21st Century Rail Propulsion: Examining Costs and Emissions across Motive Power Technologies

Part I: Simulating Fuel Consumption

Raphael Isaac (with assistance from A. Hoffrichter (MSU), P. Erickson, and L. Fulton)

Institute of Transportation Studies, University of California, Davis – December 7, 2017

RESEARCH QUESTION

Passenger rail has been on the upswing (APTA/Amtrak). As this mode of travel continues to thrive, reducing emissions from rail will depend largely on fuel technologies (as with automobiles) This research, which will eventually also incorporate freight rail, is utilizing a simulation tool (known as a 'Single Train Simulator') to estimate fuel consumption from a variety of powertrains, including a "benchmark" diesel, a hydrogen fuel cell, and each of these hybridized via batteries (so as to fully take advantage of regenerative braking).

FUELS BACKGROUND

Diesel-Electric: Currently powers approximately 87% of all domestic rail service (US DOE, 2013), >99% of freight rail operations.

Hydrogen/Fuel Cell - Fuel cells produce zero pollutant or GHG emissions at the "tail pipe," and are more efficient than ICEs. This reduces the fuel requirement and, potentially, the cost, though hydrogen, where available, is currently rather expensive.

- HDV applications of fuel cells have been demonstrated in U.S. bus systems. In Europe, Alstom has partnered with Hydrogenics, and plans to have 40 passenger trains operating on compressed H2 in Germany by 2020.
- With a large enough distribution demand, H2 movement by dedicated pipeline is likely optimal (UC Davis, 2014); a pipeline could serve both rail facilities and other sources of demand, e.g. buses and trucks.
- Even in liquid form, hydrogen's per gallon energy density is much lower than diesel fuel. Fuel cell stack lifetime is another area of concern; however, one AC Transit (SF Bay Area) bus has a stack in operation that has required no major overhauls despite nearly 21,000 hours of operation.
- Emissions from hydrogen could vary tremendously depending on the source of the hydrogen (e.g. natural gas reformation predominating vs. a reliance on various renewable methods).

Hybridization - A hybrid vehicle has a primary power source and an on-board energy storage device.

- Primary power source/power-plant: E.g. Combustion engine (diesel) combined with electric generator, Fuel cell
- Storage device: E.g. Batteries, Flywheels, Supercapacitors

Benefits:
Capture regenerative braking energy
Operate prime mover (especially an engine) in its optimal zone(s)
Opportunity to downsize the prime mover

SIMULATION APPROACH

This research relies on the combined framework of a MATLAB®-based tool for the development of train trajectories with a MATLAB®/Simulink®-based tool that allows for s detailed analysis of the energy flows throughout the train's drive system, resulting in a "bottom-up" (i.e. beginning with the wheels) assessment of power/energy requirements and fuel consumption.

The MATLAB®-based Single Train Simulator (STS), developed by the University of Birmingham (UK), uses a combined forward/backward distance-based technique for the production of parameterized speed profiles for user-defined route and vehicle characteristics. It uses train kinematics and Euler's method to develop duty cycles, taking into consideration speed, acceleration and power limitations. (The "STS" has been utilized in several studies in Europe for the development of trajectories over specific routes and calculation of power and energy requirements at the wheel.)

Kinematic equation: $$m(1+\lambda)\frac{d^2s}{dt^2} = TE - \left[mg\sin(\alpha) + C\left(\frac{ds}{dt}\right)^2 + B\left(\frac{ds}{dt}\right) + A\right]$$

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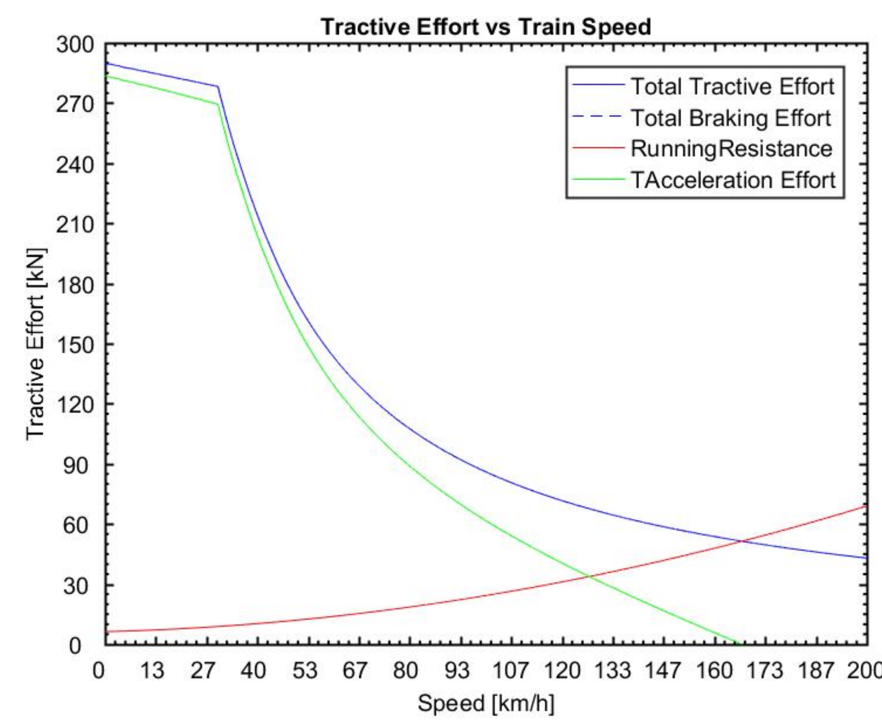
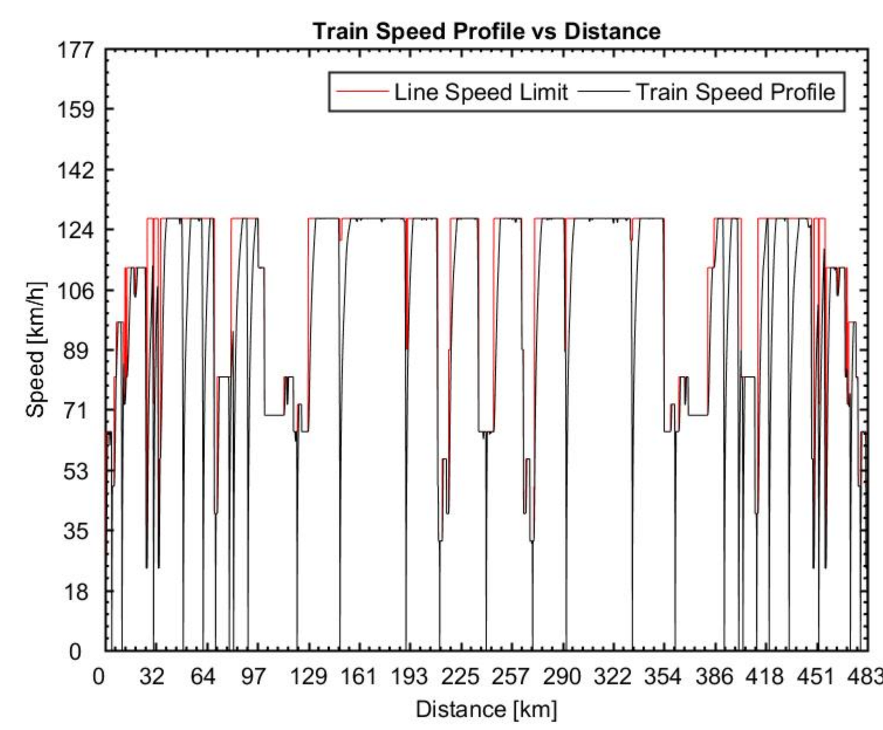
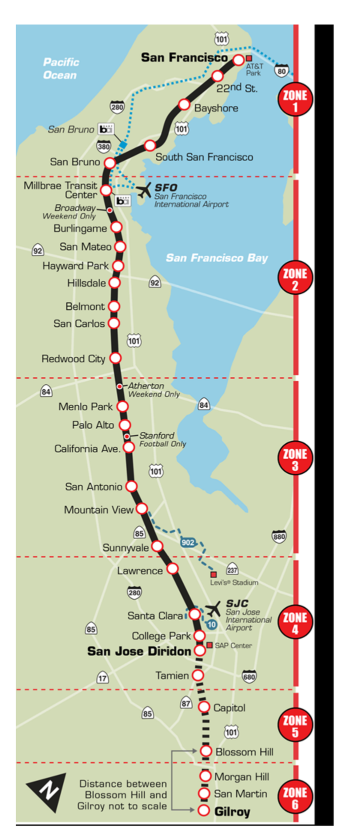


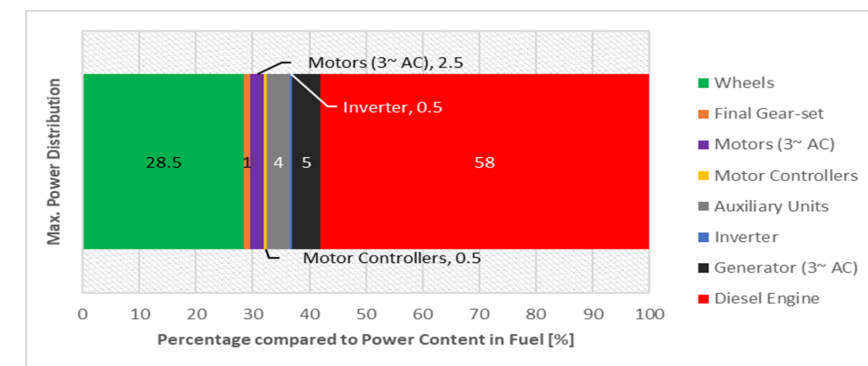


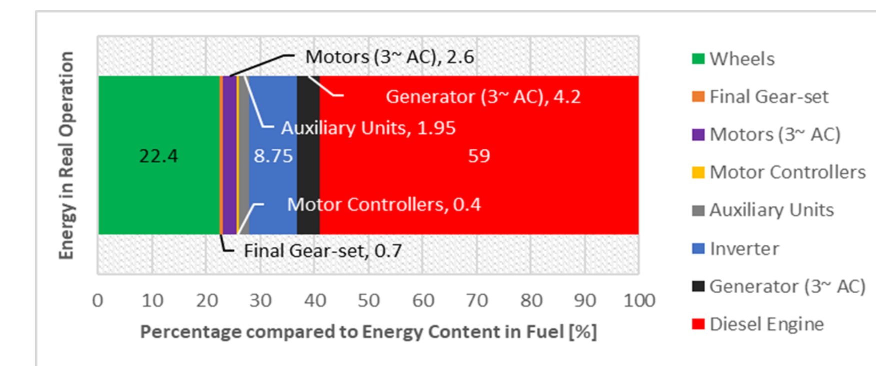
PASSENGER ROUTES/CHARACTERISTICS



Locomotive Characteristics:
→Maximum Speed: 125 mph
→Rated Voltage: 1080 V @ 50 Hz
→Rated Power (Max): 4,400 hp @ 1,800 rpm
→Operating Range: 600 to 1,800 rpm
→Head End Power: 350 kW
→Tractive Effort (Max): 65,000 lbs / 290 kN

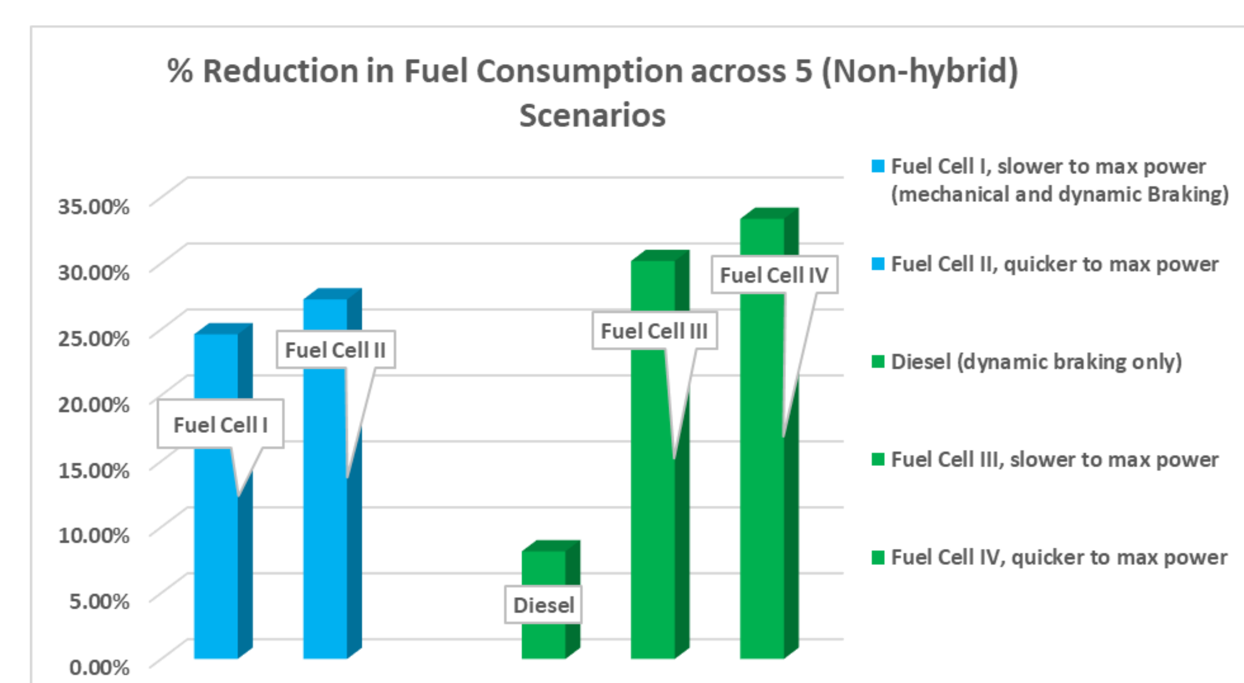
EARLY STAGE CAPITOL CORRIDOR SIMULATION CHARTS





Powertrain	Braking Scenario	Journey time (round trip)	Max. Power (per traction motor)[a]	Min. Power (per traction motor)	Total Energy Requirement (per traction motor)	Total Energy Return (per traction motor)	Maximum Hybridization Potential	Total Fuel Consumption (constant auxiliary power demand of 350 kW)	Energy Consumption Reduction compared to case DE 1
DE Only (DE 1)[b]	Maximum Braking (Partially Dynamic)	377.17 minutes	679.4 kW	-582.5 kW	5908 MJ	500.9 MJ	8.48%	90,756.8 MJ (3.3 MW)	0% (Benchmark case)
FC Only (FC 1)[c]	Maximum Braking (Partially Dynamic)	386 minutes	661.6 kW	-582.4 kW	5831 MJ	493.7 MJ	5.941%	68,420.97 MJ (3.3 MW)	24.61%
FC Only (FC 2)[b]	Maximum Braking (Partially Dynamic)	377.17 minutes	679.4 kW	-582.5 kW	5908 MJ	500.9 MJ	8.48%	66,018.97 MJ (3.3 MW)	27.257%

Powertrain	Braking Scenario	Journey time (round trip)	Max. Power (per traction motor)[a]	Min. Power (per traction motor)	Total Energy Requirement (per traction motor)	Total Energy Return (per traction motor)	Maximum Hybridization Potential	Total Fuel Consumption (constant auxiliary power demand of 350 kW)	Energy Consumption Reduction compared to case DE 1
DE Only (DE 2)[b]	Fully Dynamic	402.38 minutes	679.4 kW	-582.5 kW	5361 MJ	1710 MJ	31.9%	83,352.5 MJ (3.3 MW)	8.158%
FC Only (FC 3)[c]	Fully Dynamic	411 minutes	661.6 kW	-582.4 kW	5300 MJ	1695 MJ	31.98%	63,376.77 MJ (3.3 MW)	30.169%
FC Only (FC 4)[b]	Fully Dynamic	402.38 minutes	679.4 kW	-582.5 kW	5361 MJ	1710 MJ	31.9%	60,470.35 MJ (3.3 MW)	33.37%



RESEARCH NEXT STEPS

- Examine Caltrain, one switcher route, and two U.S. mainline freight routes
- Examine costs of different scenarios
- Analyze lifecycle CO_2 and pollutant impacts

Contact Info for Primary Author:
Raphael Isaac (*risaac@ucdavis.edu*)