SINTEF

Techno-economic Analysis of Alternative Rail Electrification Technologies

Application to the Nordland Line

Federico Zenith

22 October, 2019
MoZEES workshop on heavy-duty transport solutions
Oslo, Norway

Outline

Motivation and Context

Alternative Technologies' Cost Structure

Particular and General Results

Outline

Motivation and Context

Alternative Technologies' Cost Structure

Particular and General Results

Motivation

- Most railways worldwide are not electrified
- Diesel is less and less acceptable
- Electric *operation* is cheaper
- Electric *infrastructure* is expensive
- Variable degree of electrification
  - Switzerland 99 %
  - Norway 64 %
  - Europe 62 %
  - World 25 %
  - North America 1 %

SINTEF

SINTEF Report on Alternative Rail Electrification

Second edition

- On behalf of the Norwegian Railway Directorate
- Report unfortunately in Norwegian only
- Just released (October 2019; previous edition 2015)
- Updated parameters to latest estimates
- Wider spectrum of authors
- Stronger sections on biofuels and batteries
- Added partial catenary electrification
- Safety aspects for gaseous fuels in tunnels

SINTEF

2019:00997 - Åpen

Rapport

Analyse av alternative driftsformer for ikke-elektrifiserte baner

2. utgave

Forfatter(e)

Federico Zenith, Steffen Møller-Holst, Magnus S. Thomassen, Thor Myklebust, Julian R. Tolchard, Jon Hovland, Tonje W. Thomassen, Bernd Wittgens, Joakim Bustad, Andreas D. Landmark, Roman Tschentscher, Olav R. Hansen (Lloyd's Register)

Comparison Criteria for Alternatives

- Different lifetimes for technologies
  - Catenary, 75 years
  - Batteries, *x*-000 cycles
  - …
- Difficult to employ Net Present Value
- **Equivalent Annual Cost** (EAC)
  - “Spread” CAPEX over years (ACAPEX)
  - Sum with OPEX
  - Lose sight of investment duration
- **Benefit-Cost Ratio** (BCR)
  - Referred to diesel: EAC_{diesel}/EAC_i
  - >1 is a good investment
- **Pay-Back Period** (PBP)
  - Re-introduces time scale
  - Can be undefined
  - Gives “partial” answers
- **Up-Front Investment** (UFI)
  - Important for decision making
- Non-economic criteria:
  - Environmental requirements
  - Availability of technology
  - Availability of regulations
  - Flexibility and robustness

Outline

Reference Train: Freight on Nordland Line

- Diesel-driven freight train, 1000 t
- Locomotive Vossloh Euro 4000, 3.2 MW
- 731 km, single track
- Passing loops 600 m (length limit)
- Over 150 tunnels for 50 km
- Passes Arctic Circle at Saltfjellet
- Energy consumption 23.3 kWh/km

Traditional Technologies

Combustion technologies

- Major cost items:
  - Diesel: 2.50 NOK/kWh
  - Locomotive maintenance: 33 NOK/km
  - Emission taxes: 17 NOK/km

  Total: **4.65 NOK/kWh**
- Add 0.43 NOK/kWh for biodiesel
- Add 1.42 NOK/kWh for biogas
- No infrastructure costs
- Cost proportional to traffic

Traditional Technologies

Combustion technologies

- Major cost items:
  - Diesel: 2.50 NOK/kWh
  - Locomotive maintenance: 33 NOK/km
  - Emission taxes: 17 NOK/km

  Total: **4.65 NOK/kWh**
- Add 0.43 NOK/kWh for biodiesel
- Add 1.42 NOK/kWh for biogas
- No infrastructure costs
- Cost proportional to traffic

Electrification by Catenary

- Infrastructure costs:
  - ACAPEX: 591 NOK/m
  - OPEX: 50 NOK/m
- Energy costs:
  - Electricity: 0.53 NOK/kWh
  - Locomotive maintenance: 11.5 NOK/km
- Total: **1.02 NOK/kWh + 641 NOK/m**
- Traffic and infrastructure costs

Storing Electricity On-board

- Concept: batteries, fuel cells, hydrogen tanks on own wagon
  - 58 t capacity on a standard Sgnss platform
- Wagon delivers power to normal electric locomotive
- Reduced cargo load is usually a minor cost, compensated with more train movements
- Concept also suggested by Austrian ÖBB (RailCargo) for freight

SINTEF

New Technologies: Batteries and Hydrogen

All-battery train

- Same energy cost as catenary
- Batteries: 2.1 NOK/kWh (2020)
  - Very uncertain number, can fall
  - 0.88 NOK/kWh (2030)
  - 0.69 NOK/kWh (2050)
- Total: **3.12 NOK/kWh**
- Same structure as diesel, but cheaper
- Caveat: assuming few battery wagons

New Technologies: Batteries and Hydrogen

All-battery train

- Same energy cost as catenary
- Batteries: 2.1 NOK/kWh (2020)
  - Very uncertain number, can fall
  - 0.88 NOK/kWh (2030)
  - 0.69 NOK/kWh (2050)
- Total: **3.12 NOK/kWh**
- Same structure as diesel, but cheaper
- Caveat: assuming few battery wagons

Hydrogen train (CH_2 from electrolysis)

- Different energy cost: 1.21 NOK/kWh (power tariff, efficiency)
- Fuel cells: 0.40 NOK/kWh
- Tanks: 0.07 NOK/kWh
- Electrolysers: 0.51 NOK/kWh
- Compressors: 0.15 NOK/kWh
- Total: **2.83 NOK/kWh**

New Technologies: Hybrids and Fast Chargers

Hydrogen-battery hybrid

- Fuel cells downsized to average power
- Extra batteries handle dynamics
- Same tanks and refuelling infrastructure
- Fuel cells 0.13 NOK/kWh
- Batteries 0.75 NOK/kWh
- Total: **3.31 NOK/kWh**

Smaller battery with fast charging stop

- Batteries: 1.94 NOK/kWh
- Charging station: 834 NOK/kW
- Total: **2.96 NOK/kWh + 834 NOK/kW**
  - With Nordland line traffic 3.3 NOK/kWh
- Can be advantageous with too many battery wagons

Partial Electrification

Catenary-Battery Hybrid

- Sections of catenary (total ⅓ of track)
- Select best areas, e.g. avoid tunnels
- Other sections covered by batteries
- Batteries recharge under catenary
- Catenary cost estimate by Railway Directorate: 11.2 MNOK/km

Cost breakdown

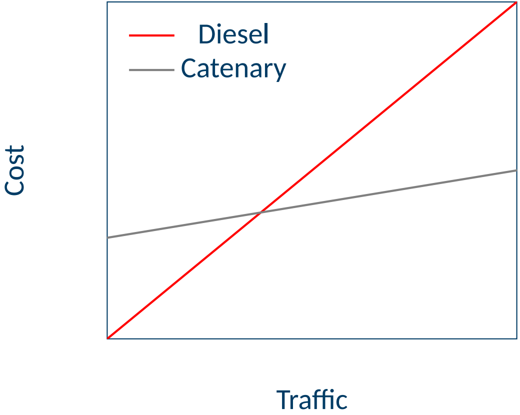
- Batteries: 1.2 NOK/kWh
- Catenary: 158 NOK/m
- Total: **2.22 NOK/kWh + 174 NOK/m**

Outline

SINTEF

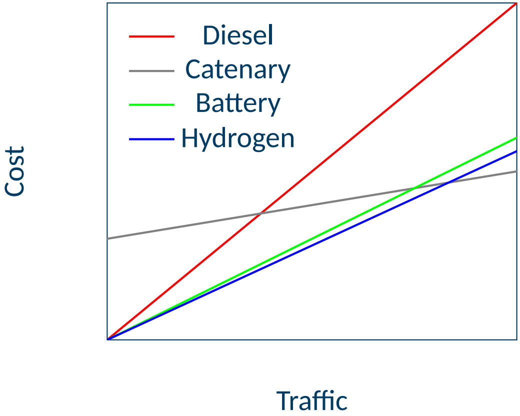
Competitiveness of Different Technologies

- Cost structures for diesel and catenary:
  - Diesel proportional to energy
  - Catenary to energy *and line length*
- Break-even energy-length ratio:
  - $E/L > 176\,\text{kWh}/\text{m} \Rightarrow$ catenary
  - $E/L < 176\,\text{kWh}/\text{m} \Rightarrow$ diesel
  - E.g.: Nordland line is 28 kWh/m



Competitiveness of Different Technologies

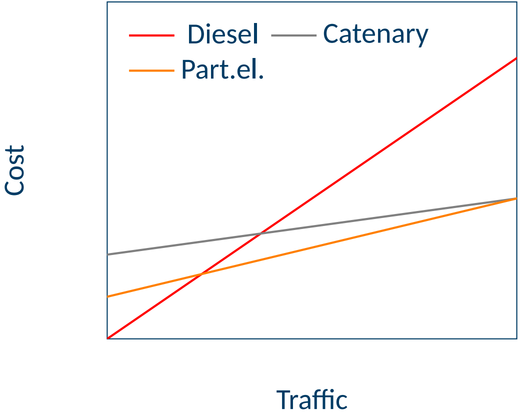
- Cost structures for diesel and catenary:
  - Diesel proportional to energy
  - Catenary to energy *and line length*
- Break-even energy-length ratio:
  - $E/L > 176\,\mathrm{kWh/m} \Rightarrow$ catenary
  - $E/L < 176\,\mathrm{kWh/m} \Rightarrow$ diesel
  - E.g.: Nordland line is 28 kWh/m
- Hydrogen & battery:
  - Cost structure like diesel but cheaper
  - $E/L > 354\,\mathrm{kWh/m} \Rightarrow$ catenary
  - $E/L < 354\,\mathrm{kWh/m} \Rightarrow$ hydrogen



Competitiveness of Different Technologies

Hydrogen and Batteries

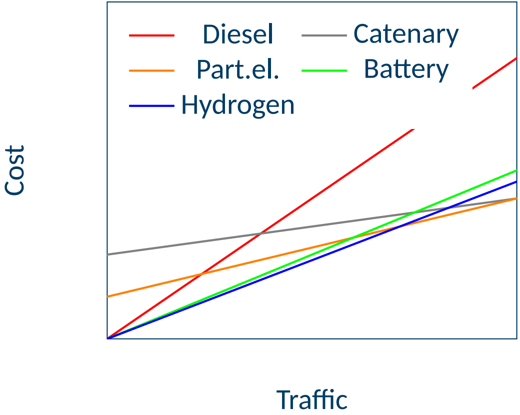
- Partial electrification break-evens:
  - $E/L < 389\,\mathrm{kWh/m}$ against catenary
  - $E/L > 72\,\mathrm{kWh/m}$ against diesel
  - Niche between diesel and catenary



Competitiveness of Different Technologies

Hydrogen and Batteries

- Partial electrification break-evens:
  - $E/L < 389\,\text{kWh}/\text{m}$ against catenary
  - $E/L > 72\,\text{kWh}/\text{m}$ against diesel
  - Niche between diesel and catenary
- New technologies change thresholds:
  - $E/L > 276\,\text{kWh}/\text{m}$ against hydrogen
  - Significantly shrunk niche between hydrogen and catenary
  - Niche starts at $10\times$ actual traffic



Economic Indicators for Nordland Line

Technology	BCR —	PBP years	UFI MNOK
Catenary	0.22	—	9900
Biodiesel	0.93	—	0
Biogas	0.79	—	180
Battery	1.33	3.5	400
Hydrogen	1.41	3.3	326
Battery+H_2	1.38	6.1	452
Fast charging	1.23	2.3	312
Partial electrification	0.66	—	2750

Note:

- On previous slides: only major cost components
- Here: report results
- Some inconsistencies due to different detail

Economic Indicators for Nordland Line

Technology	BCR —	PBP years	UFI MNOK
Catenary	0.22	—	9900
Biodiesel	0.93	—	0
Biogas	0.79	—	180
Battery	1.33	3.5	400
Hydrogen	1.41	3.3	326
Battery+H_2	1.38	6.1	452
Fast charging	1.23	2.3	312
Partial electrification	0.66	—	2750

Note:

- On previous slides: only major cost components
- Here: report results
- Some inconsistencies due to different detail

Economic Indicators for Nordland Line

Technology	BCR —	PBP years	UFI MNOK
Catenary	0.22	—	9900
Biodiesel	0.93	—	0
Biogas	0.79	—	180
Battery	1.33	3.5	400
Hydrogen	1.41	3.3	326
Battery+H_2	1.38	6.1	452
Fast charging	1.23	2.3	312
Partial electrification	0.66	—	2750

Note:

- On previous slides: only major cost components
- Here: report results
- Some inconsistencies due to different detail

Economic Indicators for Nordland Line

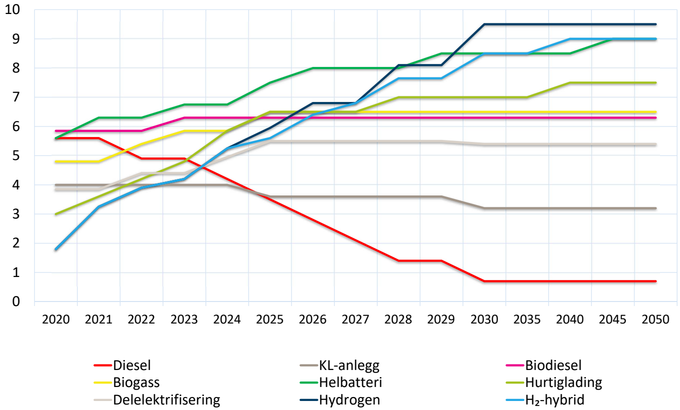
Technology	BCR —	PBP years	UFI MNOK
Catenary	0.22	—	9900
Biodiesel	0.93	—	0
Biogas	0.79	—	180
Battery	1.33	3.5	400
Hydrogen	1.41	3.3	326
Battery+H_2	1.38	6.1	452
Fast charging	1.23	2.3	312
Partial electrification	0.66	—	2750

Note:

- On previous slides: only major cost components
- Here: report results
- Some inconsistencies due to different detail

Actuality Evolution towards 2030

- Diesel environmentally unacceptable in 2030
- New technologies to market by 2025
- Hydrogen fully regulated by 2030



SINTEF

Upfront Costs for Test Project on Nordland Line

- Lock-in effect for catenary and partial electrification
  - Need large & expensive infrastructure
  - Several years of construction
  - Once built, cannot change course
- Biofuels, battery & hydrogen can run one single test train

Technology	UFI / MNOK
Biodiesel	0
Hydrogen	81
Battery	100
Hydrogen-battery hybrid	113
Fast charging	114
Partial electrification	2640
Catenary	9800

Conclusions

- Battery and hydrogen have similar performance—both better than diesel
- Partial electrification would have a niche between diesel and catenary…
- … but it becomes much smaller when battery and hydrogen are an option
- Partial electrification still relevant with pre-existing catenaries
- Pilot projects with one train are possible with battery and hydrogen technologies
- For the Nordland line, the best technologies appear to be biodiesel today, battery soon, and hydrogen from the late 2020's.

Conclusions

- Battery and hydrogen have similar performance—both better than diesel
- Partial electrification would have a niche between diesel and catenary…
- … but it becomes much smaller when battery and hydrogen are an option
- Partial electrification still relevant with pre-existing catenaries
- Pilot projects with one train are possible with battery and hydrogen technologies
- For the Nordland line, the best technologies appear to be biodiesel today, battery soon, and hydrogen from the late 2020's.

Thank you for your attention!

SINTEF

Technology for a better society