior to the diesel electric propulsion and red and orange colors mean inferior to the diesel electric propulsion.

		BATTERY ELECTRIC				FUEL CELL BATTERY HYBRID			
		Locomotive		RMU		Locomotive		RMU	
		No High Power Charging	High Power Charging	No High Power Charging	High Power Charging	Hydrogen Delivery	Green Hydrogen Production	Hydrogen Delivery	Green Hydrogen Production
TECHNICAL	System Efficiency	Green	Green	Green	Green	Yellow	Yellow	Yellow	Yellow
	Greenhouse Gas Emissions	Green	Green	Green	Green	Yellow	Yellow	Yellow	Yellow
	Range	Red	Red	Red	Red	Orange	Orange	Orange	Orange
	Charge/Refuel Time	Red	Red	Red	Red	Orange	Orange	Orange	Orange
	Hardware/Software Complexity	Orange	Orange	Orange	Orange	Red	Red	Red	Red
	Technology Maturity	Orange	Orange	Orange	Orange	Red	Red	Red	Red
	Meeting Metrolink's Operational Requirements	Red	Red	Red	Red	Orange	Orange	Orange	Orange
	Synergy with Overhead Catenary System	Green	Green	Green	Green	Red	Red	Red	Red
	Seating Capacity	Green	Green	Orange	Orange	Green	Green	Orange	Orange
	Platform Height and Length Issues	Green	Green	Red	Red	Green	Green	Red	Red
	Shunting Issue	Green	Green	Red	Red	Green	Green	Red	Red
	Facility Modifications	Orange	Red	Red	Red	Orange	Red	Red	Red
FINANCIAL	Unit Cost	Orange	Orange	Red	Red	Red	Red	Red	Red
	Electricity/Hydrogen Cost	Green	Yellow	Green	Yellow	Red	Red	Red	Red
	Life Cycle Cost	Orange	Orange	Red	Red	Red	Red	Red	Red
	Infrastructure Cost	Orange	Red	Orange	Red	Orange	Red	Orange	Red
STRATEGIC	Holistic Approach	Red	Green	Red	Green	Red	Green	Red	Green
	Synergy with California High-Speed Rail Plan	Green	Green	Green	Green	Red	Red	Red	Red
	Complements SBCTA's Pilot Fuel Cell Project	Green	Green	Yellow	Yellow	Orange	Orange	Red	Red

TABLE 25: OPTIONS FOR PILOT IMPLEMENTATION - SUMMARY

5 ZERO EMISSIONS PILOT

5. ZERO EMISSIONS PILOT

5.1 Procurement Strategy

As outlined in the Metrolink Fleet Management Plan, Section 10 - Planning for Future Fleet and Facility Needs, fleet expansion is defined by the Southern California Optimized Rail Expansion (SCORE) program. The goals of the SCORE program are to increase train frequency at regular service intervals, provide balanced bi-directional service, align service to facilitate transfers and improve service reliability. The SCORE program will occur in three phases starting in 2023 and extending through 2035.

In the initial phases (milestones 1A and 1B) an increase in trainsets from 40 to 50 of 4- to 6-car trainsets will be required to meet anticipated passenger growth by 2028.

Milestone	Weekday Trainsets (not including spares)
2019 Baseline (Observed)	40
Milestone 1A	44 (10% increase from Baseline)
Milestone 1B	50 (25% increase from Baseline) (3 of 50 can be potential RMU application)
1B + SB Line 30 min (Both Ways All Day)	+3*
1B + 91/PVL peak/reverse/off-peak 30 / 60 / 60-120 min 30 / 30 / 60-120 min	+4 +5
1B + OC Line Peak/reverse/off-peak 30 / 30 / 60-120 min	+1
1B + IEOC Peak/reverse/off-peak 60 / 60 / 120 min 30 / 60 / 60-120 min 30 / 30 / 60-120 min	+1 +4 +5
...	...
Milestone 2	92 (130% increase from Baseline)

FIGURE 36: MILESTONE PROJECTIONS FROM METROLINK FLEET MANAGEMENT PLAN

To meet the long-term growth goals of increased service through 2035 (milestone 2), up to 92 4- to 6-car trainsets are forecast, a 130% increase from today's baseline.

Part of this growth may result in new routes or sub-routes (i.e., LAUS to Burbank Airport shuttle) as LAUS will become a major regional transit connector. Other routes may include LAUS to Santa Clarita on the AVL line, and LAUS to Moorpark on the Ventura Line.

Metrolink's current fleet of 40 F-125 Tier 4 locomotives will serve though 2042 (assumes a useful life of 25 years), at a minimum. As recently determined, the 15 locomotive MP36PH Tier 2 fleet will likely be partially replaced in the next few years with new Tier 4 locomotives , subject to funding availability. The remaining few would extend their useful life 25 to 30 years beyond their procurement. Thus, it would be expected that this fleet of 55 diesel locomotive would serve Metrolink through all phases of the SCORE programv. Metrolink's current fleet of passenger rail cars, with proper maintenance and rehabilitation, should maintain near-term fleet needs of 40 to 50 4- to 6-car consists through 2028 and beyond.

However, the third phase of the SCORE program requires an increase of number of trainsets to 92 4- to 6-car trainsets from 2028 through 2035.

In the Fleet Management Plan, Metrolink defines several strategies to support this procurement, such as teaming with other agencies to develop common specifications and share procurements for the next generation commuter rail vehicles, developing state cooperative purchasing contracts, and risk-sharing. Metrolink has been actively sharing procurement strategies with the California Department of Transportation, and other state agencies such as Illinois Department of Transportation (IDOT). Metrolink strongly desires to supplement the diesel fleet with zero emission vehicles in keeping with the Climate Action Plan goals.

Development of strong relationships with car builders of promising alternative propulsion technologies was also included as a strategy in the Fleet Management Plan. In this regard, Metrolink has been reaching out to those builders, who are either developing and/or conceptualizing next generation battery or fuel cell battery hybrid locomotives and RMUs as discussed in Section 2.11.

Locomotive	Activity	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
MP36	Retirement (staggered)	15	15	15	15	12	9	5	5	5	3	0	0	0	0	0	0	0	0	0	0	0
New Tier 4	10 Locomotives				1	8	10	10	10	10	10	10	10	10	10	10	10	10	10	8	8	8
Tier 4 to Zero Emissions MOD	Overhaul/modify (2/yr.)																			2	2	2
Zero Emission Locomotive	Demonstration (1 unit)						1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
Zero Emission Locomotive	Production (45 units)									1	4	8	13	20	27	34	44	45	45	45	45	45
F125	Overhaul (3/yr.)	40	40	40	40	40	40	40	40	40	40	40	40	40	37	37	37	37	37	37	37	37
Total In-Service		55	55	55	56	60	60	56	56	57	58	59	63	70	74	81	91	92	92	90	90	90

TABLE 26: TRANSITION TIMELINE FOR FLEET - EXAMPLE

5.2 Zero Emissions Demonstration Plan

5.2.1 Near-Term (1-3 years)

Metrolink will continue to collaborate with Caltrans on a possible demonstration. Caltrans will lead the procurement which may take as long as 18 months and the design and build of the pilot vehicle are expected to take between 36 and 48 months upon notice to proceed issuance. Therefore, the last year of the 3-year period is planned to pass with the design reviews of the pilot vehicle.

The infrastructure RFP will follow the vehicle RFP to allow the vehicle design to progress sufficiently to accurately foresee the required infrastructure updates. As a result, at the end of the second year, it is planned to prepare and issue an RFP for the development and installation of required infrastructure for the target vehicle. At the end of the third year, it is expected to issue NTP to the selected consultant and builder of the infrastructure updates.

5.2.2 Mid-Term (4-5 years)

The fourth and fifth years will pass through the design and construction of the pilot vehicle and the completion of the required infrastructure work. The delivery of the vehicle is expected to happen at the end of the fifth year or in the middle of the sixth year. It is also planned to complete the infrastructure updates at the end of the fifth year to synchronize it with the pilot vehicle delivery.

5.2.3 Long-Term (6+ years)

In the sixth year, first the acceptance tests of the pilot vehicle and infrastructure updates will be conducted. Next, the pilot vehicle will operate on the applicable routes within the state. The pilot tests may last for at least two years to assess vehicle and infrastructure performance, reliability, and system integration issues in real-world conditions of revenue service. Lessons learned in the pilot implementation will be compiled and shared with other transit agencies in California, and nationally, to close the knowledge gaps.

With the operational experience gained during two years of pilot testing and the lessons learned from other transit agencies with different vehicle types and zero emission propulsion technologies, Metrolink will be in a position to develop the fleet-wide zero emissions implementation plan in the middle of the eighth year, which is shown as the future state in Table 27.

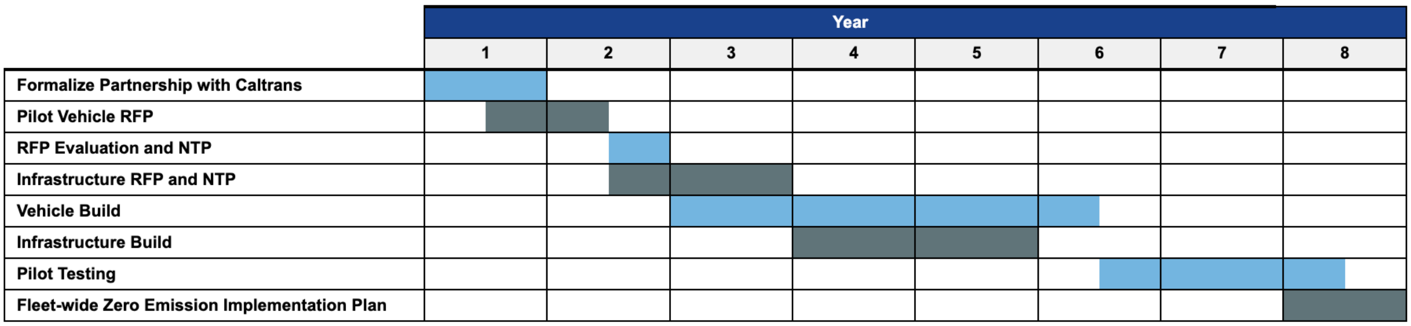


TABLE 27: DRAFT PILOT SCHEDULE

5.3 Implementation Strategy

The success of the pilot program depends greatly on the success of the propulsion system and integration of new electronics. Since many builders have expressed concepts or built off existing platforms, the propulsion system reliability and duty cycle will be proven. During this phase it is important that Metrolink have spare, service ready, locomotives or train sets.

5.3.1 Pilot Program Performance Measures and Tests

Pilot performance is measured by several methods including reliability metrics such as:

- Mean Miles Between Failures (mechanical reliability over vehicle miles traveled)
- Mean Time Between Failures (measure of availability over a period of time)

Since the pilot car is new and includes new propulsion systems, the key items to measure are:

- Range
- Fault and data collection
- Battery or Fuel Cell degradation
- Temperature limits
- Routes with peak traction loads
- Hydrogen refill/battery charge time
- Regenerative braking test
- Software Management

The pilot vehicle must be able to operate the line designated in the contract as defined by Metrolink. The pilot locomotive, if such is selected, will operate with a maximum set of four coaches/cars and must operate for a short period with an extra off-line locomotive in the consist in case of the locomotive fails in route or runs out of energy before finishing the trip. The battery locomotive can also operate in tandem with a diesel locomotive sharing the load. This double head locomotive hybrid consist will test out in-line charging of the Head End Power (HEP), and further evaluate the following:

- Train Consist Compatibility
- Trainline Compatibility
- Propulsion Test
- Schedule Adherence
- Charging - Stationary and HEP 480 VAC Trainline
- Electrical Load Shed
- Regenerative Braking Test (800 kW minimum)

5.3.2 Pilot Train Consist Configurations and Test Cycles

The zero emissions vehicle will not equal the duty cycle performance of Metrolink's existing diesel electric fleet unless refuel and re-charge activities are implemented along each route. It is recommended that the zero emissions vehicle initially operate in revenue service within close proximity of Metrolink's Central Maintenance Facility, located north of downtown Los Angeles. The cycles that would be preferred are:

Antelope Valley Line

Possible Options:

- Shuttle service to Burbank Airport North – as a new service
- Shuttle service to Santa Clarita
- Train 205 and 210 if new simulation results suggest multiple round trips
  - LAUS - Lancaster as a non–revenue test for trials

Simulations of these lines can be further modeled for changing scenarios and funding on behalf of Metrolink in support of a zero emissions demonstration pilot vehicle on the Antelope Valley Line. The initial test runs of any pilot service should also include an additional complete train and crew in the event of problems.

5.4 Required Facility Modifications and Timeline

FRA may not immediately allow operation in tunnels with battery or hydrogen

Battery charging at CMF will require a new service feed from San Fernando Road, along with new transformer and switchgear, which are long-lead procurement items. This also requires early coordination with Los Angeles Department of Water and Power (LADWP) for the necessary service connection. Estimated duration is 30-36 months for coordination, design, construction, and testing.

5.5 Regulatory Process

At a minimum, the selected vehicle must conform to the regulations included in 49 CFR 229, 236 and 238. These are considered the minimum requirements for any new rail vehicle operating on a US FRA-regulated railroad. A rail vehicle must meet the crashworthiness standards of 238. Although the selected vehicle is part of a pilot program, the FRA may require a pre-revenue test plan to demonstrate all safety requirements have been met. This pre-revenue service plan is a basic requirement needed from all rail passenger vehicles regardless of propulsion type.

As the FRA is still studying battery and hydrogen technologies there may be objections to using the vehicles in tunnels or other circumstances where a safety case has not yet been established. Specifically, the presence of tunnels on the AVL may cause delays in the commissioning of a pilot service as the FRA considers their safety-related impacts. The AVL has three tunnels along the route, with the longest tunnel located between Sylmar and Newhall having a length of approximately 1.3 miles.

The FRA's Rolling Stock Research Division issued a request in April 2022 seeking information from contractors interested in, and capable of, supporting FRA to investigate the safety and performance of advanced energy propulsion technologies for railroad applications. Research will seek to gain knowledge on the fire safety, crashworthiness performance and durability of hydrogen storage media, fuel cells and ancillary components used in hydrogen fuel cell locomotives and multiple units (MU) under extreme loads and environmental conditions observed on railroads.

In addition to meeting FRA requirements, the vehicle itself, and any associated infrastructure such as charging stations, must comply with the clearance requirements of the California Public Utilities Commission (CPUC) General Order 26D, Burlington Northern Santa Fe (BNSF) and Union Pacific Railroad (UPRR) on applicable shared track, and Metrolink track standards. Furthermore, hydrogen leak detection systems will require coordination with the City of Los Angeles Fire Department, and possibly with Metrolink's insurer.

Various stakeholder groups are currently active in developing standards and recommended practices for these new technologies. This includes the following organizations:

- American Public Transportation Association (APTA), has embarked on a process of creating a Recommended Practice for a Battery and Hydrogen Safety Standard. This action will attempt to try and consolidate all the safety issues of each of the fuels from production through consumption and disposal. FRA may cite or adopt the language of the APTA standard and create a regulation.

- National Fire Protection Association (NFPA) 130 working groups are considering new codes for battery storage systems, which may be created before the pilot vehicle is introduced.

- International Electrotechnical Commission (IEC) is currently developing a European Standard for Fuel Cell applications for propulsion.

5.6 Concerns and Comments of Class I Railroads

The Class I railroads have safety considerations and shared use agreements in place to provide for quality operations of the freight railroad. The agreement allows the freight carrier to operate in a competitive manner over the railroad. Metrolink must operate their trains reliably and timely so there is not a disruption to the freight rail traffic. This will not be an exception as a host or tenant on the railroad. The zero emissions vehicle would need to be FRA complaint for safety considerations.

5.7 Success Criteria for Pilot Implementation

Success of any new locomotive or car is that the vehicle operates reliably. In the commissioning of a new locomotive the performance must meet the criteria set forth in a Technical Specification and must meet that reliably. For a pilot vehicle, the measure of success beyond safe operations would be:

- The locomotive operates successfully in revenue and non-revenue service testing without unscheduled maintenance

- The locomotive meets the range expectations for designated two-to four-car train.

- The cooling and charging operate without failure to maintain battery state of charge

- The locomotive completes a burn-in period

- The locomotive does not require an excess of field modifications

- Ease of maintenance

These bulleted items represent a high bar for any new vehicle. As with any new locomotive there are periods where reliability is low. In a practical sense, the new zero emissions vehicle will exhibit reliability issues. The ease of maintenance personnel to execute repairs and obtain replacement parts is highly important during the pilot implementation. The expectation is the locomotive builder will monitor faults in the diagnostics and quickly characterize type and provide solutions. Success will also come from the improvement in reliability and completion of the daily mission of transporting passengers.

6 CONCLUSIONS

6. CONCLUSIONS

Metrolink has rigorously evaluated battery electric and fuel cell battery hybrid propulsion systems on new and rebuilt locomotives and rail multiple units from technical, financial, and strategic perspectives for a zero emissions pilot implementation. It concluded that undertaking an in-depth multiple unit implementation planning effort for the Antelope Valley Line as well as exploring a partnership with Caltrans on their Zero Emissions Research and Development Program best serves the interests of Metrolink. This is the optimal option available to Metrolink which meets the agency's strategic goals while also providing a financial and operationally sustainable zero emissions pilot solution.

APPENDIX A

Action Item List from Gap Analysis

Gap Item	Action Plan Listed in Gap Analysis	
1.1	**Availability of Zero Emissions Rail Vehicles**	
	1	Metrolink and consultant team will interview OEM locomotive manufacturers to discuss the development and maturity of the market.
	2	Metrolink and consultant team will interview RMU builders to discuss the potential RMUs which would be compatible on Metrolink System.
	3	Metrolink and consultant team will evaluate performance of current and completed zero emissions pilot projects.
1.2	**Uncertain Path to Commercialization and Long-Term Support**	
	1	Metrolink and consultant team will develop performance measures that can be evaluated and used for success of the pilot. Outcomes of the pilot will help scalability for the broader system.
	2	***Metrolink long term actions***
	a	Explore collaboration with other agencies to have a common and standardized vehicle design which all agencies could share.
	b	Carefully evaluate the ZEV pilot proposals from candidate builders and their long-term commitments
	c	Evaluate training and maintenance of the ZEV from the builder if available.
1.3	**Regulatory Compliance**	
	1	Project team will continue to monitor regulatory updates within duration of the project.
	2	Project team will continue to explore regulatory requirements. This may include inquiry with the FRA for disposition as a waiver for testing from the FRA
	3	***Metrolink long term actions***
	a	Update the PTC plan to the FRA and run the vehicles in test, in the worst-case condition, for stopping distance performance.
	b	Present the design of the ZEV if new with test results and safety analysis to the FRA for approval prior to placement in revenue service.
	c	Monitor developments with SBCTA and FRA approvals or concurrence during development of pilot technical analysis relative to the SBCTA test vehicle
1.4	**Slow Fleet Turnover and Fleet Planning Alignment**	
	1	Metrolink and consultant team will review the Fleet Management Plan and try to align key dates for zero emissions vehicle transition to retirement of vehicles and into the technical analysis.

	2	Metrolink and consultant team will identify in pilot plan for a zero emissions locomotive demonstration on Metrolink's existing line.
	3	Metrolink may have to reconsider the timing and scope of mid-life overhauls of equipment during transition to zero emissions vehicles.
	4	***Metrolink long term actions***
	a	Operate a pilot locomotive in multiple demonstrations varying in scale and scope.
1.5	**Scaling Zero Emissions Solutions to the Metrolink Fleet**	
	1	Metrolink and consultant team will develop a technical analysis based a propulsion technology which would close most of the gaps and can be implemented in a cost-effective manner.
	2	Metrolink and consultant team will meet with OEM and suppliers to determine a manufacturer's broad schedule for delivery of a zero emissions vehicle.
2.1	**Duty Cycle**	
	1	Metrolink and consultant team will simulate routes with 4 coach cars to replicate current duty cycle. This will provide a better picture of where the ZEV can operate.
	2	Metrolink and consultant team will develop information about equipment cycles to show where and times of day a pilot can be deployed.
	3	Metrolink and consultant team can give suggestions for data to measure performance to help gauge the outcomes of the pilot program as it relates to duty cycle.
	4	***Metrolink long term actions***
	a	Create a new operating plan for these zero emissions trains to accommodate different performance characteristics in terms of capacity and dwell time requirements for refueling or charging.
2.2	**Signal Systems Track Shunting**	
	1	Metrolink and consultant team will discuss operations with Texas agencies which currently operate DMU vehicles.
	2	Metrolink will continue to engage with IDOT/Amtrak test campaign to leverage findings.
	3	If an RMU is deployed, Metrolink will need to investigate the shunting issue through the collection of field data. Consultant team can suggest instrumentation to evaluate occupancy of track of Electrocode and Overlay track circuits to confirm if one is more consistent than the other.
	4	***Metrolink long term actions***
	a	Metrolink can learn lessons from deployment of Arrow service DMU vehicles on Redlands line
2.3	**Vehicle Reliability**	
	1	Metrolink and consultant team can give performance measures to help gauge the outcomes of the pilot program as it relates to vehicle reliability.
	2	***Metrolink long term actions***

	a	Carefully evaluate the ZEV pilot proposals from candidate builders and their long-term commitments
	b	Carefully evaluate training and maintenance needs and procedures of the ZEV from the builder.
	c	Metrolink will need monitor performance measurements and provide data points in contract language for availability and reliability.
2.4	**Interoperability**	
	1	Metrolink and consultant team will explore deployment with the host and tenant class I railroads.
	2	Metrolink and consultant team will discuss deployment of a pilot vehicle on a selected line.
	3	***Metrolink long term actions***
	a	Consider commissioning the vehicle on an isolated line during a period of no freight activity and build a reliability case.
2.5	**Operational Characteristics**	
	1	Metrolink and consultant team will provide suggestions for a specification that requires any new vehicle builder to meet current and prospective maximum speeds.
	2	Metrolink and consultant team to determine what, if any future plans exist for speed increases on the Metrolink system.
2.6	**Operational Characteristics - Speed**	
	1	Metrolink and Consultant team will investigate ridership of peak versus non-peak service.
	2	Metrolink and consultant team will investigate seating capacity and luggage capacity of RMUs versus Rotem cars.
3.1	**Battery Charging and/or Hydrogen Fueling**	
	1	Metrolink and consultant team will develop, with energy/fuel supplier input, a rough order magnitude of cost and complexity for each re-fueling and/or recharging system.
	2	Metrolink and consultant team will need to determine the most viable alternative propulsion for a pilot project.
	3	Metrolink and consultant team will identify issues such as noise and vehicle traffic in CMF that may affect the community.
	4	Metrolink and consultant team will identify potential fueling and or recharging location for CMF.
3.2	**Facilities Modifications**	
	1	Metrolink and consultant team will need to determine feasibility of modifying existing facilities to support a pilot project.
	2	Metrolink and consultant team will meet with hydrogen suppliers to discuss potential delivery and storage options.
	3	Metrolink and consultant team will meet with Los Angeles area utility agencies to determine upgrade and viability of new electrical service at specific sites.

	4	Metrolink and consultant team will identify possible charging location for the locomotive(s) at yard locations
	5	Metrolink and consultant team must determine CPUC clearance requirements to charging infrastructure.
	6	***Metrolink long term actions***
	a	Determine if additional ventilation is required for hydrogen.
	b	Provide safety awareness training for all staff, whether high-voltage electric or hydrogen equipment.
	c	Determine whether existing fans need to be upgraded to non-sparking materials if hydrogen is used.
	d	Determine if the Fire Dept (or SCRRA's insurer) will require any upgrades to the fire protection systems due to the presence of hydrogen.
	e	Determine new safety measures will be required to work on the hydrogen fuel cell locomotives.
	f	Determine availability of existing spare conduits to bring in the new copper lines for electrical power.
	g	Determine storage for unique spare parts.
	h	Explore existing Light Rail Vehicle facilities as a potential for RMU maintenance.
3.3	**Station Platforms**	
	1	No action required if Metrolink pilot is a locomotive with current coach and cab cars using a bridge plate on the high platform.
	2	Metrolink and consultant need to examine the complexity of requiring the pilot vehicle compatibility with current platform height.
	3	***Metrolink long term actions***
	a	Assess the options of building up a platform if other non-compatible cars are procured.
	b	Assess potential standard floor height for joint procurement of vehicles.
4.1	**Zero Emission Rail Vehicle Costs**	
	1	Consultant team will refine estimates for new and conversion locomotives for each propulsion type.
	2	Consultant team will meet with Metrolink subject matter experts to review the vehicle costs.
	3	Metrolink and consultant team will gain understanding of OEM development and rough order magnitude vehicle costs.
	4	Metrolink and consultant team will consider cost of any vehicle-based platform station interface for level boarding.
	5	Metrolink and consultant team will consider cost of other recent projects and closely monitor the Metra BEL retrofit kit award for cost data if available.
4.2	**Facilities Modifications Cost**	
	1	Consultant team will develop a rough order magnitude of costs for modifications.
	2	Consultant team will meet with Metrolink subject matter experts to review the facility costs.

	3	Metrolink and consultant team will gain understanding of hydrogen vendor and utility ROM costs.
	4	Metrolink and consultant team will determine if there are additional costs to provide sufficient power for charging.
4.3	**Signal Systems (Track Shunting) Costs**	
	1	Metrolink and consultant team will develop a list of possible capital and operating cost scenarios to address the shunting issue for the track system. These include testing a change in signal frequency based on the pricing from RPRP DMU related investments.
	2	Discuss supporting costs for rail brushing and additional wear parts for Texas operators which currently operate DMU vehicles.
	3	***Metrolink long term actions***
	a	Consider a time duration for testing such as 1 month with person hours for test crews for an RMU as required.
4.4	**Lifecycle Costs**	
	1	Consultant team will develop rough order magnitude lifecycle cost for the Pilot ZEV.
	2	Metrolink and consultant team will monitor developments of each emerging technology cost during duration of task.
	3	Metrolink and consultant team to explore whether use of different propulsion systems or vehicle types will impact insurance policies held by the agency.

APPENDIX B

Completed Zero Emissions Rail Projects

Multiple Units

East Japan Railway Company (JR East)

NE Train KuMoYa E995 Fuel Cell MU

In 2006 JR East retrofitted a single MU car with a hydrogen fuel cell. This was the first hybrid fuel cell vehicle ever produced. The vehicle had six hydrogen tanks with a total capacity of 71 gallons and 19kWh of lithium ion batteries. The vehicle was tested as part of a pilot in the area during 2007 at speeds of up to 100 km/h.

NE Train KuMoYa E995 Battery MU

In 2009 JR East replaced the fuel cell in the NE train with four lithium battery units located beneath the passenger seats. The battery sets provided enough power to move the vehicle 30 miles at speeds up to 60 mph. According to JR East a charge of 10 minutes provided a range of approximately 12 mi. The vehicle was operated over various lines within the system including Ōmiya Works in 2009, on the Utsunomiya Line in 2010 and Karasuyama Line in 2012.

EV-E301 Series

The research and insights gained from the KuMoya E995 battery MU were used to develop a production vehicle termed the EV-E301. In 2014 JR East began operating the two-car battery electric multiple unit on the 12 mi Karasuyama Line. The vehicles have 190 kWh lithium-ion battery capacity which is used to provide traction power in unelectrified sections. The pilot program has been a success according to JR East and as of 2017 all vehicles on the line are equipped with battery systems.

EV-E801 Series

In 2017 JR East began operating a two car MU referred to as the EV-E801. The vehicles operate on battery power over 16.5 miles of non-electrified Oga Line tracks between Oiwake and Oga. The vehicles remain in service and no major issues have been reported.

FV 991

In 2019 JR East, Hitachi and Toyota began designing a fuel cell powered MU referred to as the FV-E991. The vehicles will have a hybrid fuel cell system. The vehicles will operate as two car trains, with the power car housing 180kW fuel cell stacks which supply electricity for two 25kWh li-ion electric batteries. The trailer car housing the hydrogen storage tanks. The tanks can store up to 1020 liters of hydrogen at 690 atm. The vehicles will have a maximum speed of 62 mph and a range of 87 miles on a tank of compressed hydrogen. The vehicles are scheduled to commence testing on the Tsurumi and Nambu lines in Spring 2022. To date no results or further information have been made available.

JR Kyushu

BEC819 series

In 2016 JR Kyusha began a pilot study with a two-car battery MU on the Chikuhō Main Line. The vehicles have 360 kWh battery capacity. Subsequently 17 additional trains were introduces as part of a revenue service demonstration which eventually replaced diesel service the Fukuhoku Yutaka Line, Chikuhō Main Line, and the Kashii Line. No issues have been reported, and the increase in vehicles deployed over time demonstrate that JR Kyushu is satisfied with the vehicle's performance.

Class 379 Electrostar

In 2015 Network Rail finished retrofitting a Bombardier MU with battery packs for operation on the Mayflower Line in Essex of the UK. The batteries provide sufficient capacity for the train to travel up to 60 miles on a charge. No major issues have been reported from this pilot.

Class 777

In 2021 Liverpool City Region Combined Authority (LCRCA) completed a pilot study on its Merseyrail line with a battery MU produced by Stadler. The pilot confirmed that the vehicle type was capable of traveling up to 20 miles on a charge. No major issues were reported from the pilot study.

Class 230

In 2017 Vivarail completed the conversion of a D-stock train to a two-car battery powered MU. As part of the project a fast charger was developed which reportedly provided 100 miles of range in 10 minutes. The vehicles have a 106-kWh lithium-ion battery capacity, which Vivarail estimates will need to be replaced every 7 years. The vehicles are planned for a pilot on the Valley Lines in South Wales, UK, but no details on the pilot have been published to date.

Alstom Hydrogen Fuel Cell Coradia iLint MU

In 2013 Alstom began production of hydrogen fuel cell powered iLint MU's. Since that time demonstration studies have been completed with iLint's in Austria, the Netherlands, Sweden and France. In 2019 Alstom released minor details on the study conducted in the Netherlands. The pilot was conducted on a 40 mile section of track between Groningen and Leeuwarden traveling at speeds of up to 87 mph. The service was repeated over the course of 10 days. Following the study, Alstom reported that the trainsets have an approximate range of 620 miles. In 2018 the first commercial service with iLint vehicles began in Germany, and since then 41 trainsets have been purchased.

Stadler Flirt

In 2018 San Bernadino County Transportation Authority (SBCTA) used a $30 million grant to procure a Zero Emission Multiple Unit from Stadler. The vehicles will be 2-car, 3 module trains with hydrogen tanks and fuel cells installed in the center module. The vehicles have not been delivered yet, so no information is currently available on the performance of the vehicles.

In 2020 Stadler began pilot testing of a Flirt Akku prototype which uses battery propulsion in Denmark. The vehicle will be tested over a 9 mile track section between Helsingør and Hillerød line in North Zealand, and a 11 mile section of the Lemvig line in northern West Jutland. The results of this pilot have not yet been made public. Similar trains are also contracted to be delivered for service on Schleswig-Holstein rail authority system starting in 2022.

Bombardier AGC

In January 2021, Société nationale des chemins de fer français (SNCF) signed a contract with Bombardier to retrofit five Autorail à Grande Capacité (AGC) MUs with battery propulsion. The vehicles will be delivered by 2023. The pilot program is meant to serve as a proof of concept. No further details on the pilots or the vehicle design have been revealed at this time.

Alstom BEMU

In April 2021 Long Island Railroad (LIRR) and Alstom announced plans to conduct the first battery MU pilot in the US. The program will retrofit a two-car Bombardier M7 married pair batteries to service the 13-mile track section between East Williston and Oyster Bay which currently does not have third rail. The agency plans to recharge batteries at station stops with small sections of third rail. Part of the pilot program will involve determining the appropriate sizing batteries for future fleets. No other technical details have been revealed at this point. The current pilot is budgeted to cost $850,000 to complete.

Siemens Desiro ML Cityjet Eco

In 2015 a prototype conversion of a Siemens Desiro ML to battery electric propulsion was completed for use on the Vienna S-Bahn in Austria. In 2019 the Austrian Federal Railways began a pilot program with the train on the Kamp Valley line between Horn and St. Pölten. The prototype is capable of operating off of overhead wires, or in battery only mode for up to 50 miles. The vehicles have 528 kWh of battery capacity. The vehicles have a maximum speed of 62 mph. The results of the pilot study have not been published to date.

Siemens has also contracted to deliver the Mireo Plus H and Mireo Plus B that are meant to serve as the successors to the Desiro MU series vehicles. The Plus H model will operate with a fuel cell hybrid system, while the Plus B will use battery propulsion to provide up to 50 miles of range. In 2019 NV Baden-Württemberg in Germany ordered 20 of the Mireo Plus B trains for their unelectrified Rench Valley Railway, Harmersbach Valley Railway and Acher Valley Railway. None of the Mireo vehicles have entered service yet.

STREETCARS AND LIGHT RAIL VEHICLES

Brookville Liberty

Although no commuter trains in the US currently operate with battery propulsion, several streetcars operating in the US currently do.

In 2015 Dallas Area Rapid Transit (DART) commissioned a fleet of Liberty Streetcars manufactured by Brookville Equipment Corporation. The vehicles have 750 V lithium-ion batteries that enable the vehicle to operate off-wire for 1.6 miles. Since the initial DART order, these vehicles have also been procured for operation in Detroit, Milwaukee, Oklahoma City, Portland, Tacoma and Tempe. Although early integration and performance issues were reported, the majority of issues have been resolved and the vehicles have been operating in service successfully for several years.

CAF Urbos 3

New Castle Light Rail in New South Whales Australia currently operates a fleet of CAF Urbos 3 supercapacitor trams. The vehicles operate within a 1.7-mile system, where the vehicles are powered in sections from overhead wire, and in other sections by charging the supercapacitors at stations. The vehicles were delivered in 2018, and no major issues have been reported.

CRRC TRC Tram

In 2017 CRRC conducted pilot testing on the world’s first hydrogen powered Light Rail Vehicle (tram). The trams operate as three car trains with a top speed of 44 mph and a range of 25 miles. The vehicles have a 12 kg hydrogen storage capacity which is refueled at 4 fueling stations along the route.

LOCOMOTIVES

BNSF Pilots

Fuel Cell Locomotives

Between 2008 and 2009 BNSF conducted a pilot program on a Proton-Exchange Membrane Fuel Cell (PEMFC) switcher locomotive. The PEMFC used hydrogen as a fuel as part of a hybrid battery system to perform switching operations at a BNSF yard in Topeka Kansas. The locomotive was built in a cooperative effort between Vehicle Projects, LLC, BNSF and the US Army. The locomotive had roughly 2 MW of power and used lead acid batteries due to cost constraints. No other results or information on this pilot are publicly available.

In December 2021 Progress Rail, Chevron and BNSF announced that they will be conduct a hydrogen locomotive pilot program which will be conducted on BNSF freight lines. Further details on the vehicle design and the pilot study scope have not been made available at this time.

Battery Electric Locomotive

Between January and March 2021 BNSF conducted a pilot study in cooperation with the California Air Resource Board (CARB), the San Joaquin Valley Air Pollution Control District, and Wabtec. The study was funded through a $22.6 million grant from CARB to demonstrate potential emission reductions possible for the pilot three locomotive consist compared with standard diesel only consists.

The pilot study used a consist composed of the battery powered locomotive coupled between two Tier 4 diesel locomotives, where all three locomotives provided tractive effort to the consist. The battery locomotive used for the pilot was a Wabtec FLXdrive which was equipped with 18,000 lithium-ion battery cells with a combined 2,400 kwh of energy capacity. The locomotive weighs approximately 215 tons, roughly 3 tons heavier than a typical diesel locomotive.

The consist operated repeatedly over a roughly 350-mile route from Barstow to Stockton, CA during the pilot. The total milage logged during the 3-month pilot study was 13,320 miles. The battery locomotive was charged through a wayside charging station at BNSF's railyard in Stockton, CA. During operation batteries were recharged through regenerative braking.

Detailed results from the study have not been published, but Wabtec has reported that the pilot was successful in reducing the GHG's produced by the consist by 11% compared to a typical diesel consist. No reliability or other performance information has been released at this time.

Union Pacific Pilots

Battery Electric Locomotive

In January 2022 Union Pacific (UP) announced the purchase of 20 battery electric locomotives from Progress Rail and Wabtec for use in yard operation in California and Nebraska. To date this is the largest carrier owned battery electric fleet ordered. UP has set the goal of net zero emissions for its fleet by 2050. UP estimates that the vehicle procurement and yard and infrastructure upgrades will exceed $100 million in capital.

Ten (10) of the locomotives will be the previously described Wabtec FLXdrive locomotives and the other ten (10) will be Progress Rail EMD Joule locomotives. The Progress rail locomotives are 118.1-ton switchers with 2.4 MWh batteries. The locomotives have power of up to 3,000 HP, and an advertised operating time of up to 24 hours on a charge. The units are expected to begin operation in 2023. Part of the intent of the pilot program is to test the performance of the locomotives in hot and cold climates and to inform the whether the technology is feasible for long haul operations in the near future.

Canadian Pacific Pilots

Fuel Cell Locomotives

In January 2022 Canadian Pacific announced that it was converting three SD40 diesel locomotives to hydrogen power. The project is being funded through a $15 million grant from Alberta which is being matched by CP, for a total project cost of $30 million. The project will also include the development of an electrolysis plant in Calgary and the construction of a reformation plant in Edmonton to generate hydrogen for the locomotives.

Battery Electric Locomotive

In November 2021 CP announced the purchase of a Wabtec FLXdrive battery electric locomotive. Details on how the railroad will use the locomotive of the pilot study parameters have not yet been released.

Austrian Federal Railways (OBB)

Battery Electric Locomotive

In 2020 CRRC delivered four battery locomotives to OBB. Two of the locomotives were designed for shunting while the other was procured for mainline operation between Hungary and Croatia. The vehicle reportedly weighs 90 tons with top speed of 74 mph. No further information on the pilot has been released at this time.

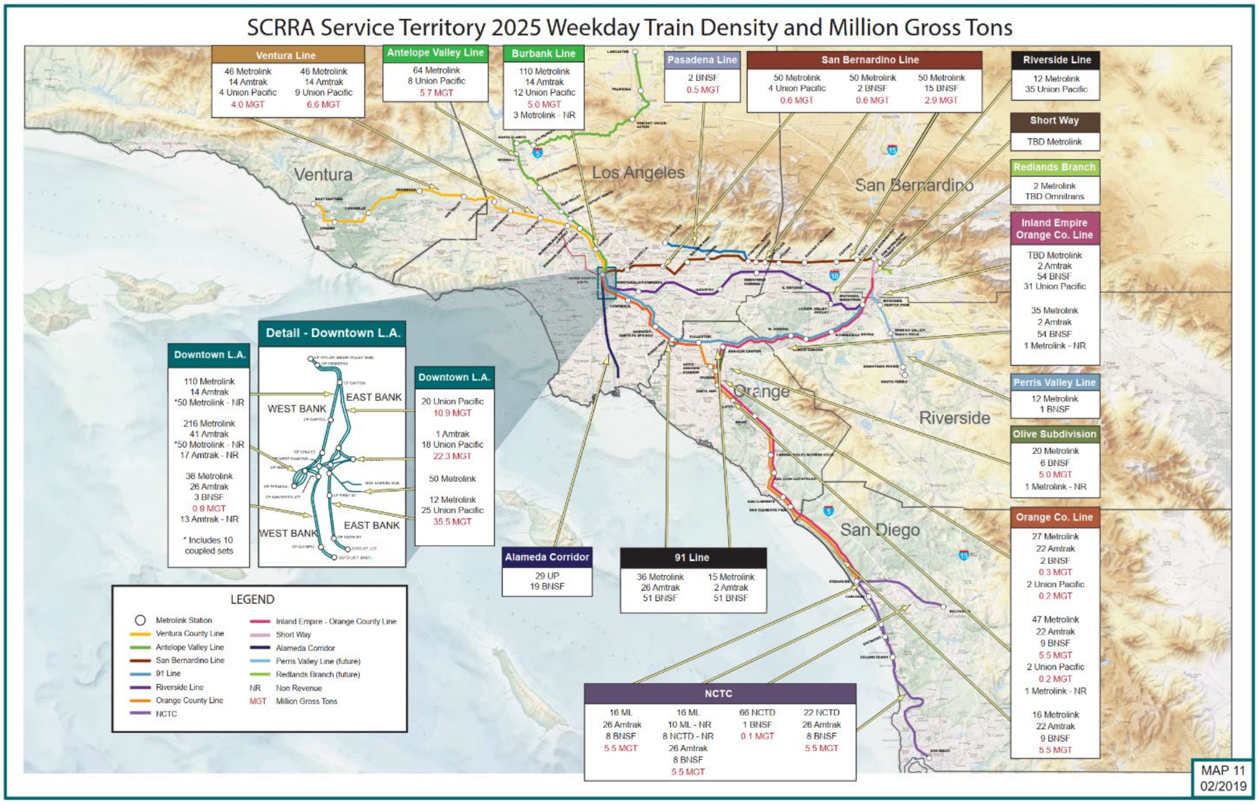
METRA (Chicago)

Battery Electric Locomotive

In August 2022 METRA announced Progress Rail Services will provide a kit, convert three existing F40's to Battery Electric. Included is an option for three more.

APPENDIX C

Predicted Rail Freight Traffic on Metrolink Routes



APPENDIX D

Zero Emissions Technology Adoption in Transportation

The purpose of this appendix is to discuss the adoption of zero emissions vehicles in other transportation modes to help inform of potential similarities and differences to zero emission adoption in passenger rail. Adoption, as defined herein, includes the current state of the practice for these modes, as well as the anticipated timing for when zero emissions vehicles may become the dominant transport for that mode. The three modes of transportation examined include road-based vehicles (i.e., passenger cars, buses, and trucks), maritime (i.e., container ships), and commercial aviation. Considerable research has been conducted on the feasibility and timing of zero emission vehicles in each of these modes, which may offer perspective and experience that can directly apply to passenger rail.

The entire transportation sector currently relies on traditional fossil fuels as their primary fuel source, meaning that the vast majority or all vehicles use those fuels when serving that mode. Highway, marine and air have examined the potential use of battery-electric vehicles (BEV) or hydrogen electric vehicles (HEV), as well as other renewable carbon-neutral fuel options like biofuels (i.e., biomass-derived fuels that use organic matter, such as plant or animal waste) or increased engine efficiencies to reduce current fossil fuel consumption. All three modes have found similar challenges with transitioning from fossil fuels to a zero emission alternative: 1.) BEV options have a substantially lower energy density than their fossil fuel equivalent[1], 2.) HEV options (i.e., fuel cell options) have more challenging storage, production, and distribution requirements both on the transportation network and on-board the vehicle, and 3.) biofuel options themselves are considered carbon-neutral by the U.S. Energy Information Administration[2], but the land use impacts (i.e., forests cut down for biofuel farms) are widely cited to increase the carbon footprint.

With this, differences between the three modes can delve into a few key categories:

Technology Readiness and Applicability – Zero emissions vehicles have been heavily researched by the industry as a whole and examined for feasibility in all three modes; thus, the technology is considered "ready" for application, even with annual improvements to these technologies offering better efficiencies in the future than those today. That said, because each mode has differing operational requirements (e.g., mechanics of flight, extremely long-distance transport, etc.) the applicability of this technology may not be relevant to a particular mode because it cannot serve the use cases of today. For example, a shipping company that moves containers across an ocean will not be interested in a zero emission vessel that can only travel 100 miles.

Governance and Industry Motivation – Climate change initiatives have been in the public forefront for decades, but has accelerated as the result of recent events (e.g., increase in severe storms and flooding, greater media coverage of polar ice cap reduction, better data visualization of rising temperatures, etc.). Many governments across the world are seeking ways to reduce carbon footprint and operate a sustainable,

[1] Energy density (approximate): automotive gasoline is 47.5 MJ/kg; diesel is 45.5 MJ/kg; aviation fuel is between 43 and 48 MJ/kg. Hydrogen is 120 MJ/kg; Lithium ion battery has 0.3 – 1 MJ/kg. Biodiesel is 37.8 MJ/kg.

[2] The U.S. Energy Information Administration (EIA) cites biofuels as carbon-neutral because emissions are offset by the plant itself that absorbs carbon dioxide.

net-zero transportation system. Many industries have recognized that their consumer base is seeking practices that align with these policies, incentivizing them to set goals to reduce greenhouse gas emissions. Levels of interest range from establishing future-year goals (e.g., net-zero by 2030) to deploying operations-ready vehicles.

Fleet Transformation Rate – All modes use vehicles with a scheduled service life, and have varying levels of users that are willing and/or able to upgrade to newer vehicles. Individuals can upgrade their personal transport based on their household incomes, whereas larger corporations with big balance sheets have different financial cushions available to upgrade vehicles on a more predictable basis. Similarly, some modes have such a high upfront cost component that they must take on a long service life in order to be financially viable.

This appendix focuses only on vehicles in each mode that are operated by an on-board engine and an on-board fuel source. Externally-powered vehicles, such as buses that receive electricity from catenary wires, are not included in this because Metrolink's comparative use cases does not utilize external power sources. Roadway, maritime, and aviation modes are highlighted; their current and forecasted use of BEV, HEV, and others; and then ties relevance of a particular mode to Metrolink's operations and vision for zero emission vehicles.

Roadway Industry (passenger vehicle, buses, trucking)

The road transportation system carries passenger vehicles, trucks, buses, and other users (e.g., bike and pedestrian). It succeeds as a transport mode for many reasons, mostly centered around its versatility. It provides the access to destinations that most users seek, often creating the last-mile link that is not economical to be served by other modes. Its footprint is wide and vast, providing both advantages for accessibility as well as challenges for service coverage. Fueling is not centralized; currently, fueling stations are scattered anywhere that is permitted by local land use, and free market economics encourages how stations are positioned and how long they survive as a business. Trips along the road network can range widely; many household trips by car (76.7 percent in 2017[3]) are fewer than 10 miles, whereas trucking can travel hundreds of miles. The road network also is used by vehicles that have a relatively short service life than other modes, resulting in a vehicle fleet turnover rate that is quicker to adopt new technologies—road-based vehicles still have an average turnover period in the 10- to 15-year range[4], as opposed to multiple decades for rail, maritime, and aviation.

Road-based vehicle transport is probably the most advanced in terms of zero emission adoption, motivated primarily by strong regulatory agencies and the quicker fleet turnover period. In the United States, many roads are funded primarily through federal funds, providing greater influence of federal policies focusing on emissions reductions. Federal incentives for zero emission vehicles are being actively pushed in the United States through legislation, with similar pushes in the European Union due to pro-environment regulations. Federal tax incentives existed for many years to subsidize purchase of energy-efficient vehicles, and many states and local governments have offered similar incentives. Most recently, the Infrastructure Investment

---

[3] Office of Energy Efficiency and Renewable Energy. FOTW #1042, August 13, 2018: In 2017 Nearly 60% of All Vehicle Trips Were Less than Six Miles. https://www.energy.gov/eere/vehicles/articles/fotw-1042-august-13-2018-2017-nearly-60-all-vehicle-trips-were-less-six-miles

[4] The Fuse. America's Aging Vehicles Delay Rate Of Fleet Turnover. January 23, 2018. http://energyfuse.org/americas-aging-vehicles-delay-rate-fleet-turnover/

and Jobs Act[5] (IIJA) looks to support a variety of alternative fuel vehicle technologies through grant programs, standards, loans, studies, research, fleet funding, and other measures. IIJA is cited to include provisions that increases investment in light-, medium-, and heavy-duty zero emission vehicles. As a result, many auto manufacturers have brought technology to market that aims to get away from traditional fossil fuels. Additionally, several states have adopted ZEV program policies, where signatories commit to increasing sales of ZEVs over the next decade, helping spur the market for these vehicles.

Among passenger vehicles, most automakers pushed toward BEV technologies, noting specifically that most household trips were local and that electricity was available at owner's homes to charge. Several car manufacturers[6] (Ford, Chevy, Volkswagen, Nissan, Audi, Porsche, and Tesla) are offering electric vehicles in their current model year. The range for these vehicles varies, with 149 miles (Nissan Leaf) on the lower end and 402 miles (Tesla Model S) on the higher end. Consumer resistance often cites the lower range and charging wait time as major detractors, but this has led to an expanded rollout of EV charging stations at certain key destinations, such as shopping centers where an owner's trip there may exceed the time required to recharge a vehicle. While BEV still represent less than 1 percent of the total global car stock[7], this business model seems to offer initial promise, and the rollout in states with strong ZEV programs is trending very positively toward wider adoption.

Buses have been pushing the zero emissions envelope for several decades, being closely tied to environmental initiatives that are pushed by its owner city. When discounting catenary systems, zero emission bus options include both the battery-electric and hydrogen-fuel cell buses; other buses aim to reduce emissions through cleaner fuels (but not zero emission), including compressed natural gas. Transit agencies often have added these buses to their fleets in small percentages, tied to a pilot demonstration project or federal grant opportunity. The power choice often comes down to political motivations and specific use cases – for example, electric buses tend to be used along short-range urban routes, whereas hydrogen fuel cell options appear on routes that have longer distances[8]. Most transit agencies strategically deploy their charging or fueling infrastructure at key route termini, such as turnaround sites or depots, which limits the investment of fueling infrastructure to a few strategic locations.

The trucking industry has attempted to add BEV and HEV to their fleet; however, their operational requirements are different than passenger vehicles or buses. "Range" is often the metric used to gauge feasibility of operation for a passenger vehicle or bus. In trucking, the term "load capacity" is the more appropriate metric that applies, as it ties into the amount of cargo that a truck can transport. In the United States, federal law controls the maximum gross vehicle weights and axle loads on the Interstate Highway System to 80,000 pounds gross vehicle weight; some states have routes that are exceptions, but often still align maximum axle weights to the 20,000-pound (single axle) and 34,000-pound (tandem axle) federal requirements. This gross vehicle weight includes the truck and trailer, as well as their fuel source. With batteries having a lower energy density than traditional fuels, the additional weight required to provide the

---

[5] U.S. Department of Energy. Infrastructure Investment and Jobs Act of 2021. https://afdc.energy.gov/laws/infrastructure-investment-jobs-act

[6] Car and Driver. 12 Bestselling Electric Vehicles of 2021. January 19, 2022. https://www.caranddriver.com/features/g36278968/best-selling-evs-of-2021/

[7] International Energy Agency. Electric Vehicles Tracking Report – November 2021. https://www.iea.org/reports/electric-vehicles

[8] Government Technology. Batteries or Hydrogen? Cities Weigh Making Buses Electric . June 11, 2019. https://www.govtech.com/products/batteries-or-hydrogen-cities-weigh-the-best-way-for-buses-to-go-electric.html

same energy output as traditional fuels consumes a significant amount of the remaining weight allowance, leaving less load capacity for cargo. Logistics companies have cited this as a prevalent concern, as it will—in theory—take more BEV trucks to move the same cargo than a single traditional-fuel truck. While some battery manufacturers claim that they will be able to increase the energy density, it is not currently forecasted to be competitive.

As a result, most truck manufacturers are focused on HEV over BEV. Several began operation in Europe in 2021 at a relatively small scale. The Hyundai Xcient[9], considered the world's first mass-produced fuel cell truck, provides 400 kilometers of range using a combination 190 kW hydrogen fuel cell system, and an average refueling time of 15 minutes. Hyzon Motors operated a fuel cell truck, with a commitment to supply 1,000 vehicles and 25 refueling stations by 2025. In comparison, BEV trucks are a bit less developed. Tesla claims to offer an all-electric battery-powered Class 8 truck concept claiming up to 500 miles of range, but mass production is not scheduled until 2023 at the earliest. A competitor, Nikola Motors, started production of a battery-powered semi truck, designed for shorter hauls of 350 miles or less. Given these limitations and the lack of hydrogen infrastructure, the push in the trucking industry has been more toward use of biofuels, specifically biodiesel which is capable of being used in most vehicles. While a biodiesel mix often is more expensive than traditional diesel, it is relatively easy to roll out to fueling stations around the country, similar to how ethanol mixes were rolled out to many passenger vehicles. Biodiesel offers comparable energy densities to regular diesel, overcoming the load capacity constraint without requiring a major change to the vehicle design.

Maritime Shipping Industry

The maritime transportation system utilizes shipping vessels to move primarily large volumes of freight over the ocean, although a significant portion utilizes smaller vessels (e.g., barges) to move cargo on inland waterways or regional coastal areas. Cargo is its primary commodity; passenger transport waned away in the 20th century due to competition from other modes. Accessibility is limited to the available waterways that can be serviced by that vessel, and the number of destinations is significantly smaller than those served by road; as such, fueling tends to be located at port facilities. Maritime moves nearly 80 percent of all trade with projected future growth, but also represents 3 percent[10] of total CO2 emissions that is forecasted to rise by as much as half by 2050 if no corrective action is taken.

Unlike the road network, maritime routes are more likely to span international boundaries, resulting in a mix of policies and interests that are not easy to influence. That said, interested stakeholders in this industry have cited goals to help facilitate a reduction in vessel emissions. The International Maritime Organization (IMO) has mandated emission reductions of 50 percent for all vessels by 2050, with a number of heavy trade countries declaring a target for net-zero shipping emissions in the same time frame. In parallel to this, a call to action was developed by a multi-stakeholder task force, convened by the Getting to Zero Coalition and its membership that makes up the entire maritime ecosystem, including shipping, chartering, finance, ports, and fuel production; this call to action aims to deploy commercially-viable zero emission vessels by 2030 as an immediate urgent action, sets a target for zero emission shipping by 2050, and acknowledges a need for private sector action to go hand-in-hand with government action. However, unlike the ease of

---

[9] Fuel Cell Works. The First Hydrogen Trucks Are Rolling In Europe. December 27, 2021. https://fuelcellsworks.com/news/the-first-hydrogen-trucks-are-rolling-in-europe/

[10] European Commission. Reducing emissions from the shipping sector. Accessed on March 29, 2022. https://ec.europa.eu/clima/eu-action/transport-emissions/reducing-emissions-shipping-sector_en

fleet turnover found in road transportation, maritime vessels often have a 25-year service life and require advance forethought.

Concepts for zero emission cargo ships have been proposed over the years, varying widely in fuel type from liquid hydrogen to electric (solar panels, batteries, and wind) to liquid natural gas. The most prevalent prototype in operation is the 120 TEU Yara Birkeland[11] in Norway, which is a cargo ship that operates using only electricity. Its range is fairly limited—12 nautical miles—but the owner, Yara International, had a specific commercial use case to move fertilizer between two ports that are a short distance apart and thus provided a good demonstration. This vessel move is claimed to reduce an estimated 40,000 truckloads per year from the roads by doing so. The Yara Birkeland also is touted to include autonomous features, with a goal to demonstrate these in practice in 2022 after clearing local regulations. Unfortunately, it is the only vessel of its kind in operation; all other zero emission cargo ships are concept-only, usually with a target goal to be operational in 2025 or 2030, but almost always for a short-distance or very-low-speed application. For over a decade, Wallenius Wilhelmsen Logistics conceptualized the E/S Orcelle, a vessel that is claimed to operate using wind, sun, and wave energy alone to transport cars and goods, but this has not been deployed. Another firm, NYK, created a different concept called the Super Eco Ship, envisioned to use solar power and liquified natural gas, but this remains only a concept. Similarly, the GL Group offered a concept for a container ship that operates on liquid hydrogen, primarily for 15-knot operation in northern European waters; it too remains in development[12]. The key takeaway here is that the use cases served by zero emission vehicles are limited and do not include the long-distance transport options that many container ships do.

When seeking a means to reduce carbon footprint, interest in maritime has been on biofuels as a means to transport. One proposal in the industry is to establish “green corridors”[13], which include key strategic shipping routes that allow policy makers to establish regulatory measures, financial incentives, and safety regulations that facilitate operation of a zero emission shipping lane. For example, with zero emission fuels costing significantly more than conventional fuels, policies could be established on either end of the shipping lane to help subsidize those costs. Success of these corridors requires committed stakeholders, viable fuel accessibility, customer demand for green shipping, and policies/regulations to narrow cost gaps to help facilitate adoption. This proposal is silent on the proposed fuel type (suggesting both liquid hydrogen and green ammonia), citing instead the need to work collaboratively as an industry when establishing these corridors to find the right fit.

Aviation Industry

The aviation transportation system moves both passengers and freight over long distances in a short period of time, relative to the speed of either road-based or maritime transportation. Aviation loses that advantage in certain markets—namely short-distance trips or regional links also served by high-speed rail—but it retains the distinct advantage of time under most other circumstances. Accessibility is limited to airports

---

[11] Offshore Energy. Yara Birkeland, world’s 1st zero emission containership, completes maiden voyage. November 19, 2021. https://www.offshore-energy.biz/worlds-first-zero-emission-containership-completes-maiden-voyage/

[12] Marine Insight. Top 5 Zero Emission Ship Concepts of the Shipping World. December 21, 2021. https://www.marineinsight.com/green-shipping/top-5-zero-emission-ship-concepts/

[13] McKinsey and Company. Green corridors: A lane for zero carbon shipping . December 21, 2021. https://www.mckinsey.com/business-functions/sustainability/our-insights/green-corridors-a-lane-for-zero-carbon-shipping

that can serve a particular aircraft type, and the number of destinations is significantly smaller than those served by road; as such, fueling is almost exclusively done at airports. The complex mechanics of flight require extensive fuel use, which has placed the aviation industry as a heavy emitter, roughly 2.5 percent of total CO_2 emissions in 2018[14] despite being a smaller fraction of all emitters (including power industry, personal vehicles, etc.). Some proposed supersonic airliners are anticipated to consume five to seven times as much fuel as a subsonic aircraft[15].

While aviation does span international boundaries, its operations are governed closely by national aviation agencies, thus providing some degree of influence on zero emission goals. The U.S. Federal Aviation Administration[16] (FAA) published the United States Aviation Climate Action Plan in November 2021, which outlines an approach to put the sector on a path toward net-zero emissions by 2050. A month prior, the International Air Transport Association[17] (IATA) passed a similar resolution to commit member airlines to achieving net-zero carbon emissions by 2050 as well, given policies being developed in local and overseas markets. Both groups acknowledged that a coordinated effort was required across the industry for this to be successful, including contributions from airlines, airports, air navigation service providers, manufacturers, and government. However, rather than look toward electrification or hydrogen, these initiatives focus more toward changing to sustainable aviation fuels, produced from renewable and waste feedstocks (residues, biomass, sugar, oils, and gaseous sources of carbon). Similar to biodiesel for semi trucks, many aircraft in operation are able to use these sustainable aviation fuels, citing that it is a lack of production capacity for biofuels that forces use of traditional fuels. In addition to sustainable fuel use, the aviation industry anticipates development of new aircraft technologies, operational efficiencies (i.e., using national airspace more efficiently), and infrastructure improvements at airports to also support this goal.

The power requirements necessary to sustain flight and the current use case for long-distance flights make the aviation mode less likely to veer away from traditional fuels without incentive. Prototype aircraft have aimed to demonstrate battery-power (often through solar) and fuel cell operation on aircraft for decades; however, similar to maritime, many concepts are proposed (for either BEV or HEV), but only a limited number of prototypes have actually flown. Most BEV aircraft prototypes are usually two- to four-seat aircraft with limited flight range (e.g., up to 90 miles). Several aerospace companies have focused on electricity-powered commercial aircraft development, with a goal to be certified in the 2026 or later; these aircraft generally carry up to 19 passengers, and have ranges of under 250 nautical miles[18]. Hydrogen-powered aircraft have been demonstrated in isolated contexts, but have remained exclusively as concept ideas.

---

[14] Our World in Data. Climate change and flying: what share of global CO2 emissions come from aviation? October 22, 2020. https://ourworldindata.org/co2-emissions-from-aviation

[15] The International Council on Clean Transportation. The Environmental and Health Impacts of a New Generation of Supersonic Aircraft could be immense. January 30, 2019. https://theicct.org/the-environmental-and-health-impacts-of-a-new-generation-of-supersonic-aircraft-could-be-immense/

[16] Federal Aviation Administration. U.S. Releases First-Ever Comprehensive Aviation Climate Action Plan to Achieve Net-Zero Emissions by 2050. November 9, 2021. https://www.faa.gov/newsroom/us-releases-first-ever-comprehensive-aviation-climate-action-plan-achieve-net-zero

[17] International Air Transport Association. Our Commitment to Fly Net Zero by 2050. Accessed on March 29, 2022. https://www.iata.org/en/programs/environment/flynetzero/

[18] FlightGlobal. Sweden’s Heart Aerospace presents all-electric regional aircraft. September 24, 2020. https://www.flightglobal.com/airframers/swedens-heart-aerospace-presents-all-electric-regional-aircraft/140307.article

Relevance to Metrolink

The three transport modes presented in this appendix show general industry progress for that mode in moving toward a zero emission vehicle. Without surprise, no single mode has identified a clear winner between BEV or HEV, and despite target-year goals, no single mode is "running" toward a zero emissions vehicle, but rather cautiously maneuvering. Road-based vehicles are furthest along due to government incentives and public policy, but over 99 percent of vehicles on the road still use traditional fuels and the "preferred" fuel type still varies based on need (e.g., passenger cars may only need BEV for their typical short trips, but long-haul trucking may need HEV to support a financially-viable load capacity). Other modes seem more aligned with transitioning toward a net-zero biofuel option, citing either their complex use cases or operational requirements necessitating something closer to traditional fuels. As such, when trying to index a given mode to a commuter rail service that is of design similar to Metrolink, it comes as no surprise that no one mode is entirely comparable. However, each provides relative benchmarks that can help provide backing for or against certain initiatives.

The closest comparable mode to Metrolink's operations is likely the maritime mode. When doing a side-by-side comparison, some similarities emerge:

- Commuter rail locomotives and maritime vessels have a relatively long service life, which impacts their rate of fleet turnover. Road-based vehicles—where most aggressive investment in BEV and HEV is being explored—have much shorter service lives and are easier to substitute in.

- Commuter rail locomotives and maritime vessels both tend to have a limited number of serviceable destinations. Specifically, commuter rail is access-controlled and has defined stations or yards, whereas maritime—abet not access-controlled—only has a limited number of ports to access. This helps allow fueling stations to be strategically placed and consistently applied (i.e., HEV fueling stations only). Road-based vehicles have greater access to destinations and a greater spectrum of user needs between trucks and passenger vehicles, and thus requires a more complex, more extensive rollout of fueling stations for a given type.

- Commuter rail and maritime vehicles are less constrained by certain operational challenges that necessitate fuels with higher energy densities. Aviation, on the other hand, requires fuels with high energy densities, meaning that BEV will likely never be a viable option for long-range flights.

Despite this comparison, some notable differences exist. With the exception of the Yara Birkeland, most maritime zero emission vehicles are concepts. Rail, on the other hand, has zero emission vehicles in demonstration today[19], which is more similar to the road-based mode and the various demonstration and consumer-ready vehicles on the market. Commuter rail bears more similarities to passenger vehicles in terms of making many local trips ("local" being within region) and could potentially utilize battery-electric options, whereas most maritime applications require trips that are longer distance and lean more toward a

[19] The Guardian. 'Dramatically more powerful': world's first battery-electric freight train unveiled. Accessed on March 29, 2022. https://www.theguardian.com/us-news/2021/sep/16/battery-electric-freight-train-wabtec-rail-transport-emissions;

Railway Age. CP's Hydrogen Locomotive Powers Up. January 25, 2022. https://www.railwayage.com/mechanical/locomotives/cps-hydrogen-locomotive-powers-up/;

Railway Technology. East Japan Railway unveils hydrogen-powered train. February 18, 2022. https://www.railway-technology.com/news/japan-railway-hydrogen-train/

higher-energy-density fuel. Maritime also services many international ports and is less likely to be influenced by a single country's policies on zero emissions, whereas commuter rail is wholly contained to a given country and state and subject to political preferences in that locale.

Still, while maritime is not a perfect one-to-one-match, many of the proposed approaches in that industry apply to commuter rail, and commuter rail can take advantage of advances both there and in the road-based vehicle space to help expedite a deployment. A proposed concept of green corridors, offered by McKinsey and Company for the maritime industry, is a model that could be replicated on a commuter rail system because a commuter rail system is essentially a corridor. This model identified the building blocks for success, regardless of fuel type—committed stakeholders, a viable fuel pathway, customer demand for reduced emissions, and policy/regulation that could narrow costs. Scaling down for Metrolink's applications, establishing internal and external stakeholders, as well as identifying fuel pathways, is an effort that is already ongoing as part of this study. Metrolink may not be able to set policy beyond its operations, but establishing a procurement policy—such as procuring a zero emission vehicle investment only when several vendors exist in the marketplace—is one step toward a zero emissions goal that reduces risk of a failed prototype. It is important to recognize that most other modes are only at a goal-setting point, aiming toward a target year 2050 goal to dramatically reduce emissions , but falling short of staking a claim to HEV, BEV, or others. While some trends are apparent among road-based vehicles to use BEV for passenger cars and likely HEV for trucking, this represents less than 1 percent of all vehicles on the road and is hardly a trend.

While this continues to be an ongoing discussion, many modes are leaning toward biofuels, despite the controversy, because biofuels are the easiest to retrofit into an operation. While the land use impacts of biofuels cannot be ignored, it must also be considered that alternative production methods may arise in the future that many alleviate the cited land use challenges. The only known is that the future is uncertain, but even with relatively limited progress in these other modes, Metrolink may best be positioned by watching closely how the road-based vehicles and maritime industry evolve over the next decade, and pursue incremental improvements based on the best practices in either industry to help advance it toward its own zero emission concept.

APPENDIX E

Simulation Assumptions and Results

Locomotive Weight	268,000 lbs.
AW2 Bombardier Trailer Car	148,845 lbs.
AW2 Rotem Trailer Car	179,950 lbs.
AW2 Bombardier Cab Car	152,075 lbs.
AW2 Rotem Cab Car	184,060 lbs.
Wheel Diameter	40"
Gear Ratio	57:20
Gear Efficiency	0.98
Locomotive Auxiliary Power Consumption	30 kW
Air Compressor Power (20% duty cycle)	25 kW*0.2
Cab and Trailer Car HEP Power Consumption	35 kW

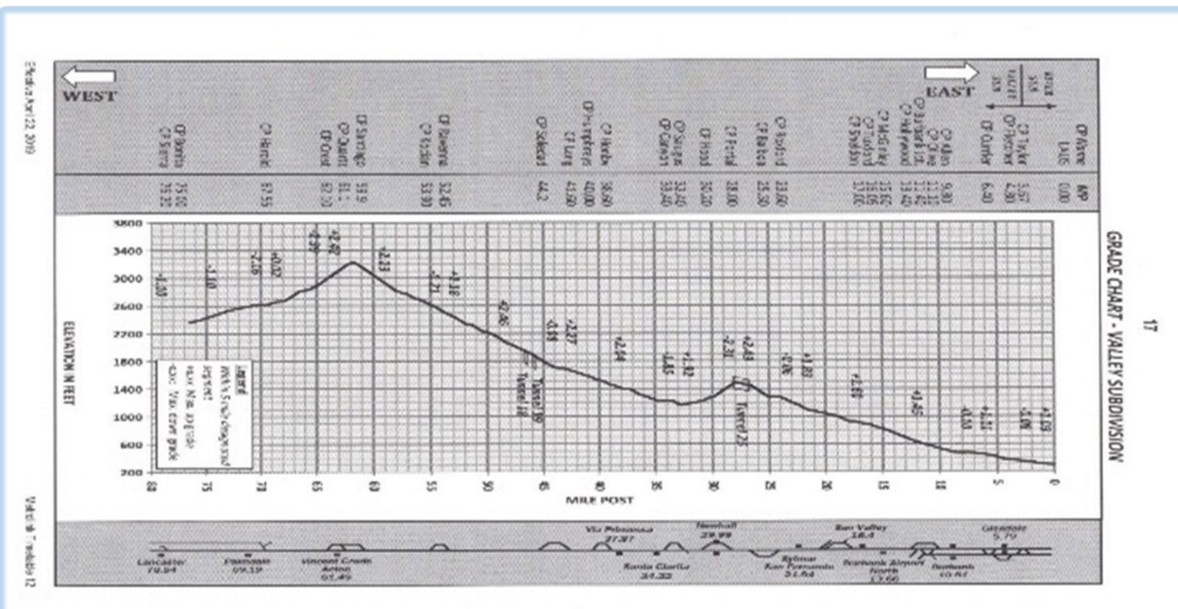
Battery Electric Locomotive Simulation

Criteria	San Bernardino Line	Antelope Valley Line
Number of Cars in the Consist	4	2
Trip Length (miles)	58	75
Max Speed (mph)	77	77
Consumed Energy (kWh)	1987 (one-way)	2725 (round-trip)
Number of Trips without	1 one-way	1 round-trip
Required Battery Capacity	3320	4260

Hydrogen Battery Hybrid

Criteria	San Bernardino Line	Antelope Valley Line
Number of Cars in the Consist	4	2
Trip Length (miles)	58	75
Max Speed (mph)	77	77
Fuel Cell Power (kW)	900	800
Battery Capacity (kWh)	825	800
Qty of H2 Required	271	312
Number of Trips without H2 Refill	1 round-trip	1.5 round-trips

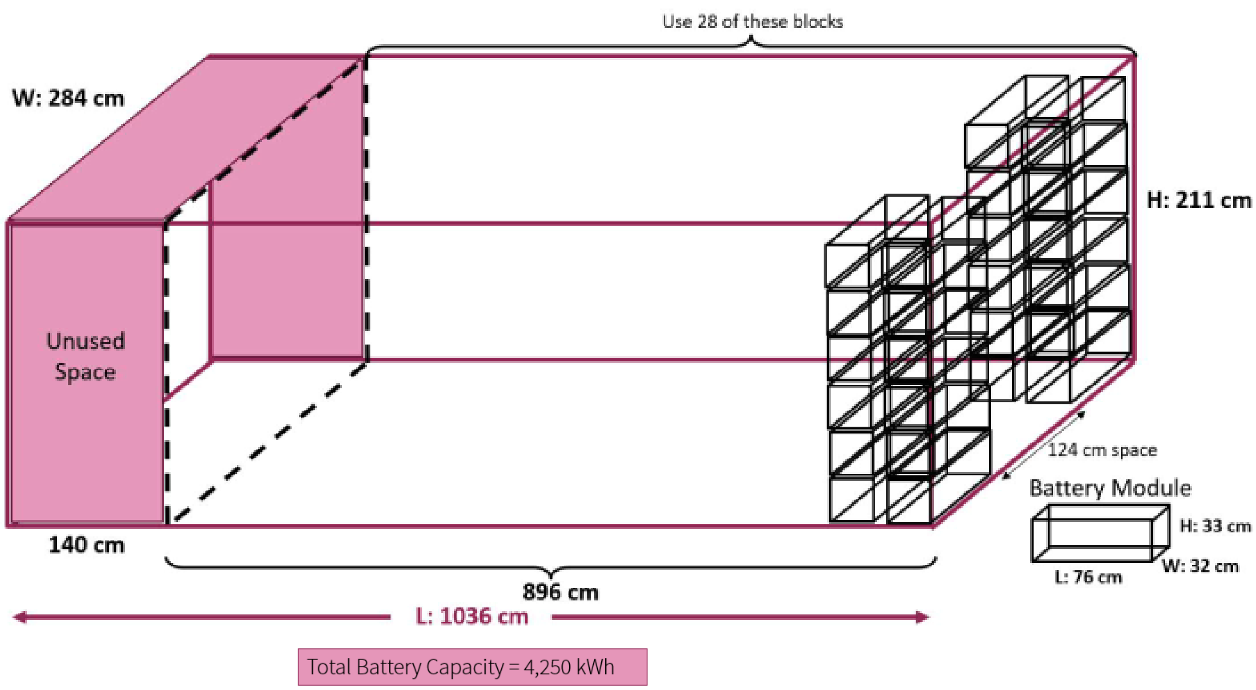
Grade on Antelope Valley Line



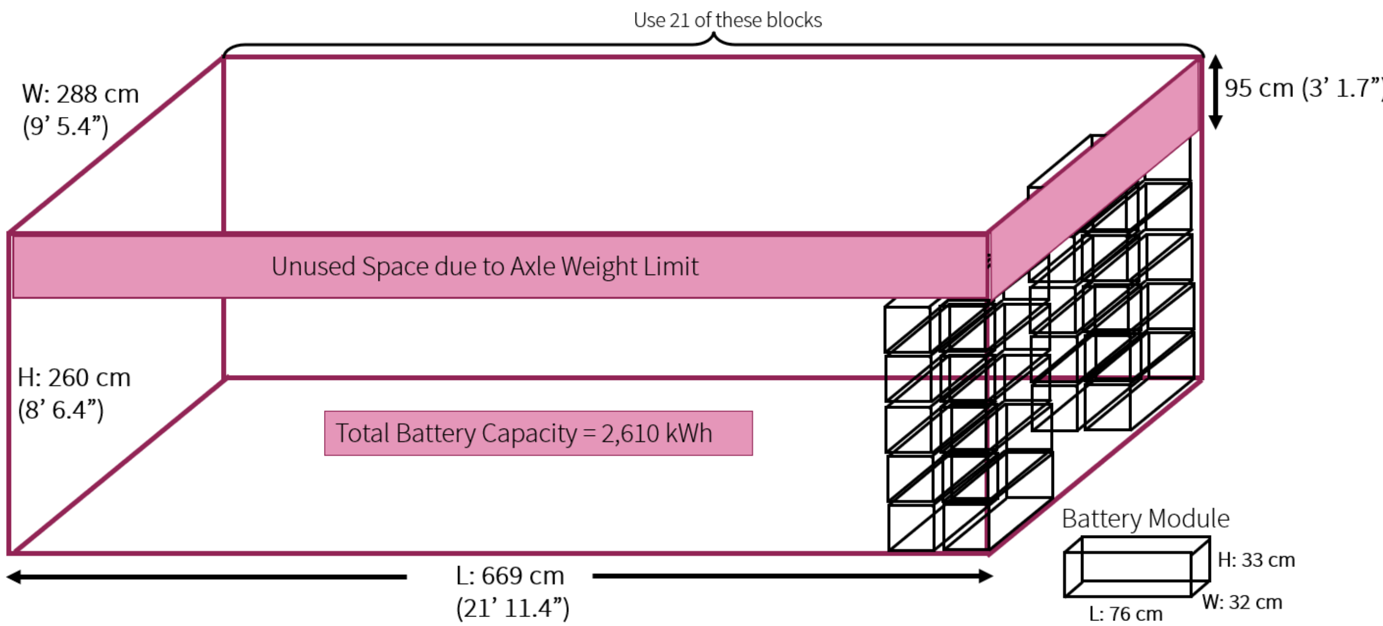
APPENDIX F

In the “Metrolink Fleet Modernization Alternate Propulsion Study”, the feasibility of battery electric and fuel cell battery hybrid locomotives and RMUs is analyzed on some of the Metrolink’s routes. In this analysis, first battery capacity, fuel cell power, and hydrogen tanks a locomotive and an RMU can accommodate are estimated and then the energy consumption of each vehicle type with a zero emission propulsion system is simulated on Antelope Valley Line and San Bernardino Line. For the battery electric propulsion, the battery capacities an F-59 PHI locomotive and a 4-car RMU can accommodate are calculated as 4,250 kWh and 2,610 kWh, respectively. For the fuel cell battery hybrid locomotive, on-board hydrogen storage capacity of an F-59 PHI locomotive and a 4-car RMU are estimated as 330 kg and 200 kg, respectively.

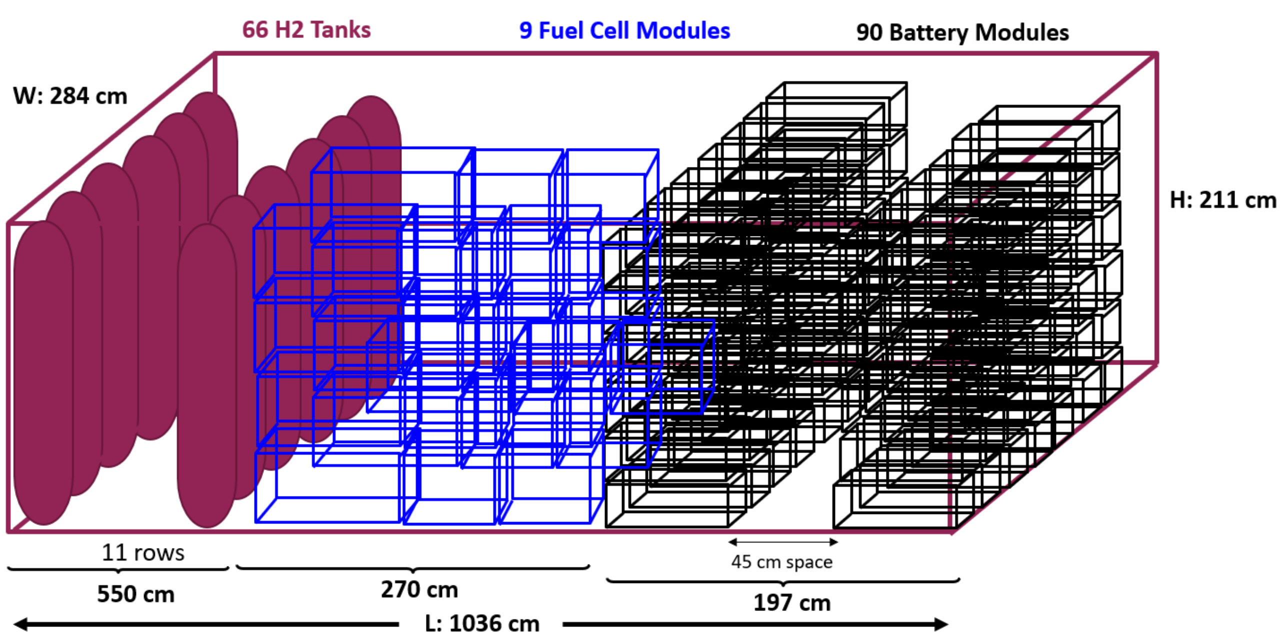
Battery Placement on an F-59 PHI Locomotive



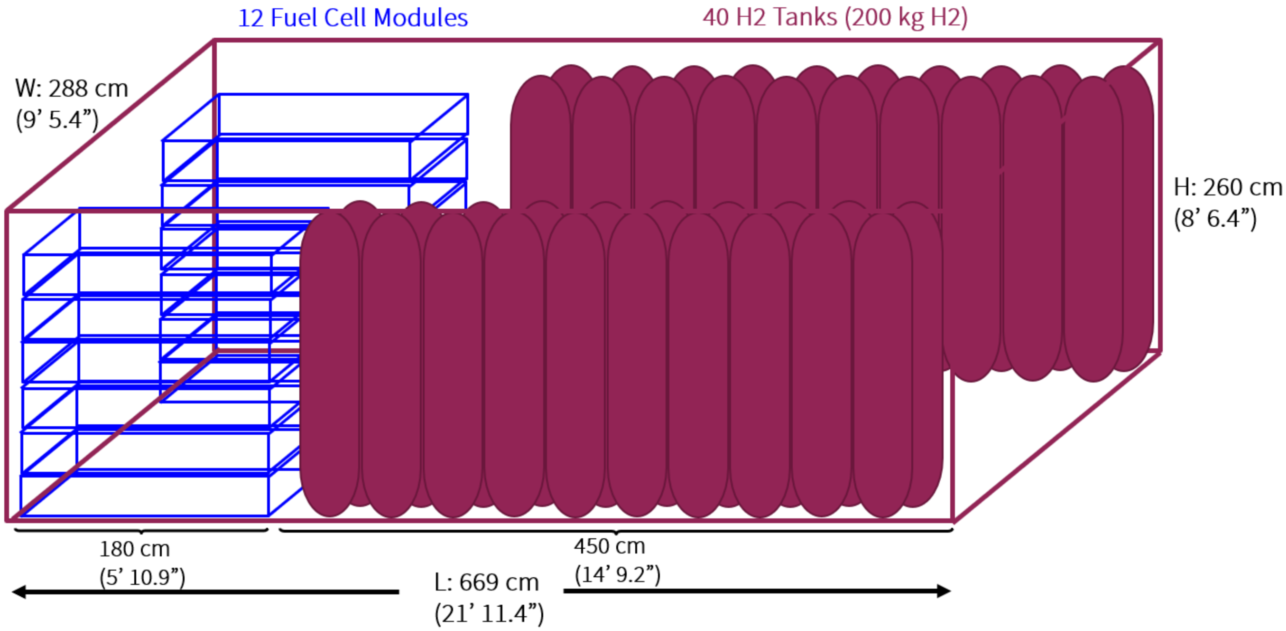
Battery Placement on an RMU



Fuel Cell Battery Hybrid System Placement on an F-59 PHI Locomotive



Fuel Cell Battery Hybrid System Placement on an RMU

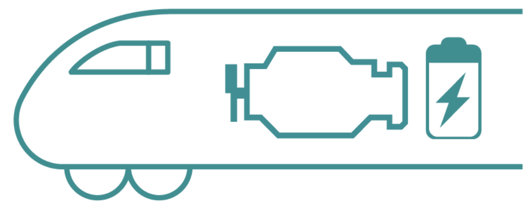


APPENDIX G

Low Emission Vehicle Alternative to Zero Emission Locomotive

If Metrolink would not be able to invest in a costly pilot zero emission vehicle. In this scenario, Metrolink can plan to pursue the acquisition of a pilot vehicle with diesel battery hybrid propulsion shown in the figure below. The technical specifications of this type of vehicle will be as follows:

- Smaller diesel engine than the engine of a conventional diesel electric propulsion
- High power Li-Ion battery pack to provide additional traction power and store regenerative braking energy
- High power Li-Ion battery pack to propel the train without the support of diesel engine (turned off diesel engine)
- Approximately 15-mile zero emission range (the range would depend on the route profile and train configuration)
- When the battery charge level drops below a certain threshold, diesel engine turns on and the propulsion switches from zero emission mode to diesel battery hybrid mode.
- The vehicle can be charged by the diesel engine and wayside 480 VAC voltage source.



Pilot Propulsion Technology for Low-Funding Case: **Diesel Battery Hybrid**

To limit the project budget, a high-power overhead charging system will not be installed, electricity grid capacity at CMF will not be upgraded and the battery will be charged with the existing 480 VAC capacity at CMF and layover stations.

The initial goals set for a pilot battery electric vehicle can be achieved with the proposed low-cost diesel battery hybrid vehicle. According to the initial evaluation, it is expected that 60% of initial goals set for a battery electric vehicle can be achieved with a diesel battery hybrid vehicle. However, the advantages of this type of vehicle would be its comparable range to a diesel electric locomotive and hence the feasibility of operating the pilot diesel battery hybrid vehicle in revenue service for many years even after the end of the pilot project. Moreover, if the diesel engine in this vehicle consumes renewable diesel, the net emissions would be close to zero and the vehicle can operate quietly with zero local emissions in battery only mode at CMF or heavily populated residential areas.

Pilot Goal	Evaluation Capability	Explanation
Range of the train on the target routes during actual operating conditions		Since the diesel battery hybrid vehicle can run in battery mode, the range of the train with the on-board battery capacity can be evaluated.
Battery capacity determination on the target vehicle for the target routes		Since the vehicle will have limited range due to small battery capacity, the testing time will be longer than a battery electric vehicle because a route would need to be divided into small segments and the vehicle needs to run each small segment in battery mode in a separate test to evaluate the required battery capacity for a target route.
Alternative battery charging methods		High power charging through a pantograph could not be evaluated.
Infrastructure limitations on the charging system		Since high power charging will not occur, the resiliency and power capacity of the grid infrastructure will not be assessed.
Reliability of the propulsion system and charging system		Although the reliability of a battery electric propulsion system will be evaluated successfully, the reliability of a high-power overhead charging system could not be assessed due to its unavailability.
Battery aging		Since high power Li-Ion battery pack is needed for hybrid applications and a battery electric vehicle uses high energy Li-Ion battery pack, the battery aging information obtained from a diesel battery hybrid vehicle cannot fully represent the battery aging in a battery electric vehicle. Moreover, since there will not be high-power charging, its effect on battery life cannot be assessed.
Electricity cost		Electricity cost due to wayside 480 VAC charging will be evaluated. But the effect of high-power charging on demand charges by the electric utility will not be assessed.
Maintenance practices and cost		Maintenance practices and related cost items about a battery electric propulsion can be evaluated.
Performance under different weather conditions		The performance of the propulsion in terms of discharge/charge power and battery mode range in different climate conditions can be evaluated.

APPENDIX H

CalSTA TIRCP Selected Grant - Project Detail Summary

Los Angeles County Metropolitan Transportation Authority (LA Metro) and Southern California Regional Rail Authority (Metrolink)

Project: Metrolink Antelope Valley Line Capital and Service Improvements

Award:	**$107,050,000**
Total Budget:	**$220,850,000**

Estimated TIRCP GHG Reductions: **584,000 $MTCO_2e$**

The proposed Metrolink Antelope Valley Line Capital and Service Improvements Project will add targeted capacity-increasing infrastructure on the Antelope Valley Line, increase service in step with new capacity, and assess the feasibility of rail multiple unit and zero-emission propulsion service through a pilot project on the Metrolink Antelope Valley Line. The 4 infrastructure projects included allow Metro to initiate regular 60-minute, bi-directional service, followed by introduction of regular 30-minute bi-directional service from Los Angeles Union Station to Santa Clarita, in deployment waves that accelerate delivery of new service as planned under the Southern California Optimized Rail Expansion (SCORE) program.

The 4 infrastructure projects include:

1. Balboa Double Track Extension
2. Lancaster Terminal Improvements
3. Canyon Siding Extension
4. Brighton-McGinley Double Track

This award builds on the investment in Phase 1 of the Southern California Optimized Rail Expansion (SCORE) Program awarded in 2018 and expands those benefits. This award accelerates delivery of key AVL Projects, which provide regional "bookend" capacity for state-supported Intercity and High-Speed Rail, as well as significantly advances the County's ability to integrate the regional rail system into the Metrolink station communities.

In addition, this project includes funding for a zero-emission rail multiple unit (ZEMU) equipment pilot to assess potential to provide more cost-effective and flexible rail service and reduce the carbon and emissions footprint of rail service. The ZEMU pilot tests rail technology in one of the more challenging Metrolink corridors due to topography, density, temperature variations and elevation differences between Lancaster and Los Angeles. If the pilot project is successful on this corridor, it will bode well for ZEMU operations throughout the entire Metrolink regional rail network and help provide data and performance measurements useful to other agencies in California seeking to implement similar ZEMU rail technology. Technical assistance will be provided by the California Department of Transportation to integrate rail demonstration pilot efforts with statewide rolling stock planning.

Over 1 million residents of the 3.3 million residents in the census tracts in the Antelope Valley station catchment areas are from Disadvantaged Communities. The AVL investments will improve rail mobility and access for these priority populations to major employment centers and other regional destinations, including Hollywood Burbank Airport.

Due to the extended timeline for delivery that goes beyond this cycle's 5-year program (completion date: 2027), the project is expected to receive allocations over the life of the implementation schedule.

Key Project Ratings:	
Cost per GHG Ton Reduced:	High
Increased Ridership:	Medium-High
Service Integration:	High
Improves Safety:	Medium-High
Project Readiness:	Medium-High
Funding Leverage:	Medium-High
Multi-Agency Coordination/Integration:	High
Priority Population Benefits:	Medium
Housing Co-Benefits:	Medium

Excerpt from LA Metro TIRCP Grant Application

Metro is applying for Network Integration funding in the amount of $10 million to advance clean vehicle technology and test rail service delivery options. The proposed Zero Emissions Rail Multiple Unit Pilot Project (ZEMU Pilot) would begin with nearly two years of study, collaboration with the Southern California Regional Rail Authority (SCRRA), operator of Metrolink, and regional partnering to create a robust evaluation framework and plan for data sharing with state stakeholders. and then the actual procurement and, first, three years of revenue service testing of conventional (market-ready) diesel multiple units (which allows the ZEMU Pilot to move forward following an opportunity to test the DMU equipment type in revenue service) and then a final year of revenue service testing with hydrogen fuel cell, or other zero-emissions technology multiple units (ZEMUs), which is more in alignment with the sustainable goals of both Metro and Metrolink. The 2020 TIRCP request for $10 million funds the conversion of the rail multiple unit from diesel to hydrogen fuel cell, or other zero-emission propulsion technology, as determined through a proposed Regional Collaborative Planning Process.

TABLE 2: AVL CAPITAL AND SERVICE IMPROVEMENTS PROJECT-SOURCES AND USES OF FUNDS (IN YOE$*)	
USES OF FUNDS	
Studies & Permits (E&P) and Project Approval & Environmental Document (PA&ED)	$3,250,000
Plans Specification and Estimates (PS&E)	$13,500,000
Right of Way	$1,600,000
Construction (for the four capital investments)	$192,500,000
Network Integration (ZEMU Pilot Project)	$10,000,000
TOTAL USES	$220,850,000
SOURCES OF FUNDS	
Transit and Intercity Rail Capital Program Funds (2020 Request)	$107,050,000
Metro Local Transportation Funds	$113,800,000
TOTAL SOURCES	$220,850,000

*Note: Totals may not sum due to rounding. *includes 3% annual cost escalator*
Source: Metro/LACMTA

APPENDIX I

Platform Studies and Waivers

The purpose of this appendix is to discuss the requirements for platform and vehicle height regarding whether level boarding is required. Requirements for Commuter Rail Vehicles are covered in *49 CFR 38.91 General* and requirements for vehicles that are not level boarding due to it being structurally or operationally impracticable are in *49 CFR 38.95 Mobility aid accessibility.* Station/platform requirements are covered in *49CFR 37.42 Service in an Integrated Setting to Passengers at Intercity, Commuter, and High-Speed Rail Station Platforms Constructed or Altered After February 1, 2012.*

FRA and Peer studies have identified the justifications for using min-high platforms when stations are operating in mixed service, including freight and passenger service where trains may pass stations at speed.
Study of Methods to Improve or Correct Station Platform Gaps, dated October 2010, was an FRA sponsored document provided as a *Report to the House and Senate Authorizing Committee.* This study examined current conditions and looked at the possible mitigation measures and the relative costs of those strategies. Mini-high platforms where full length level boarding were not available or practicable were an acceptable mitigation strategy.

Level Boarding Challenges for Commuter Rail Systems, dated 2010 was an APTA paper presented when the Notice for Proposed Rulemaking regarding level boarding was proposed. It examined the specific challenges faced by the railroads and transit agencies.

Peer Services have been through the review process with the FRA and gotten approval to proceed with the non level boarding approach using mini-high platforms to provide Mobility accessibility.

For the Perris Valley Line, a paper was provided recommending (and getting approval) for operation with mini-high platforms. The document was *Accessibility Compliance with USDOT Level Boarding Guidance*, dated October 25, 2010. The study went through the various steps required to demonstrate that level boarding was not practicable for this line and the vehicles that would be operating on it. It is assumed a similar study would be required for operation of an RMU vehicle on Metrolink's existing system with mini-high platforms.

If Level boarding should be required, the mini-high platform approach is an option, but will require detail placement. The San Joaquin Regional Rail Commission has taken the use of multiple types of mini-high platforms to manage their intermodal stations where multiple types of vehicles from various operators will be used on the new Valley Rail Stations. They have developed Valley Rail Station Design Guidelines, approved November 12, 2021, which describes and illustrate the approach they intend to take.