Caltrain 2.0 - Hydrogen Fuel Cell EMUs

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Alstom Coradia iLint Hydrogen Fuel Cell plus Battery Passenger Trainset (2016)
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# 1 Summary: Fuel Cell Electrify SF, SJ, Gilroy, Dumbarton - Save $1.8B

This study advocates changing the current Caltrain Modernization Electrification Project ...

- from **traditional catenary overhead contact system** (OCS) electric multiple units (EMUs)
- to hydrogen fuel cell EMUs.

This **fuel cell with hydrogen generation approach is viable and applicable** to Caltrain, and should merit serious consideration in 2017 as an alternative to the currently-planned traditional OCS EMUs approach.

The fuel cell approach would **provide electrified service not just from San Francisco to San Jose, but also to Gilroy and across the Dumbarton Corridor**.

The **fuel cell approach could save over $1.8B** over the OCS approach to provide electrified service for San Francisco, San Jose, Gilroy, and the Dumbarton Corridor.

> It would be unfortunate if our railway serving Silicon Valley were to construct one of the last catenary OCS rail systems rather than one of the first of many hydrogen fuel cell rail systems.

This report provides estimated costs for various approaches:

- Figure 1.1 - Current OCS plan, San Francisco to San Jose only, but with 132 OCS EMUs.
- Figure 1.2 - Long-term OCS plan, including OCS to Gilroy and the Dumbarton Corridor.
- Figure 1.3 - Fuel Cell EMUs plan, with 132 OCS EMUs - which inherently includes electrification to Gilroy and the Dumbarton Corridor.

This study increases the EMU fleet and costs from 96 (16 6-car trainsets) to 132 (22 6-car trainsets) to provide 100% electrified weekday service, rather than the 75% that 96 EMUs would provide.  
[Caltrain2014e]

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Figure 1.1: Catenary OCS SF to SJ Only

Figure 1.2: Catenary OCS All Routes

Figure 1.3: Fuel Cell All Routes

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1.1 Fuel Cell Independently-Powered EMUs

Fuel cell EMUs have achieved sufficient maturity to support the Caltrain situation. Hydrogen technology for transportation has been advancing in the past few years, with increasing testing and production of fuel cell locomotives, passenger rail cars, automobiles, and busses.

A fuel cell approach has the following characteristics, plus the independently-powered benefits listed below. (See section 2.1.)

- Feasible with advancing fuel cell and battery technologies
- Desirable quick acceleration and braking recovery characteristics of an OCS EMU
- Travel range of the fuel cell
- Zero operational emissions, like an OCS system

1.2 Independently-Powered EMUs

For over 150 years, locomotives have been independently-powered, which has provided flexibility in operation. Now that technology is providing viable fuel cell alternatives to diesel-electric propulsion, Caltrain should maintain the flexibility and extendibility for Caltrain's trainsets.

Independently-powered EMUs have compelling benefits over OCS EMUs:

- Less expensive due to much less infrastructure (see section 2.2)
- Less impact to surroundings and operations (2.3)
- Visually more attractive without overhead wires and poles (2.4)
- Extendable to additional locations without additional infrastructure (2.5)
- Operable during power outages for as long as the EMUs have power reserves (2.6)
- Enables other independently-powered options in the future (2.7)

1.3 On-site hydrogen generation from natural gas, later seawater

On-side generation provides benefits to Caltrain, and technologies to support this continue to advance. (See section 2.1.3.)

- Hydrogen production during low electricity demand periods (2.8)
- Cost control of Caltrain fuel, separate from electricity rates from a utility (2.9)

1.4 Additional Characteristics

Two additional characteristics pertain to the fuel cell approach:

- Separates Caltrain 2.0 from California High Speed Rail (CA HSR) (2.10)
- Impacts regarding freight traffic on the Peninsula and nearby (2.11)
2 Benefits and Characteristics

An independently-powered EMU approach, implemented with fuel cells supported by batteries, provides compelling benefits and characteristics, compared with a catenary / OCS approach.

Studies have shown the drawbacks of OCS electrification. One example includes: [vehicles] confined to electrified areas; maintenance of OCS; train immobilization due to OCS damage - or hydro failure; reduced mobility for on-track cranes; visual intrusion of OCS. [GoTransit2001a]

2.1 Feasible with advancing fuel cell, battery, and hydrogen technologies

2.1.1 Fuel Cell Technology

By early 2018, the Alstom Coradia iLint fuel cell EMU will enter revenue service on a 60-mile route in Germany. This model has a maximum velocity of 87 mph, a range of 497 miles, a capacity of up to 150 sitting or 300 standing passengers, and zero emissions [CityLab2016a]. It successfully completed its first test run in March 2017. It is also being considered for operation in the UK by 2021 [Wired2017a] and in Canada [Star2017a].

The Alstom Coradia iLint uses the battery to boost energy power during acceleration [Alstom2014a].

Figure 2.1: Alstom Coradia iLint component diagram

Alstom Coradia iLint diagram; copyright Alstom [Alstom2014a]

A Caltrain version by Alstom or another manufacturer might require a heavier carriage for more passengers and at higher speeds up to 110 mph, which might reduce the range. Even if the range were reduced from 497 miles to perhaps about 300 miles, that would still enable 6 San Francisco to San Jose round trips before a quick refueling stop of 5 to 15 minutes.

In addition to the iLint, between 2002 and 2015, more than a dozen instances of fuel-cell locomotives and passenger cars have been built and tested. [Wikipedia2017b] A Chinese light rail line will start using hydrogen fuel cell trams in 2018. [SmartRailWorld 2017a] A University of Birmingham study has concluded that it is practical to convert the diesel powertrain of a diesel multiple unit (DMU) to a fuel cell powertrain. [IEEE2016a] Studies supporting fuel cell technology for railroads continues to appear. [Abdelrahman2016a], [Zenith2016a].
Fuel cell automobile and bus usage is growing. Between 2002 and 2016, Chevrolet, Ford, Honda, Hyundai, Mercedes-Benz, Nissan, and Toyota have produced and leased or sold fuel-cell vehicles (FCVs), in California, Canada, Europe, Japan, South Korea, and the UAE. Fuel cell buses have been deployed in Canada, England, Germany, and the United States [Wikipedia2017a]. Fuel cells are also becoming common for forklift applications in warehouses. [Energy.gov2017a]

Fuel cell, and hydrogen generation and storage costs are reducing dramatically [Energy.gov2016a].

A commuter / interurban train such as Caltrain is an ideal application for fuel cell technology. A major obstacle for fuel cell automobiles is the lack of a widespread hydrogen fueling station infrastructure. The fixed limited-distance Caltrain route requires only 1 or 2 trackside hydrogen fueling stations.

2.1.2 Battery technology

Battery electric motor units (BEMUs) are the subject of at least one study that shows their cost-effectiveness vs. catenary systems [JES2017a].

Fuel cell EMUs also contain batteries, which are charged when the fuel cell electricity generation is otherwise idle, and to capture electric power from regenerative braking. Therefore, advances in battery technology will also benefit fuel cell EMUs.

Battery-powered rail locomotion is not new - experiments began about 1890 [Wikipedia2016d] and initial applications occurred in the 1910s [Wikipedia2016c]. Business and government organizations are exploring BEMUs and battery-powered locomotives in the 2010s, in Japan, the UK, Spain, Qatar, and Portugal [Wikipedia2016d]. Austrian Federal Railways are prototyping an electric-supercapacitor-battery locomotive: power of 200 to 800 kW, 60 mph, range 20 miles with 400 tonne load [RailwayGazette2016b].

Starting is 2013, Bombardier tested the Abellio Greater Anglia Class 379 with 6 battery rafts on a test track in Derby, UK [Thorpe2013a]. In January 2015, the battery-driven Bombardier Electrostar began service in the UK - up to 72 mph for up to 30 miles on battery power [Bombardier2015a]. BEMU development is continuing, with a prototype trainset by 2018 [RailwayGazette2016a].

In 2016 and 2017, Hitachi is supplying BEMUs for full revenue operation on the Fukuhoku Yutaka Line and Chikuhō Main Line in Fukuoka Prefecture in Japan [Wikipedia2016e].

Battery locomotives exist and are in use; for example, the Clayton Metro CB40 [Clayton2016a]. Starting in 2009, Norfolk Southern began testing a battery-powered locomotive, a conventional diesel-electric loco retrofitted by replacing the diesel engine with batteries [Brown2012a].

Research and development continues - for example, at the The Birmingham Centre for Railway Research and Education’s (BCRRE) Traction Systems Research Group in the UK [Hillmansen2015a].

Other catenary-free technologies are also being developed and applied, so far mostly for short-distance light rail applications, in locations from Nice to Birmingham, Dallas, Spain, and elsewhere. ([RailNews2015a], [RailNews2016a], [RailwayAge2015a], [SpanishRailways2011a] and many others.)

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2.1.3 Hydrogen generation technologies

Most fuel cell power plants use compressed hydrogen gas (H2) as the power storage medium. In 2017, most of the H2 in the US is produced from natural gas. [Energy.gov2017a]

For Caltrain, both hydrogen (H2) and hydrogen peroxide (H2O2) are potential likely candidates to power the fuel cell EMUs. Research and development is progressing for both, with just a few examples mentioned here. Caltrain could start with EMUs powered by H2 or H2O2 obtained from vendors, and implement the sea water on-site generation facility at a later time.

For H2 production: One research study concludes, "Hydrogen could be produced from abundant sources of sea water along with solar energy, for countries where fresh water is scarce [OpenFuelCellsJournal2010a].” The US Navy is experimenting with generating H2 from seawater [CleanTechnica2015a]. In an approach somewhat parallel to this study's suggestion of using solar power to generate H2, Norway is investigating using offshore wind energy to power H2 production through electrolysis [IJEEE2014a].

For H2O2 production: "Scientists have used sunlight to turn seawater (H2O) into hydrogen peroxide (H2O2), which can then be used in fuel cells to generate electricity.” It is much easier and safer to store and transport liquid H2O2 at high densities than gaseous hydrogen (H2) [Phys.org2016a]. Separately, a University of Glasgow team has an approach, "The new method allows larger-than-ever quantities of hydrogen to be produced at atmospheric pressure using lower power loads, typical of those generated by renewable power sources. It also solves intrinsic safety issues ...” [Phys.org2014a]

Efficient solar generation of both hydrogen (H2) and hydrogen peroxide (H2O2) has been demonstrated by research scientists. Caltrain's proximity to the San Francisco Bay provides Caltrain with the opportunity to develop a complete end-to-end system: pump seawater to a trackside generation facility, generate hydrogen, and fill the fuel cell EMUs. Solar panels and batteries to power the seawater pumps and the fueling station pumps would complete the system.

2.2 Less expensive due to much less infrastructure

A fuel cell approach eliminates the need for the overhead catenary wires, support poles, notching the existing tunnels, one electrical substation, the switching station, and the 7 paralleling stations. Costs related to removing and trimming trees, land acquisition, etc. would be reduced or eliminated. (Section 3 has detailed cost and savings estimates.) The elimination of these OCS wires and stations also eliminates the long-term maintenance costs for these items.

Also, an independently-powered approach avoids future built-in costs. If Caltrain electrifies first, then completes grade separations by raising or lowering the tracks, the OCS catenary infrastructure would also have to be raised or lowered, incurring extra costs.
2.3 Less impact to surroundings and operations

With OCS, impacts to current Caltrain operations would be considerable [Tellier2016a]. Such impacts are entirely avoided with an independently-powered solution.

With OCS, up to 1,000 trees would be removed and up to 3,200 would be pruned due to the placement of OCS poles, substations, switching stations, and paralleling stations [Caltrain2015a]. With an independently-powered approach, only trees in the vicinity of one substation and refueling / charging station might be impacted.

With OCS, up to 1.4 acres would be required for the substations, and up to 1.1 acres for placement of OSC poles [Caltrain2015a]. The independently-powered approach would require only the one substation and refueling / charging station.

A non-OCS system avoids operational complexities, such as: "„the overhead contact system, however, may have to be de-energized at some overhead bridge locations in order to operate certain freight trains over the JPB-owned right-of-way during non-passenger revenue hours." [Caltrain2004a]

2.4 Visually more attractive without overhead wires and poles

An independently-powered approach is visually more attractive, by eliminating the OCS catenary wires above the tracks. Peninsula residents’ views across the tracks, somewhat impacted by elevated tracks to achieve grade separations, would not be further impacted by tall OCS poles and wires.

For Caltrain, these contact wires would be taller than necessary for just passenger traffic, to accommodate double-stack freight requirements - up to 23.5 feet [Caltrain2004a] rather than the typical 18 feet [Jackson2010a] for just passenger traffic.

2.5 Extendable to additional routes - Gilroy, Dumbarton Corridor

An independently-powered approach enables complete electrification of Caltrain from San Francisco to Gilroy, and perhaps someday to Hollister. If and when the Dumbarton Rail Corridor is implemented, fuel cell EMUs could make use of that route with no additional infrastructure upgrades or costs.

Union Pacific owns the tracks from 2 miles south of the Tamien Station through Gilroy, preventing the construction of OCS poles [Caltrain2004a]. Such poles and any other infrastructure upgrades would not be necessary for the fuel cell EMU approach. Even without that restriction, it is unlikely that funding would soon be available for an OCS approach for either the Gilroy or Dumbarton Corridor routes. Both would remain diesel-powered for the foreseeable future.

With Caltrain taking the lead, the ACE and Capitol Corridor services could also consider changing from diesel locomotives to fuel cell locomotives or EMUs, and perhaps leverage a common fueling station at the Union City transit center.
2.6 Operable during power outages

As with the current diesel-electric locomotive fleet, fuel cell EMUs could continue to operate for some hours during a power outage. With some battery backup for the hydrogen fueling station, fuel cell EMUs could continue to operate as long as stored hydrogen fuel is available.

With on-site solar hydrogen generation from pumped-in seawater, and pumps and other equipment powered by solar panels and battery storage, a fuel cell system could operate indefinitely. In essence, Caltrain could be "off-grid".

An OCS system would be inoperable in such situations, except for any diesel-electric locomotives kept in reserve for such a situation.

2.7 Enables other independently-powered options in the future

As battery and solar options improve in the coming years and decades, one can easily imagine an entirely battery-powered EMU, or perhaps even EMUs with solar panels on the roof.

Once a catenary wire approach is implemented at great expense, there will be no future motivation to explore other approaches. The fuel cell EMU approach enables the future consideration of other independently-powered options.

2.8 Hydrogen production during low electricity demand periods

On-site production of hydrogen would occur during periods of low electricity demand, reducing the impact of hydrogen production on the electric grid, and reducing the cost of that electricity. [IEEE2016a] In contract, the heaviest electrical usage in an OCS system is during peak daytime hours.

2.9 Cost control of Caltrain fuel

Initially, hydrogen would be generated from natural gas. But as hydrogen generation technologies advance, this could be replaced by hydrogen generation from seawater.

With on-site hydrogen generation from pumped-in seawater, Caltrain would be almost entirely separate from the electric utility grid. Caltrain would be independent of changes in electricity rates.

Caltrain would be "almost entirely separate" because the hydrogen generation system and pumps should be connected to the power grid as a backup, in the case of an extended period of minimal sunlight.

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2.10 CA HSR would terminate in San Jose

With an independently-powered approach, Caltrain 2.0 would not be compatible with the currently-planned California High Speed Rail (CA HSR) OCS approach. Caltrain 2.0 would not construct the OCS wires, support poles, and other infrastructure that CA HSR requires.

The result would be that northbound passengers would disembark CA HSR in San Jose, cross the platform or go up or down a level, to transfer to a Caltrain express train to San Francisco, a Caltrain local train, BART, VTA Light Rail, VTA buses, rental cars, personal cars, or walk to their San Jose destinations. With well-designed scheduling, the time added to the Los Angeles to San Francisco HSR journey would be minimal. Many northbound passengers will disembark to another option anyway, so the number of passengers impacted might be a very small percentage of CA HSR passengers.

One source expresses this opinion: "... in an ideal world, Caltrain would be a seamless feeder service for long distance trips. A rider could buy a single ticket, get on at San Mateo or Redwood City or Palo Alto, transfer in San Jose and head on to Los Angeles." [GreenCaltrain2014a]

Separating Caltrain from HSR also avoids compatibility complexities, such as EMUs that support differing Caltrain and HSR platform heights [Caltrain2014d]. There are cogent arguments for separating Caltrain from HSR [Brown2015a], so that Caltrain can provide, service, and manage the passenger traffic between San Jose and San Francisco without the complications of integration with HSR.

There is no a priori reason that the best solution for HSR long-distance travel across mostly rural California would also be the best solution for interurban travel along the Peninsula between San Francisco and San Jose.

2.11 Impacts regarding freight traffic on the Peninsula and nearby

It is conceivable but unlikely that freight traffic will discontinue on the Peninsula. It is more probable that Union Pacific might agree to limit such traffic to "light freight", which enables options for grade separations and also reduces wear-and-tear on tracks relative to the current "heavy freight".

With either the fuel cell or OCS approach, freight traffic would initially continue with diesel-electric locomotives, still generating emissions and locomotive noise that electrification intends to eliminate.

The fuel cell approach provides an opportunity to replace diesel-electric freight locomotives with fuel cell locomotives. Fuel cell locomotives could travel anywhere Union Pacific would choose to send them. Caltrain and UP could enter into a cost-sharing agreement for the hydrogen fueling stations. Fuel cell locomotives are in development, with minimal technical risk involved. [Hydrogenics2015a]

An OCS approach would likely assure that Union Pacific would continue to use diesel-electric locomotives for freight transport. Freight locomotives cannot be restricted in their movements just to Caltrain tracks - they need to travel to freight routes connecting to Caltrain tracks, along sidings, etc. It is unlikely that UP would install OCS catenary wires along all of those various track locations.
3 Cost Comparison

3.1 Initial Capital Costs - San Francisco to San Jose / Tamien

This fuel-cell-plus-battery EMU approach replaces the OCS infrastructure and EMU catenary connectors with fuel cells and batteries on independently-powered fuel cell EMUs.

3.1.1 Caltrain OCS Approach: $2,062M for 100% coverage

As of February 2017, the remaining cost for the OCS approach is $1,833M for 16 trainsets.

Table 3.1: Caltrain Electrification OCS Initial Capital Costs with 16 Trainsets, through February 2017.

<table>
<thead>
<tr>
<th>Item</th>
<th>Notes</th>
<th>Budget $M</th>
<th>Expended $M</th>
<th>Remaining $M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead contact system (OCS)</td>
<td>Infrastructure</td>
<td>$697M</td>
<td>$56M</td>
<td>$642M</td>
</tr>
<tr>
<td>EMUs (powered passenger cars)</td>
<td>96: 16 6-car trainsets</td>
<td>$551M</td>
<td>$1M</td>
<td>$550M</td>
</tr>
<tr>
<td>Contract and Support Costs</td>
<td>33.4% of Infrastructure and EMUs budget</td>
<td>$417M</td>
<td>$90M</td>
<td>$327M</td>
</tr>
<tr>
<td>Contingency</td>
<td>25.2% of Infrastructure and EMUs budget</td>
<td>$315M</td>
<td></td>
<td>$315M</td>
</tr>
<tr>
<td>16 Trainset Totals</td>
<td></td>
<td>$1,980M</td>
<td>$147M</td>
<td>$1,833M</td>
</tr>
</tbody>
</table>

16 6-car trainsets provide service for about 75% of 114 weekday trips. [Caltrain2014e] An additional 6 trainsets would be required to cover all 100% of 114 weekday trips. The Caltrain Stadler add-on contract is $385M for 16 6-car trainsets, or $24M per trainset.

Table 3.2: Caltrain Electrification OCS Capital Costs with 6 Additional Trainsets

<table>
<thead>
<tr>
<th>Item</th>
<th>Notes</th>
<th>Budget $M</th>
<th>Expended $M</th>
<th>Remaining $M</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMUs (powered passenger cars)</td>
<td>36: 6 6-car trainsets</td>
<td>$144M</td>
<td></td>
<td>$144M</td>
</tr>
<tr>
<td>Contract and Support Costs</td>
<td>33.4% of Infrastructure and EMUs budget</td>
<td>$48M</td>
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<td>$48M</td>
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<tr>
<td>Contingency</td>
<td>25.2% of Infrastructure and EMUs budget</td>
<td>$36M</td>
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<td>$36M</td>
</tr>
<tr>
<td>Addition Totals</td>
<td></td>
<td>$229M</td>
<td></td>
<td>$229M</td>
</tr>
<tr>
<td>Overall Totals</td>
<td>Tables 3.1, 3.2</td>
<td>$2,209M</td>
<td>$147M</td>
<td>$2,062M</td>
</tr>
</tbody>
</table>
3.1.2 Fuel Cell EMU Approach: $1,275M, saving $787M

For the passenger coaches, the fuel cell EMU approach starts with the per-unit cost of the currently contracted Stadler bilevel EMUs with their included electric motors, and adds estimated amounts for the fuel cell system, onboard hydrogen storage, and batteries. This analysis report's estimation does not reflect the savings obtained by eliminating the pantograph system on the carriages.

An independently-powered approach eliminates the need for nearly all of the on-ground infrastructure to support an OCS system: overhead catenary wires and support poles, electrical substations, switching station, and paralleling stations. The fuel cell EMU approach for the San Francisco to San Jose route retains one new substation and includes one refueling / battery charging station.

This fuel cell EMU approach relies largely on the battery component for acceleration to match the acceleration profile of the OCS system, and the fuel cell component to provide the stored power to achieve the operational range.

3.1.2.1 Fuel Cells, Hydrogen Storage, Batteries on Carriages

The Alstom Coradia iLint fuel cell / battery carriage is based on the single-level Alstom Coradia Lint 54, with a per-carriage weight of 54 US tons [Wikipedia 2017c], comparable to bilevel Stadler KISS per-carriage weight of about 50 US tons [Wikipedia2017d]. For the iLint, Alstom claims a range of 497 miles, a maximum velocity of 87 mph, and acceleration and braking performance comparable to the diesel Coradia Lint [RenewablEnergyFocus2016a].

Drawing more power for the Caltrain worst case of 110 mph for the entire distance from San Francisco to San Jose should approximately reduce the feasible range from 497 miles to 393 miles (497 * 87/110). 393 miles would comfortably enable 3 round-trips of nearly 100 miles between refuelings / rechargings. 393 miles also provides sufficient extra capacity to support 6 round-trips a day to Gilroy and 6 round-trips across the Dumbarton Corridor. A slightly larger fuel cell storage capacity, or an analysis of the typical rather than worst-case scenario, should enable more round trips between refuelings / rechargings.

> Fuel Cell Power
A Stadler KISS 6-carriage trainset delivers a continuous power level of 4000 kW [Stadler2008a], or 667 kW per carriage (4000 / 6). A fuel cell system costs $59 per kW in 2016 [Energy.gov2016a]. The fuel cell system for a modified Stadler KISS carriage would cost $39,353 (667 x 59). For 132 carriages, the additional cost would total $5.2M ($39,353 x 132 = $5,194,596).

Fuel cell cost should reduce from $59 per kW to $40 per kW by 2020. By the time some Caltrain fuel cell EMUs are delivered the price per carriage should be less than the $39,353 mentioned above. [Energy.gov2016a]
> Hydrogen Storage
A Caltrain local train takes 1 hour 38 minutes travel time from San Francisco to San Jose [Caltrain2017b]. Electrification should reduce that travel time by at least 8 minutes, to 1 hour 30 minutes or less [BayAreaCouncil2012]. 3 round trips between refueling / recharging would take 9 hours, requiring 6000 kWh of hydrogen storage per carriage (9 x 667 kw, from above). Hydrogen storage costs $17 per kWh in 2016 [Energy.gov2016a]. Hydrogen storage would cost $102,000 per carriage ($17 x 6000). For 132 carriages, the additional cost would total $13.5M ($102,000 x132).

Hydrogen storage cost should reduce from $17 per kWh to $10 per kW by 2020. By the time some Caltrain fuel cell EMUs are delivered the price per carriage should be less than the $102,000 mentioned above. [Energy.gov2016a]

> Batteries
The basis for this analysis is the Tesla Model S 90D with Ludicrous Mode, which shows that the Tesla's 90 kWh battery pack is able to support motors that deliver 762 hp [MotorTrend2015a].

Tesla's price for its battery packs is stated as $190 per kWh [CleanTechnica2016a], which means that the 90 kWh battery pack should cost $17,100 ($190 x 90), plus $10,000 for the Ludicrous Mode [MotorTrend2015a], for a total of $27,100. Prices are expected to reduce over the next few years [Romm2015a], making fuel cell EMUs less expensive and more cost effective.

A Stadler KISS 6-carriage trainset delivers a maximum / burst power level of 8000 hp [Stadler2008a], or 1333 hp per carriage (8000 / 6). Two Tesla 90D Ludicrous Mode battery packs would support electric motors up to 1524 hp (2 x 762 hp), exceeding the 1333 hp performance of a KISS carriage.

Therefore, each 6-carriage trainset would need 12 battery packs (6 carriages x 2 battery packs per carriage). Two battery packs would add $54,200 to the cost of each carriage ($27,100 x 2). The additional cost for 132 carriages would be $7.2M ($54,200 x132 = $7,154,400).

> Carriage reconfiguration
The fuel cell EMU approach would require a one-time reconfiguration of the Stadler or any other bilevel coach to incorporate fuel cells, hydrogen storage, and batteries into a bilevel independently-powered passenger coach. The cost for this reconfiguration is not included in this estimate.

3.1.2.2 Fueling / Charging Station and Electrical Substation
The approach here is to have 3 fueling / charging "bays", each to fill the fuel cell and "top off" the battery charge for one 6-unit trainset within 15 minutes. 2 such bays enable fueling / charging 2 trainsets simultaneously, as well as provide backup for maintenance and in case of failure of 1 bay.

> Fueling Station
This report assumes 114 trips each weekday [Caltrain2014e], 28 on Saturday, and 24 on Sunday [Caltrain2017b], for a total 622 trips or 311 round-trips per week. Each trainset fuels and charges every 6 trips (3 round trips; see 3.1.2.1 / Hydrogen Storage above), for 104 fuelings per week. Each fueling provides 6,000 kWh, for a total of 622,000 kWh per week.

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The fueling station is sized based on the peak daily usage of 114 trips or 57 round-trips per day. Each trainset fuels and charges every 6 trips (3 round trips; see 3.1.2.1 / Hydrogen Storage above), for 19 fuelings per day (57 / 3). Each fueling provides 6,000 kWh, for a total of 114,000 kWh per day.

1 kg of hydrogen provides 33.4 kWh of electricity [EnergyIndependence2017a]. This fuel cell EMU approach requires 3,413 kg of hydrogen per day (114,000 kWh / 33.4 kWh/kg).

The capital cost for a hydrogen fueling station is $3,370 per kg per day [NREL2013a]. A fueling station for the fuel cell EMU approach would cost $11.5M (3,413 kg per day x $3,370 per kg-day).

> Charging Station
The charging estimator shows that a Supercharger for the 90D will take 75 minutes (1 hour 15 minutes) after 300 miles [Tesla2016a]. Therefore, charging for 15 minutes would provide a "top off" of a 20% charge. Charging bays would be reconfigured to connect to and charge banks of battery packs in fuel cell EMUs.

A Tesla Supercharger charging station with 5 or 6 chargers to charge 6 90D battery packs simultaneously should cost $450,000 [SeekingAlpha2015a]. Assuming 5 bays, the cost for one charger to charge one battery pack would be $90,000.

Sets of chargers would be organized into a bay to connect to and charge battery packs in one trainset of 6 fuel cell EMUs. The total complement of 22 fuel cell EMUs trainsets with 132 carriages contains 264 battery packs, 2 per carriage. One bay to charge one trainset would cost $23.8M (264 * $90,000). Two such bays would cost $47.5M.

> Electrical Substation
One substation, likely located near the San Jose Diridon Station yards, might be required to support the hydrogen fueling / charging station. Substations cost in the range of $4.3M to $24.5M in 2016 dollars [Dagle1997]. This analysis assumes the worst case $24.5M cost.

3.1.2.3 Fuel Cell EMU Approach Summary

The fuel cell EMUs costing approach does the following:

- Eliminates the catenary wires and supporting poles;
- Reduces the count of electrical substations from 2 to 1;
- Eliminates the switching and paralleling stations;
- Adds the costs of fuel cells, hydrogen storage, and batteries to the Stadler KISS costs; and
- Revises the Contract and Support Costs and Contingency, applying the same percentages to the reduced infrastructure and EMUs costs.

With a full complement of 132 EMUs or 22 6-EMU trainsets, this conservatively-estimated fuel cell EMUs approach should cost $1,275M compared with $2,062M for the currently-planned OCS approach, saving $787M and with a better implementation and operational result.
### Table 3.3: Caltrain Electrification Fuel Cell Initial Capital Costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Notes</th>
<th>Budget $M</th>
<th>Expended $M</th>
<th>Remaining $M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead contact system (OCS)</td>
<td>Electrical substations (2), Switching station (1), Paralleling Stations (7)</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Fuel Cell EMU Infrastructure Replacement</td>
<td>Fueling Station (1) $11.5M Charging Station (1) $47.5M Elect. Substation (1) $24.5M</td>
<td>$84M</td>
<td>$0M</td>
<td>$84M</td>
</tr>
<tr>
<td>EMUs (Stadler as base cost)</td>
<td>132: 22 6-car trainsets (Tables 3.1 and 3.2)</td>
<td>$695M</td>
<td>$1M</td>
<td>$694M</td>
</tr>
<tr>
<td>EMU Cells, Storage, Batteries (Additions)</td>
<td>Fuel Cells $5.2M Hydrogen Storage $13.5M Batteries $7.2M</td>
<td>$26M</td>
<td>$0M</td>
<td>$26M</td>
</tr>
<tr>
<td>Contract and Support Costs</td>
<td>33.4% of Infrastructure and EMUs budget</td>
<td>$269M</td>
<td>n/a</td>
<td>$269M</td>
</tr>
<tr>
<td>Contingency</td>
<td>25.2% of Infrastructure and EMUs budget</td>
<td>$203M</td>
<td>$0</td>
<td>$203M</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>$1276M</td>
<td>$1</td>
<td>$1275M</td>
</tr>
</tbody>
</table>

The base cost for 132 Fuel Cell EMUs is $721M ($695 + $26M). The total cost including contract and contingency comes to: $721M + (33.4% + 25.2%) x 570M = $904M; divided by 22 trainsets = $52M per trainset; divided by 132 EMUs = $8.7M per EMU.

#### 3.1.2.4 Seawater to hydrogen generation facility cost not included

The Caltrain OCS estimate of $1,833M does not include the cost of electricity generation, which would be paid for as a recurring operational expense. Both because the hydrogen production solution is not finalized, and to keep the above estimate comparable in function to the OCS system which does not include electrical generation cost, the seawater to hydrogen production facility cost is not included here.
3.2 Initial Capital Costs - Gilroy and Dumbarton Corridor

If the OCS approach for Caltrain from San Francisco to San Jose proceeds, sometime in the future would lead to the OCS approach for extending electrification to Gilroy and the Dumbarton Corridor, so that the same EMUs could operate on all routes.

The Caltrain OCS approach will electrify from San Francisco to two miles south of the San Jose / Tamien station, a total of 51 miles [Wikipedia2017f]. The cost per mile including contract and contingency comes to: $697M + (33.4% + 25.2%) x $697M = $1,105M, / by 51 miles = $21.68M/mile. (See Table 3.1.)

This analysis assumes the 22 trainsets that provide 100% electrification coverage from San Francisco to San Jose are also sufficient to support a few trains each day to Gilroy and the Dumbarton Corridor. (See Table 3.2.)

3.2.1 OCS Electrification for Gilroy and the Dumbarton Corridor: $1,021M

This section includes estimated costs for extending the OCS infrastructure to Gilroy and across the Dumbarton Corridor on a per-mile basis proportional to the initial Caltrain San Jose to Tamien section.

The budgeted cost for Caltrain San Francisco to San Jose OCS electrification is approximately $21.68M per double track mile (see section 3.1.1).

The distance from two miles south of the San Jose / Tamien station to the Gilroy station is 26.3 miles [Wikipedia2017g]. The Dumbarton Corridor route distance from Menlo Park to the Union City Transit Center is 20.5 miles. OCS electrification infrastructure cost should be estimated at 26.3 + 20.5 = 47.1 miles, x $21.68M per mile = $1,021M.

3.2.2 Fuel Cell Approach: $0M, saving $1,021M

The fuel cell approach in section 3.1.2 includes service for Gilroy and the Dumbarton Corridor.

A fueling station might be added in Union City for $84M (see section 3.1.5), for train scheduling flexibility, disaster backup for the San Jose station, and to support ACE and the Capitol Corridor.

3.3 Fuel Cell Savings, SF / SJ / Gilroy / Dumbarton: $1,808M

Full OCS electrification of Caltrain from SF to San Jose, plus Gilroy and the Dumbarton Corridor, with a complement of 22 trainsets, totals $3,083M ($2,062M + $1,021M).

Full fuel cell electrification of Caltrain from SF to San Jose, plus Gilroy and the Dumbarton Corridor, with a complement of 22 trainsets, totals $1,275M, for a savings of $1,808M ($3,083M - $1,275).

The $1,275M to fuel cell electrify all routes is $787M less than the $2,062 to OCS electrify just San Francisco to San Jose.

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3.3.1 Lifecycle Costs

This study does not (yet) address lifecycle cost comparisons between the OCS and fuel cell approaches. A few comments:

- Fuel cell infrastructure maintenance should be MUCH less than OCS infrastructure maintenance.

The fuel cell approach eliminates the frequent routine inspection and maintenance of 98 miles of OCS catenary wires and supports (for the entire route system from San Francisco to Gilroy plus the Dumbarton Corridor), as well as the maintenance of a switching station and paralleling stations, and reduces the number of electrical substations that require maintenance. It also eliminates the infrequent (every few decades) but expensive refurbishment / rehabilitation / replacement of the OCS catenary wires and supports.

- Hydrogen fuel costs are higher than electricity costs in 2017, but are expected to reduce quickly.

Hydrogen can be generated during off-peak electrical grid demand with lower electricity rates, and stored at a fueling station for later use. An OCS system will likely make use of most of its electricity during peak electrical demand periods when rates are highest.

Fuel cell usage is spreading - busses (trams), automobiles, forklift applications, and both passenger and freight railroads (see section 2.1.1). As such usage spreads, it is expected that the cost of producing hydrogen for fuel cells will quickly reduce. The cost of hydrogen production has already dropped by nearly 25% from 2011 to 2015, and is targeted to drop another 33% by 2020. [Energy.gov2016b]

New technologies are being developed which produce hydrogen more efficiently and use sources less expensive than natural gas, e.g., seawater (see section 2.1.3).

- Fuel cell EMUs might - or might not - be somewhat more expensive to maintain than OCS EMUs.

Fuel cell EMUs are somewhat more complex than OCS EMUs, because they contain the fuel cells and hydrogen storage in place of the overhead contact system. Therefore, maintenance might be more expensive. However, maintenance on either should be much less than for a diesel engine with its many moving parts. Useful data on fuel cell EMU maintenance costs should be available soon, as fuel cell EMUs, light rail vehicles, and trams become operational in Germany, China, and likely other countries in 2018 and 2019.
4 References

[Abdelrahman2016a]

[Alstom2014a]
Coradia iLint - A full emission-free train (product sheet, 2014)
Emission-free; battery boosts acceleration.

[Amtrak2012a]
Amtrak, SPECIFICATION for PRIIA Bi-Level Passenger Rail Car - PRIIA SPECIFICATION No. 305-001 - AMTRAK SPECIFICATION No. 962 - Revision C.1 (September 20, 2012)
Section 1.4.3.1: Each passenger car dry weight limitation: approximately 75 tons (150,000 to 153,000 lbs.)

[Amtrak2013a]
News release regarding Amtrak purchase of Siemens ACS-64 electric locomotives (2013)
70 locomotives for $466M = $6.7M per locomotive.

[BayRailAlliance2013a]
Why not use ground-level third rail? (2013)
http://www.bayrailalliance.org/question/why-not-use-ground-level-third-rail

[BayAreaCouncil2012a]
Bay Area Council Economic Institute, The Economic Impact of Caltrain Modernization (2012)
http://documents.bayareacouncil.org/caltrainecon.pdf
Assumes travel time will be reduced by between 5 and 10 minutes along the full route.

[Bombardier2015a]
Battery-Driven Bombardier Electrostar - Electrical multiple unit (2015)
http://www.bombardier.com/content/dam/Websites/bombardiercom/Projects/supporting-documents/BT_Battery-Driven-Bombardier-Electrostar_LowRes.pdf
Describes the battery EMU that started in service in January 2015; up to 72 mph for up to 30 miles.

[Brown2012a]
Brown, Alan S. - Battery Powered Locomotive Does the Job, but Quietly - Penn State News (2012)
http://news.psu.edu/story/141937/2012/01/25/research/battery-powered-locomotive-does-job-quietly
Describes the Norfolk Southern retrofitted battery-powered locomotive test.

[Brown2015a]
Brown, Morris - Caltrain should back away from HSR - Palo Alto Online (2015)

© Mike Forster 2017

[Caltrain2004a]

[Caltrain2012a]
Caltrain, Caltrain / California HSR Blended Operations Analysis, prepared for: Peninsula Corridor Joint Powers Board (JPB); Prepared by: LTK Engineering Services (March 2012)

[Caltrain2014a]
Caltrain, PCEP FAQs (Spring 2014)
http://www.caltrain.com/Assets/Caltrain+Modernization+Program/Documents/PCEP+FAQ.pdf

[Caltrain2014b]
Caltrain, PCEP FAQs (December 2014)

[Caltrain2014c]
Cost estimates, 2014.

[Caltrain2014d]
Caltrain, EMU RFI (2014)
http://www.tillier.net/stuff/caltrain/EMU_RFI.pdf
EMU specifications.

[Caltrain2014e]
Caltrain, PCEP Chapter 2 - Project Description (2014)
http://www.caltrain.com/Assets/Caltrain+Modernization+Program/DEIR/Chapter+2+Project+Description.pdf
2019: 114 (weekday) train trips per day, 75% electrified. 83 million kWh of electricity per year.

[Caltrain2015a]
http://www.caltrain.com/projectsplans/CaltrainModernization/Modernization/PeninsulaCorridorElectrificationProject/PCEP_FEIR_2014.html
Impact on trees, land acquisition, etc.

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Current locomotives are 3200 and 3600 hp.

One-way local service from San Francisco to San Jose takes 1 hour 38 minutes.

Tesla battery pack pricing at $190 / kWh.
Caltrain 2.0 - Hydrogen Fuel Cell EMUs - Mike Forster - v3.2

[DieselShop2008a]
Jean-Denis Bachand, EMD 59PHI (2008)
https://www.thedieselshop.us/Data%20EMD%20F59PHI.HTML
Locomotive weight: 132.5 tons (265,000 lbs). Used on the Capitol Corridor.

[Druce2015a]
Paul Druce, Reason & Rail, A cost to benefit analysis of railroad electrification (2015)
Electrified train: 22kWh / $2.42 per train-mile for the British IC225 with a capacity of 535 passengers.

[Eaves2003a]
http://www.metricmind.com/data/bevs_vs_fcvs.pdf

[Energy.gov2016a]

[Energy.gov2016b]
Figure 1: Cost of Delivering and Dispensing Hydrogen from Central Production: approximately $4 per gge in 2011, $3 in 2015, $2 in 2020. (gge = gallon of gas equivalent.)

[Energy.gov2017a]
Mike Mueller, 5 Common Fuel Cell Myths (2017)
https://energy.gov/eere/articles/5-common-fuel-cell-myths
Hydrogen is not difficult and expensive to produce, fuel cells are not expensive, and hydrogen is safe.

[EnergyIndependence2017a]
1 kg of hydrogen provides 33.4 kWh of electricity.

[GoTransit2001a]
Electrification Study - Update - Lakeshore Line, by Hatch Mott MacDonald, for Go Transit (April 2001)
Drawbacks of electrified operation include: [vehicles] confined to electrified areas; maintenance of OCS; train immobilization due to OCS damage - or hydro failure; reduced mobility for on-track cranes; visual intrusion of OCS [page 4-2].

[GreenCaltrain2014a]
GreenCaltrain / alevin - High Speed Rail super-express from San Francisco to San Jose? (2014)

© Mike Forster 2017
Hanley, Steve - Tesla Model S 90D Now Gets 302-Mile Range From EPA - Clean Technica (2016)
Tesla Model S 90D EPA range of 302 miles.

http://www.birmingham.ac.uk/university/colleges/eps/news/college/2015/01/Are-low-carbon-battery-powered-trains-the-future-.aspx

https://www.arb.ca.gov/gmp/sfti/sfpp/sfpp-042b.pdf


http://link.springer.com/article/10.1007/s40095-014-0104-6

US Inflation Calculator
http://www.usinflationcalculator.com/

https://hydrail.appstate.edu/sites/hydrail.appstate.edu/files/11_isaac-2.pdf

Raphael Isaac et al, University of California, Davis: Rail Technologies: A California Cross-fuel Comparison, and Discussion of Hydrogen’s Potential Advantages (Hydrail 2015 conference)
https://hydrail.appstate.edu/files/10_Isaac.pdf

[Jackson2010a]
Jackson, Russ; High Speed and Commuter Rail Electrification: Is Catenary Height an Issue? (2010)

[JES2017a]
Joachim Mwambeleko et al, Battery electric multiple units to replace diesel commuter trains serving short and idle routes - Journal of Energy Storage (2017)

[MotorTrend2015a]
Christian Seabaugh / Words, Robert Guio / Photos, Brian Brantley / Photos, 2015 Tesla Model S P90D w/Ludicrous Upgrade First Test Review (2015)
Model S P90D Ludicrous Mode: 762hp, drawing 1500 amps from the 90kWH battery pack; adds $10,000 to the cost.

[NECFuture2015a]
http://www.necfuture.com/pdfs/tier1_deis/appendix/app_b09.pdf
O&M Costs - Shared Infrastructure Costs - Electric Propulsion - Total NEC: $80,900,000 annually.

[NECFuture2017a]
http://www.necfuture.com/about/facts.aspx
"The NEC is 457 miles long ..."

[Noland2015a]
Telsa P85 battery pack replacement price: $44,000.

[NREL2013a]
M. Melania, M. Penev, Hydrogen Station Cost Estimates (2013)
Table 3: Capital cost per capacity: $3,370 per kb/day for larger stations.

[OpenFuelCellsJournal2010a]
http://www.intpowertechcorp.com/H2_Seawater_1TOFCJ.pdf


[PlanetForward201]

http://www.globalrailnews.com/2015/10/15/catenary-free-trams-for-nice/
Battery-powered, with a ground-based charging system which will charge a tram at a stop in under 20 seconds.

http://www.globalrailnews.com/2016/02/12/approval-for-catenary-free-trams-in-birmingham/
Battery-powered light rail.

[RailwayAge2015a] First-of-its kind streetcar arrives in Dallas (2015)
Combination catenary and battery-powered light rail.

[RailwayAge2016a] First Charger rolls off the line
4,400 hp, 125 mph

[RailwayGazette2016a] Battery EMU development funded
Prototype trainset by 2018.

[RailwayGazette2016b] ÖBB unveils prototype electric-supercapacitor-battery loco

© Mike Forster 2017
Alstom unveils Coradia iLint hydrogen fuel cell powered regional train in Germany

Includes comments on the retirement of the existing Caltrain locomotives and passenger cars to the 2030s.

Includes a chart showing decreasing price trend for lithium-ion batteries.

Catenary maintenance, euros/km/year: min 1500, mean 8800, max 41000 in 2007-2009 [Table 5].

Cost estimates, 2000; information regarding noise.
[SoundTransit2015a]  
Sound Transit, O&M Costs - ST3 Expert Review Panel (November 2015)  
http://www.wsdot.wa.gov/partners/erp/background/O&M_costs.pdf  
Light Rail - Track O&M: Annual Cost: Catenary & TPSS: $24,977 average catenary cost per mile.

[SpanishRailways2011a]  
CAF’S ACR for catenary-free trams (2011)  
http://www.spanishrailwaysnews.com/noticias.asp?not=30  
Capacitor-based technology to eliminate catenary cables between stops.

[SPUR2016a]  
SPUR, The Caltrain Corridor Vision Plan - Appendix A - Rail: Existing Conditions and Vision Plan Methodology  
https://www.spur.org/sites/default/files/publications_pdfs/Appendix_A_Existing_Conditions_and_Methodology.pdf

[Stadler2008a]  
Electric Double-Deck train KISS (6-car train)  
https://www.wswstadsqrrailcom-live-01e96f7.s3-eu-central-1.amazonaws.com/filer_public/6c/6c632f3-af7e-43b5-811e-91e9b32ae6cb/kiss_dosbb20908e.pdf  
6-unit train weight has 297 European tonnes (326 US tons or 54 tons per carriage), 6000 kw / 4000 kW (8,000 hp maximum / 5400 hp continuous or 1333 hp maximum / 900 hp continuous per carriage), and 400kN tractive power up to 54 kmh / 32 mph.

[Star2017a]  
Tyler Hamilton, Ontario technology can fuel emission-free GO trains (June 23, 2017)  

[Strasser2014a]  
Strasser, Annie-Rose, Why The Government Just Threw Down $225 Million On Hybrid Electric Trains - Climate Progress, 2014  
http://thinkprogress.org/climate/2014/04/07/3422342/hybrid-diesel-electric-trains/

[Tesla2016a]  
Tesla Model S specifications (2016)  
https://www.teslamotors.com/models  
Model S 90D - 417 hp, 302 mile range, 75 minutes charge time.

[TeslaMotorsClub2014a]  
Infrastructure Cost, Tesla Superchargers Station Cost? (2014)  
https://teslamotorsclub.com/tmc/threads/infrastructure-cost-tesla-superchargers-station-cost.39129/  
Quotes Elon Musk as stating a supercharger station (with 6 bays) costs $150,000 (deonb, 12/9/14).
Possibly the World's First Battery-powered Train Is Undergoing Trials (2013)
http://www.sustainablecitiescollective.com/david-thorpe/321986/possibly-worlds-first-battery-powered-train-undergoing-trials
Description of upcoming (2013) trials of Bombardier BEMU.

Clem Tillier, Peninsula Rail Traffic: 2030, (14 February 2009)
In 2030, "That's a total of roughly 220 trains per weekday or 1300 trains per week."

Special Provision SP01040 (2016)
http://caltrain-hsr.blogspot.com/2016/01/special-provision-sp01040.html
An excellent analysis of the impacts to Caltrain operations during the installation of OCS electrification.

Turpen, Aaron - Pike Says 500 Hybrid Locomotives by 2020 - Big Green Truck (2011)

List of Peninsula Commute Locomotives (2016)

Siemens ACS-64 (2016)
https://en.wikipedia.org/wiki/Siemens_ACS-64

Electric locomotive (2016)
https://en.wikipedia.org/wiki/Electric_locomotive#Battery_locomotive
History of electric locomotives, including battery-powered; earliest battery-powered reference: 1917.

Battery electric multiple unit (2016)
https://en.wikipedia.org/wiki/Battery_electric_multiple_unit
History and current status of battery EMUs (aka BEMU).

BEC819 Series
Battery-powered EMUs in Japan in 2016 and 2017.

Fuel Cell Vehicle

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Hydrail (generic term for all forms of rail vehicles that used on-board hydrogen as an energy source)  
https://en.wikipedia.org/wiki/Hydrail

Alstom Coradia Lint 54 (Germany Wikipedia, Google-translated to English)  
Two-carriage trainset has an unladen mass (weight) of European 98 t (tonne), equal to US 108 (short) tons, or 54 US (short) tons per carriage.

Stadler KISS  
https://en.wikipedia.org/wiki/Stadler_KISS  
6-unit train weight has 326 US tons or 54 tons per carriage, and 8,000 hp maximum / 5,400 hp continuous or 1,333 hp maximum / 900 hp continuous per carriage.

"Calmod will electrify 51 miles ..."  

Distance from two miles south of San Jose / Tamien to Gilroy: 26.3 miles.

Length of rail route: 20.5 miles.

Matt Burgess, World's first hydrogen-powered passenger train takes to the tracks in Germany (2017)  
http://www.wired.co.uk/article/hydrogen-train-alstom-testing

Hydrogen fuel cells are a viable and cost-effective alternative to a catenary approach, for this northern rail line.