Electric Rail – An Overview

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Arizona's Black Mesa & Lake Powell Railroad, which ran coal trains 73 miles on the Najavo Nation (Kayenta mine to Navajo Generating Station near Page) with electric GE E60 50 kV 6,000 hp locomotives, from 1973 to 2019


3853
3853

Rail Electrification

- Zero emissions at point of use
- Quieter than diesel locomotives
- Lower “fuel” (energy) cost, can be powered by renewable energy via the power grid
- Simpler locomotives, lower O&M costs
- Established, proven technology
- Many main lines around the world are electrified and carry a proportionally higher level of traffic
- Regenerative braking can be fed back into overhead wire

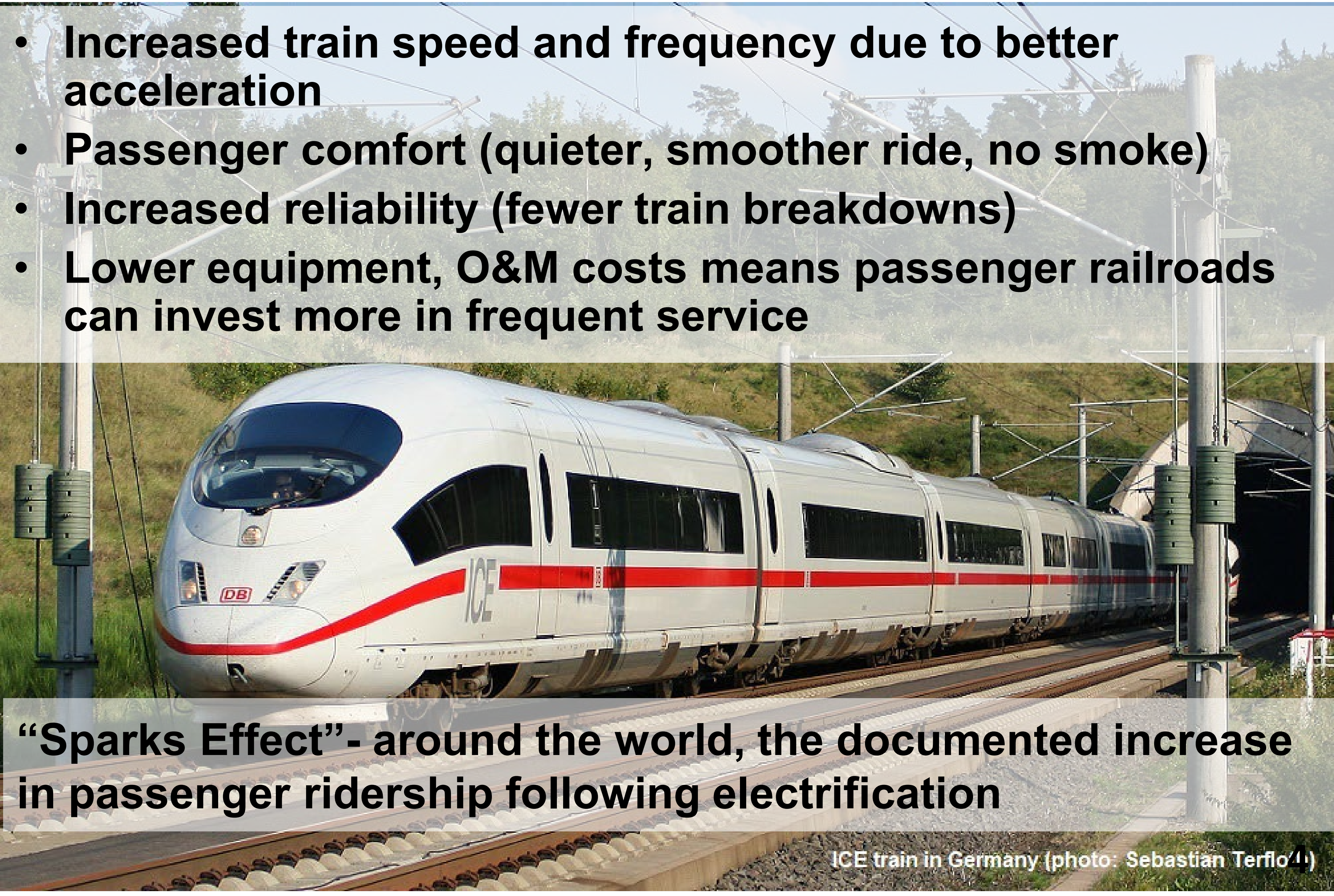
Overhead Catenary Wire:

- Required for conventional electric locomotives to run
- Upfront capital cost
- Needs clearance of overhead obstructions, i.e. bridges
- Can face NIMBY opposition for aesthetic reasons

Electric Passenger Trains

- Increased train speed and frequency due to better acceleration
- Passenger comfort (quieter, smoother ride, no smoke)
- Increased reliability (fewer train breakdowns)
- Lower equipment, O&M costs means passenger railroads can invest more in frequent service

"Sparks Effect"- around the world, the documented increase in passenger ridership following electrification



ICE train in Germany (photo: Sebastian Terflo)

Electric Locomotives

Siemens ES64U4 (photo: NÖLB Mh)

Siemens ACS-64 (photo: Fan Railer)

BC Rail GF6C
(50 kV 6000 hp)

- **All-electric locomotives (powered via overhead catenary wire), have an energy efficiency of over 90%**

- **Propulsion power can be more than double that of a diesel locomotive the same size:**
  - **Due to greater power per unit, one electric freight locomotive can be substituted for two diesel ones**

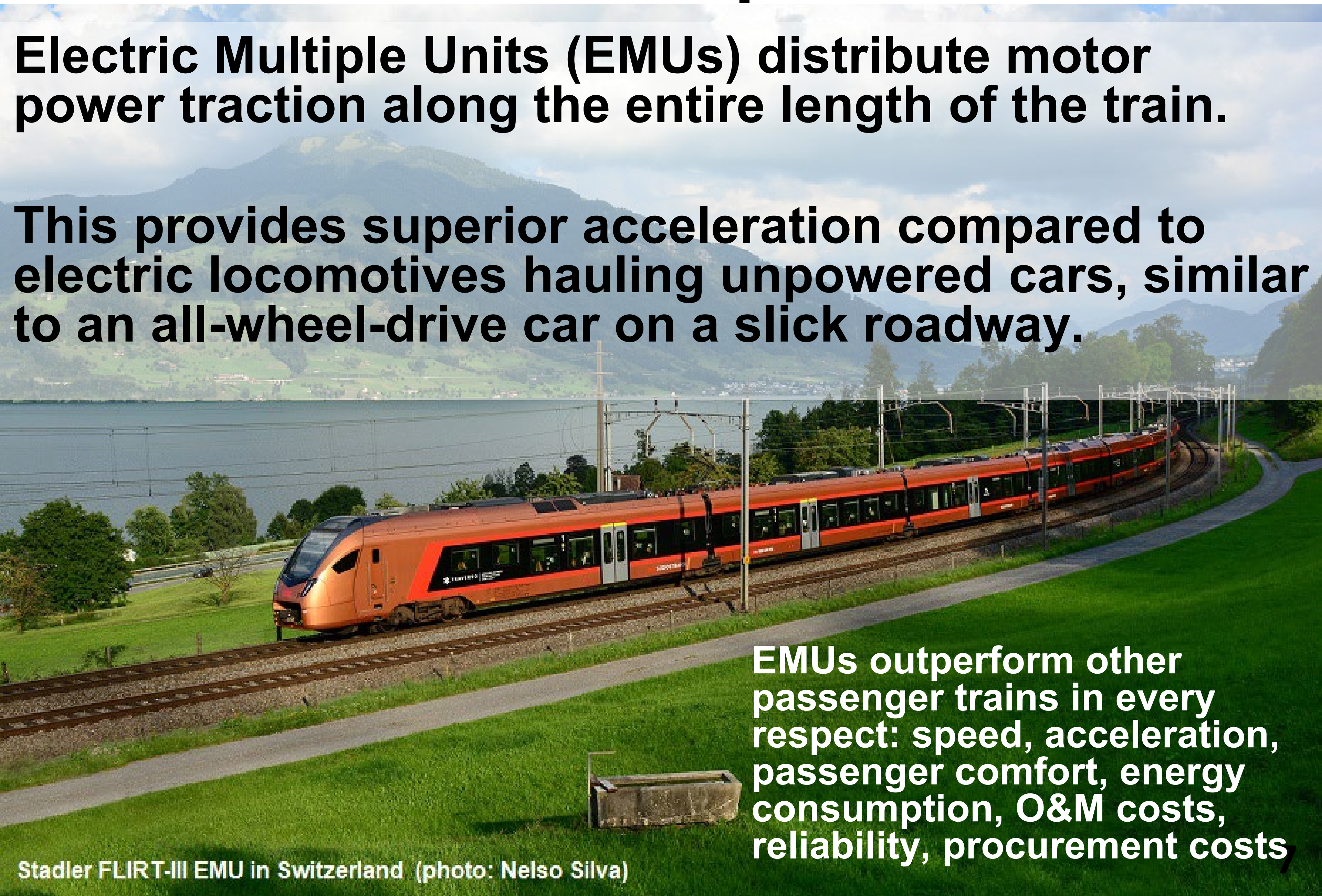
Electric Locomotives

China Railways HXD1 series 12,900 hp freight locomotive set, under 25 kV overhead catenary wire pulls 20,000 ton coal trains
(Photo: https://commons.wikimedia.org/wiki/File:HXD10004.jpg)

Electric Multiple Units

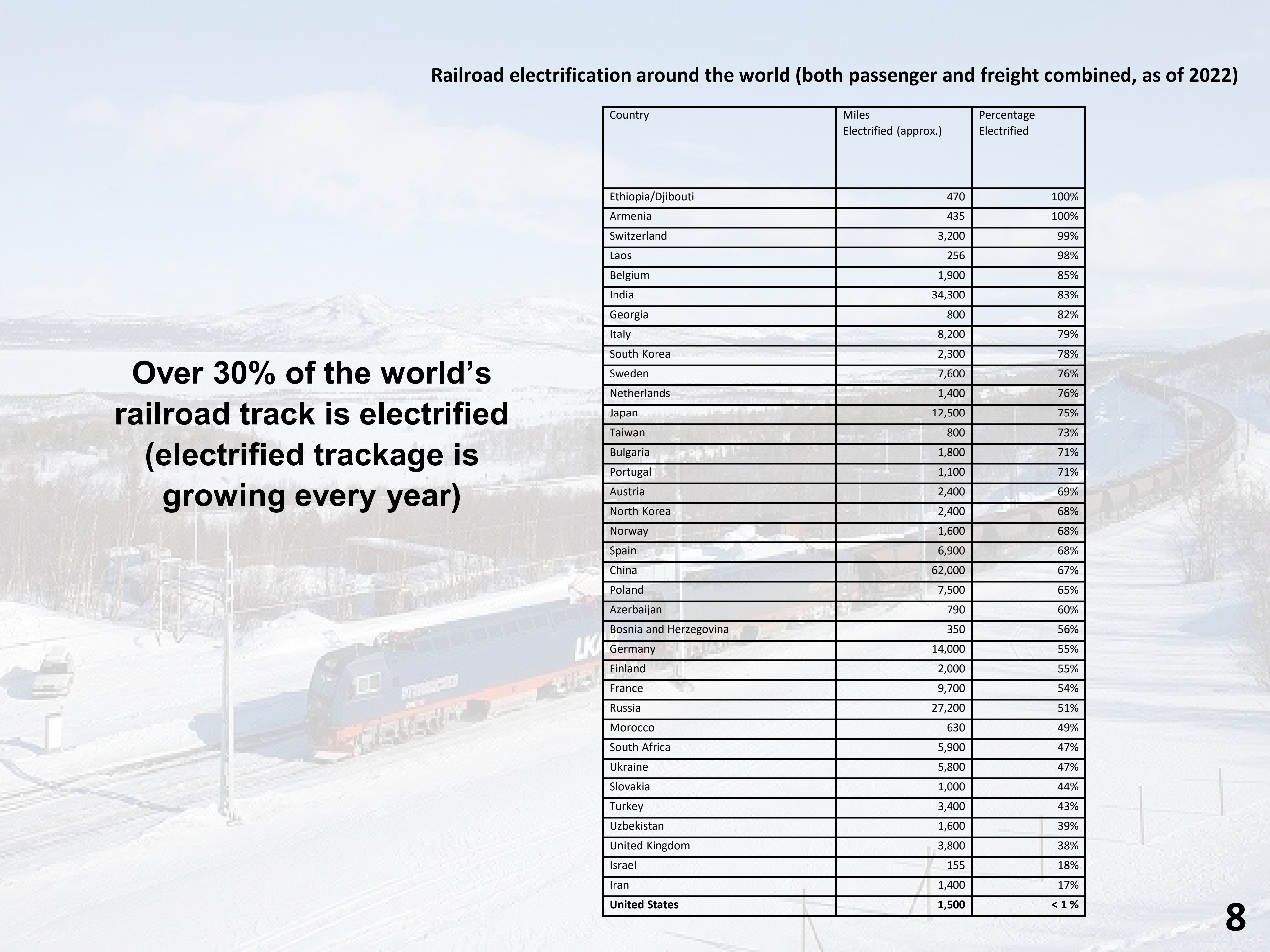
Electric Multiple Units (EMUs) distribute motor power traction along the entire length of the train.

This provides superior acceleration compared to electric locomotives hauling unpowered cars, similar to an all-wheel-drive car on a slick roadway.



EMUs outperform other passenger trains in every respect: speed, acceleration, passenger comfort, energy consumption, O&M costs, reliability, procurement costs

Stadler FLIRT-III EMU in Switzerland (photo: Nelso Silva)



Railroad electrification around the world (both passenger and freight combined, as of 2022)

Country	Miles Electrified (approx.)	Percentage Electrified
Ethiopia/Djibouti	470	100%
Armenia	435	100%
Switzerland	3,200	99%
Laos	256	98%
Belgium	1,900	85%
India	34,300	83%
Georgia	800	82%
Italy	8,200	79%
South Korea	2,300	78%
Sweden	7,600	76%
Netherlands	1,400	76%
Japan	12,500	75%
Taiwan	800	73%
Bulgaria	1,800	71%
Portugal	1,100	71%
Austria	2,400	69%
North Korea	2,400	68%
Norway	1,600	68%
Spain	6,900	68%
China	62,000	67%
Poland	7,500	65%
Azerbaijan	790	60%
Bosnia and Herzegovina	350	56%
Germany	14,000	55%
Finland	2,000	55%
France	9,700	54%
Russia	27,200	51%
Morocco	630	49%
South Africa	5,900	47%
Ukraine	5,800	47%
Slovakia	1,000	44%
Turkey	3,400	43%
Uzbekistan	1,600	39%
United Kingdom	3,800	38%
Israel	155	18%
Iran	1,400	17%
United States	**1,500**	**< 1 %**

Over 30% of the world's railroad track is electrified (electrified trackage is growing every year)

Northeast US Electrification

Amtrak

Northeast Corridor (NEC)- 457 miles

Keystone Corridor- 104 miles

Metro North - 144 miles

Long Island Railroad- 159 miles

New Jersey Transit- 250 miles (incl. 58 miles on NEC)

SEPTA Regional Rail- 280 miles (incl. 108 miles on NEC & Keystone Corridor)

MARC Train- 77 miles (on NEC)

Chicago

Metra Electric District

32 miles

South Shore Line

91 miles

Denver RTD Commuter Rail

Hyundai Rotem Silverliner V EMU at Denver Airport station (photo: Xnatedawgx)

Over 54 miles of 25 kV of electric lines completed so far, connecting Downtown Denver to:

- **A Line, to Airport (23.5 miles, opened in 2016)**
- **B Line, to northwestern suburbs (6.2 miles, opened in 2016)**
- **G Line, to western suburbs (11.9 miles, opened in 2019)**
- **N Line, to northern suburbs (13 miles, opened in 2020)**

Caltrain

- **The multi-faceted Caltrain Modernization project includes 51 route-miles of 25 kV electrification between San Francisco and San Jose, at a OCS infrastructure cost of over $20 million/route-mile**

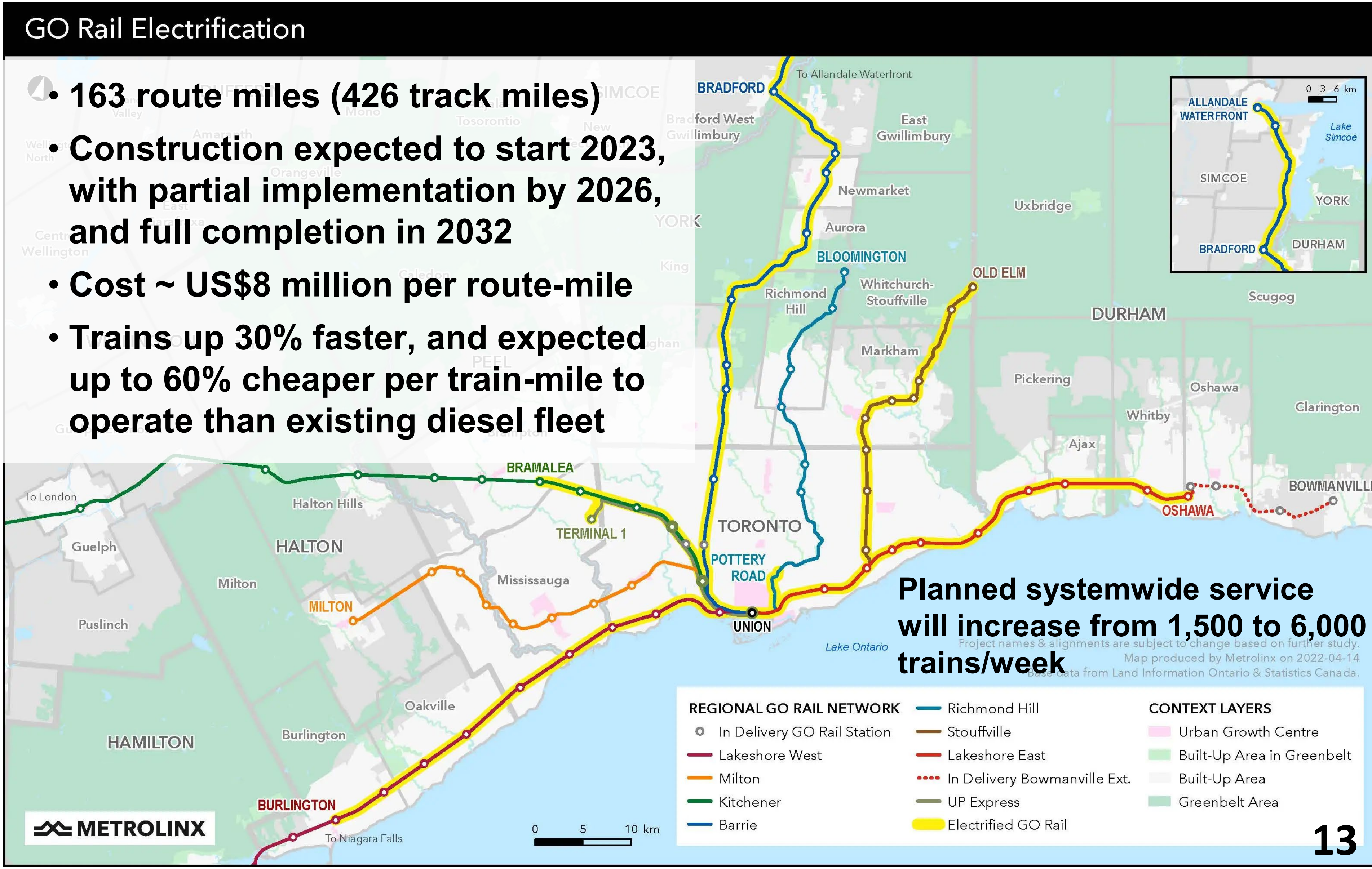
- **Zero-emissions Stadler EMU trains will replace 75% of Caltrain's existing diesel locomotive fleet**

- **First Stadler EMUs trains arrived in the Bay Area in summer 2022, service planned to start in fall 2024**
- **Total project cost, of which electrification is largest component, is $2.44 billion, or $47m/mile**

Toronto region GO Rail

- 163 route miles (426 track miles)
- Construction expected to start 2023, with partial implementation by 2026, and full completion in 2032
- Cost ~ US$8 million per route-mile
- Trains up 30% faster, and expected up to 60% cheaper per train-mile to operate than existing diesel fleet

Planned systemwide service will increase from 1,500 to 6,000 trains/week



Catenary- Diesel Hybrid Electric "Dual Mode" Locomotive

Bombardier ALP-45

(Photo: Robert Pisani, railcolor.net)

Electric Freight Rail

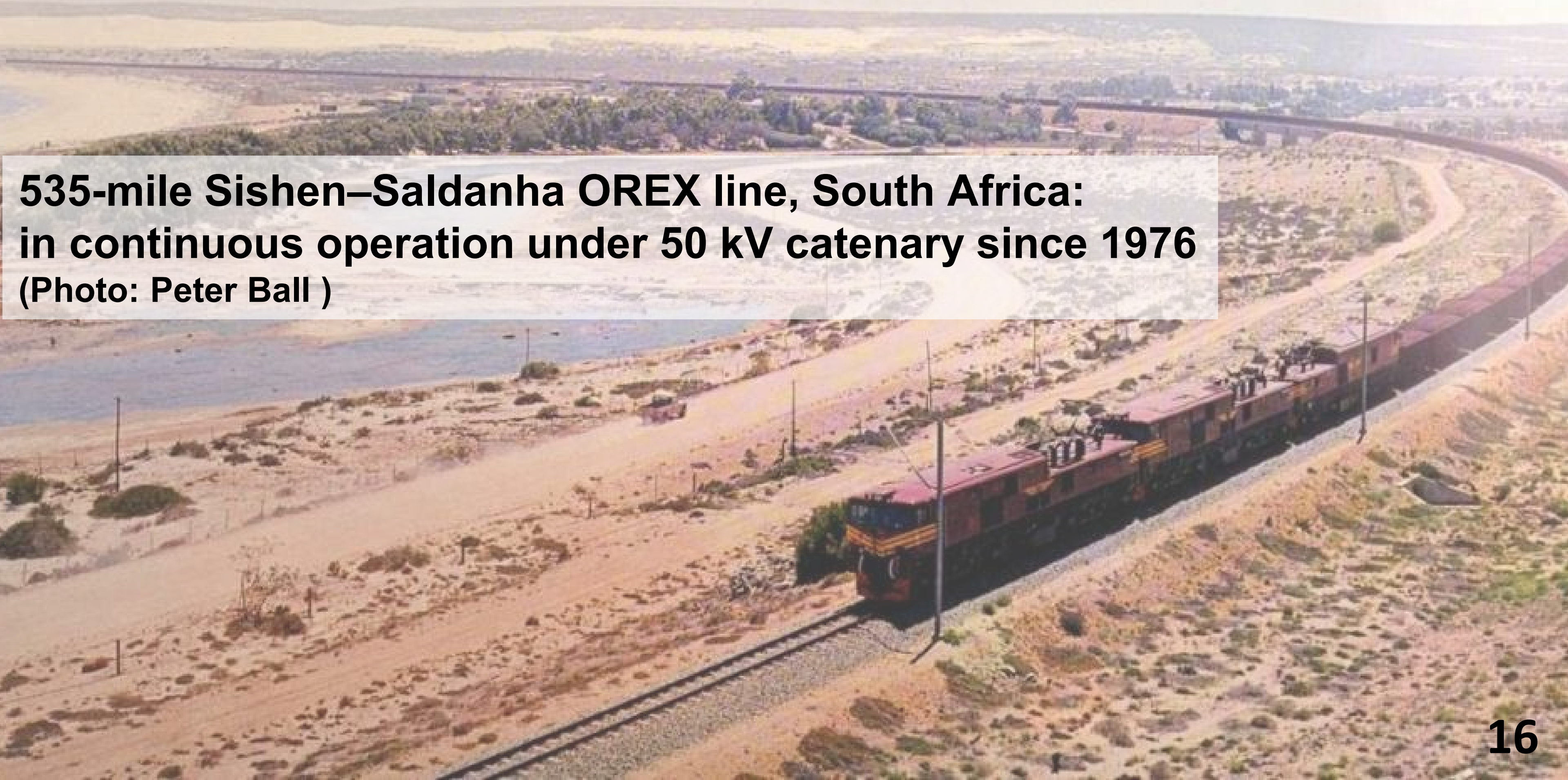
Hector Rail intermodal freight train in Germany, pulled by Bombardier TRAXX electric locomotive

(Photo: pxhere.com, Creative Commons CC0)

Electrified Heavy Freight Rail

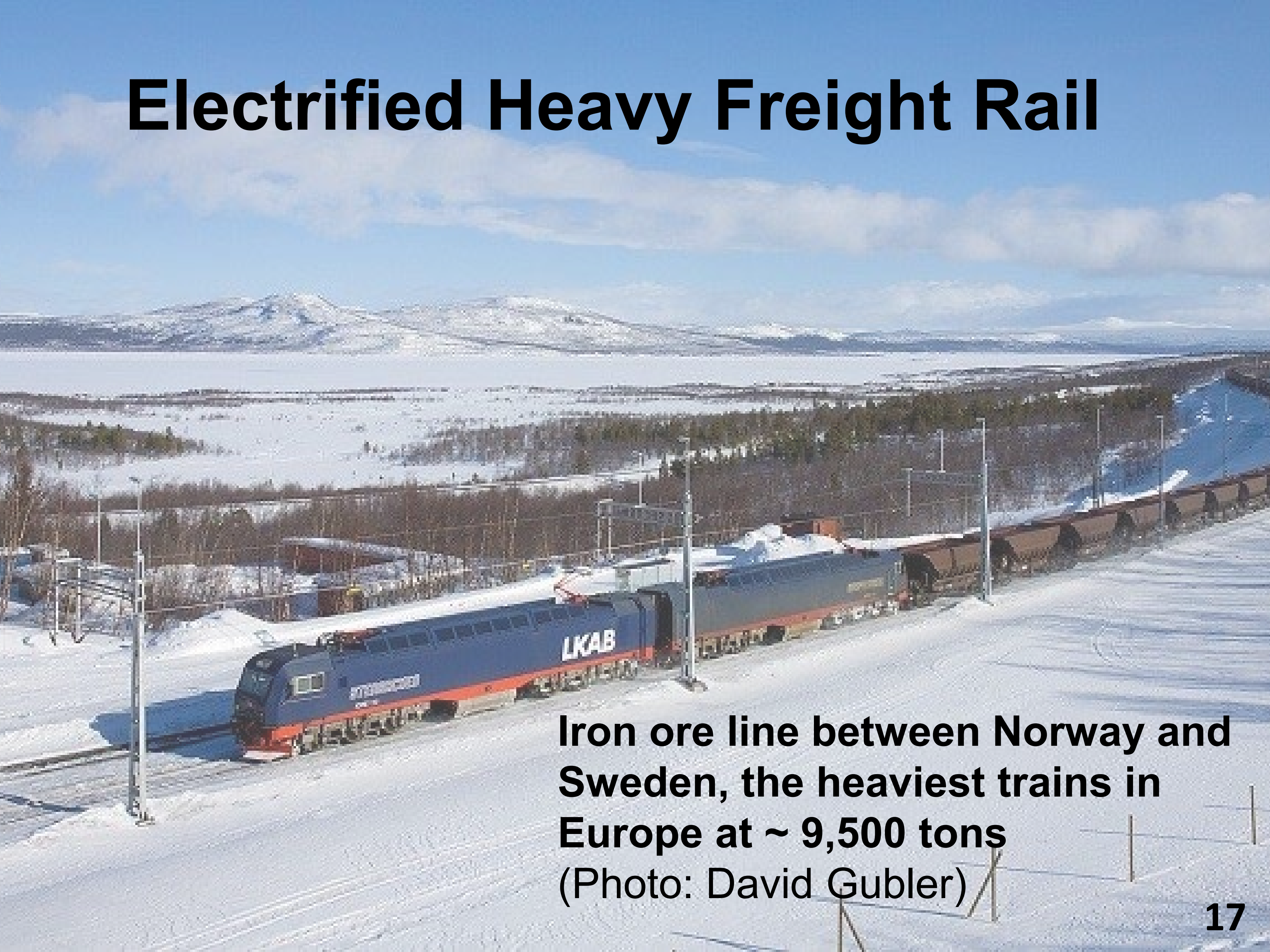
Electric iron-ore trains in South Africa routinely exceed 40,000 tons (w/ 375 cars)

(U.S. long-haul train max ~20,000 tons)



535-mile Sishen–Saldanha OREX line, South Africa:
in continuous operation under 50 kV catenary since 1976
(Photo: Peter Ball)

Electrified Heavy Freight Rail



Iron ore line between Norway and Sweden, the heaviest trains in Europe at ~ 9,500 tons
(Photo: David Gubler)

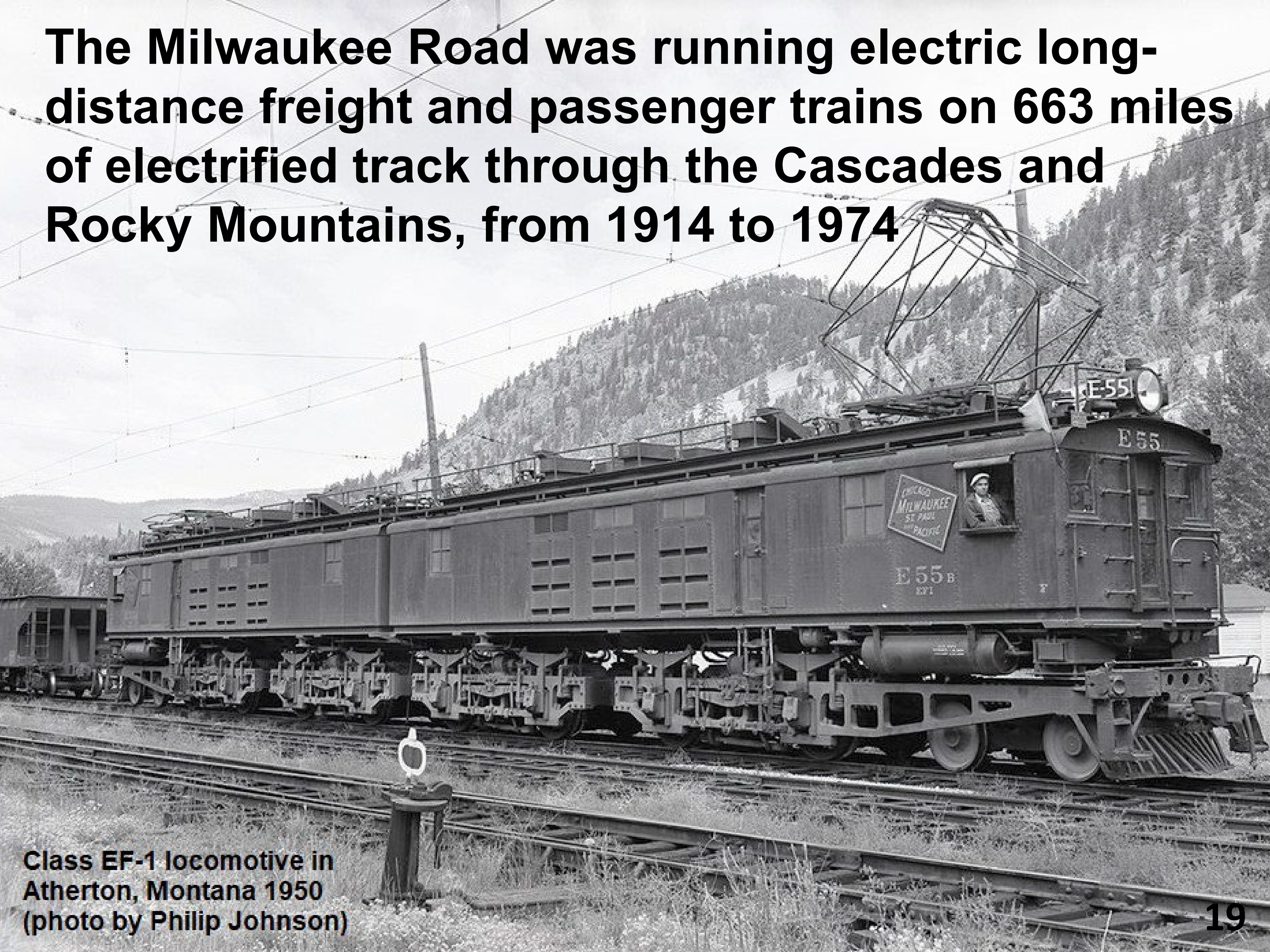
Long-Distance Electric Rail

Trans-Siberian Railway has been fully electrified since 2002

Nearly 75% of freight ton-miles in Russia (all modes except pipeline) are carried by electric train, ~10% by truck

It is possible to travel from Kaliningrad to Vladivostok (over 6,500 miles) entirely on electric trains

The Milwaukee Road was running electric long-distance freight and passenger trains on 663 miles of electrified track through the Cascades and Rocky Mountains, from 1914 to 1974



Class EF-1 locomotive in Atherton, Montana 1950 (photo by Philip Johnson)

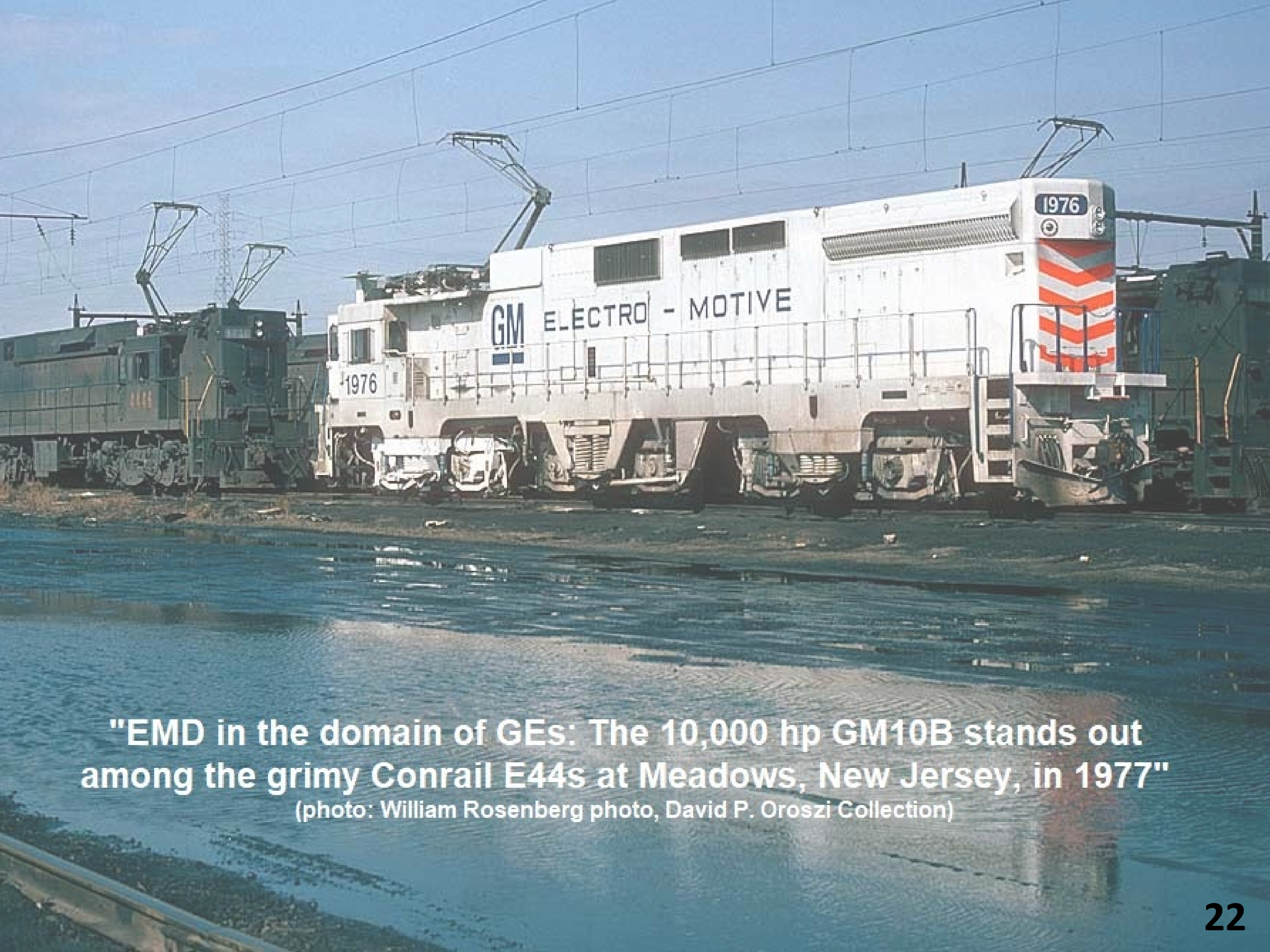
Electric freight trains were once common in America

Pacific Electric Railway all-electric local freight train in South LA, 1953

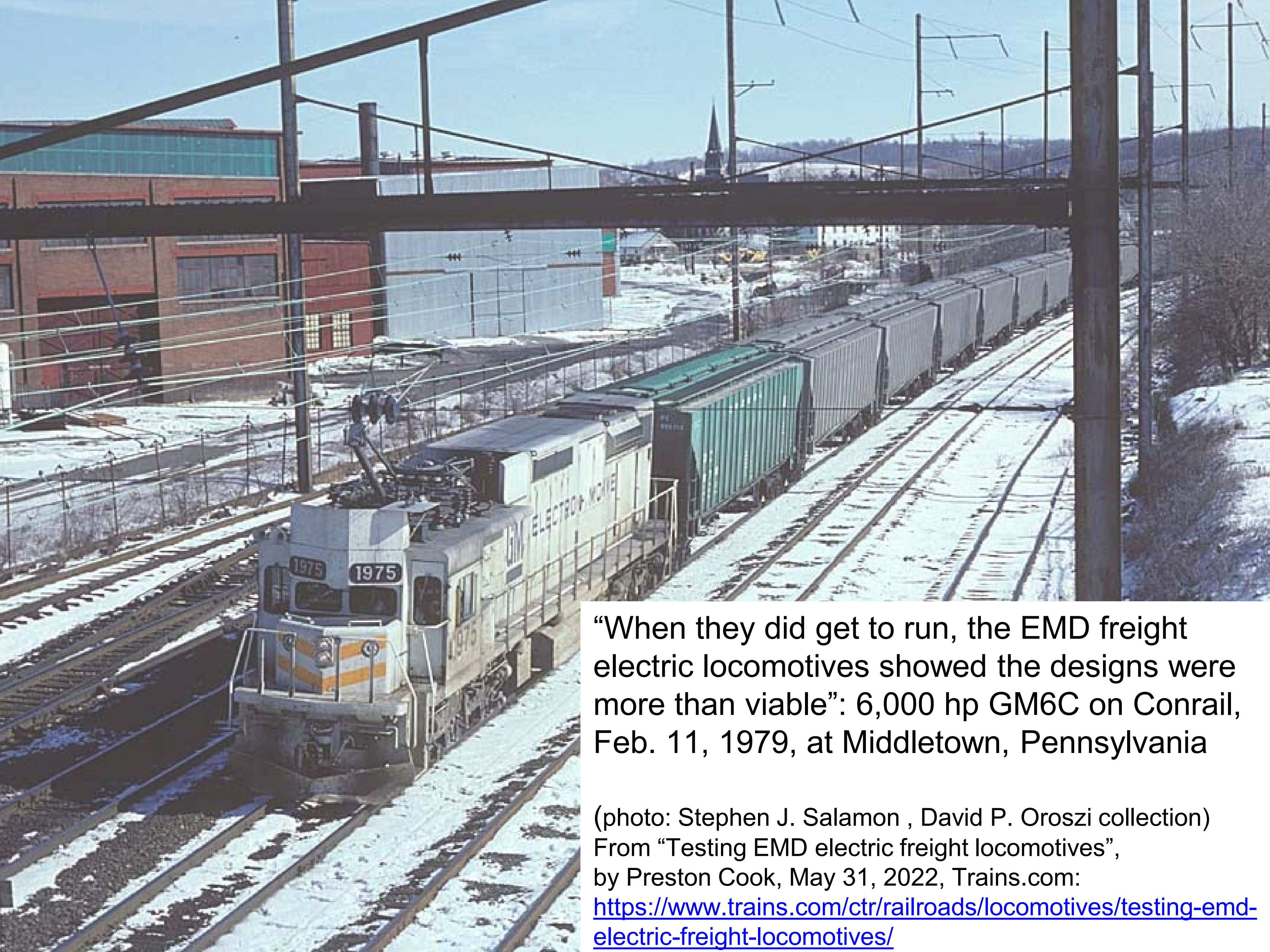
(Photo: Pacific Electric Railway Historical Society)

Sacramento Northern
electric locomotive #654 hauling a train on
Plumas St., Yuba City, CA, August 1964

Photo: Drew Jacksich
(Creative Commons)



"EMD in the domain of GEs: The 10,000 hp GM10B stands out among the grimy Conrail E44s at Meadows, New Jersey, in 1977"
(photo: William Rosenberg photo, David P. Oroszi Collection)



“When they did get to run, the EMD freight electric locomotives showed the designs were more than viable”: 6,000 hp GM6C on Conrail, Feb. 11, 1979, at Middletown, Pennsylvania

(photo: Stephen J. Salamon , David P. Oroszi collection)
From “Testing EMD electric freight locomotives”,
by Preston Cook, May 31, 2022, Trains.com:
https://www.trains.com/ctr/railroads/locomotives/testing-emd-electric-freight-locomotives/

Double-stack container train under overhead contact system (OCS) in Philadelphia area (Class 1 railroads operate diesel powered freight trains under wires on this corridor)

Yes, you *can* have electric double-stacked container trains

Electric train carrying double-stack containers under 25 kV wire in India

Overhead Catenary (or Contact) System (OCS)- International Cost Comparison

International Benchmark - Banedenmark

Railway Industry Association

The voice of the UK rail supply community

$2.1 million / single-track-mile (2019 $, including all power infrastructure)

- Programme 2014 – 2026
- Electrify 1362 stk 12Bn DKK **c£1m/ stk**
  - 13 Traction power substations
  - 42 Auto transformer stations
  - Enabling works
  - Non-electrified lines are options
- Rolled out as a joint programme
  - Functional requirements spec
  - Supplier to have TSI approved system
  - Suppliers to be responsible for innovation
  - Continuous work for 10 years
  - One approval process

Lesson	
Realistic Programme	Yes
Proven Technology	Yes
Proven Methodology	Yes
Collaboration	Yes
Efficient Cost	Yes
Low Complexity	No
Good Access	Varies
Rolling Programme	Yes

Overhead Catenary (or Contact) System (OCS)- International Cost Comparison

International Benchmark 2017 - Germany

Railway Industry Association
The voice of the UK rail supply community

$800,000 / single-track-mile (2019 $, overhead catenary only)

- Electrification of the Schönbuchbahn branch line near Stuttgart
- The €103m route upgrade project includes removing level-crossings, upgrading the route to 100kmph, double tracking on parts of the route, installing new depots, electrifying the route and providing new electric trains
- Electrification of 29.6 stk cost €9.3m (£8.11m) = €314k/ stk and includes for foundations, structures, small parts steelwork and conductors.
- Allowing 25% for client project management and design costs = €392k/ stk or c£345k/ stk
- The following should be taken into consideration:
  - No Grid or additional feeding connections were needed
  - There was no substantial route clearance required – such as bridge reconstruction, track lowering, parapet raising etc.
  - There was no Schedule 4 costs (possession access charges to train operating companies).
  - The overhead line system used is 15kV, which is standard in Germany. There would be a slight cost increase (<10%) for a UK 25kV system say **£375k/stk.**

Lesson	
Realistic Programme	Yes
Proven Technology	Yes
Proven Methodology	Yes
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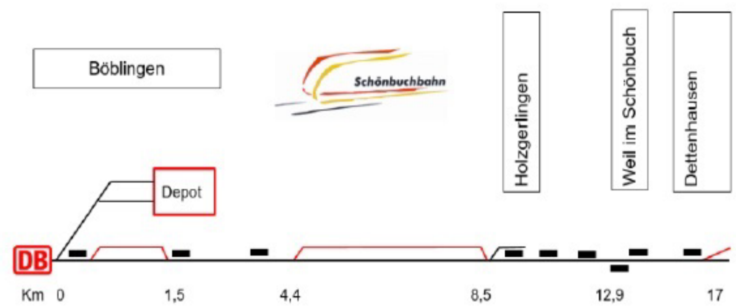
Efficient Cost	Yes
Low Complexity	Yes
Good Access	Yes
Rolling Programme	Yes



OCS wire under bridges

Several new technologies are allowing tighter clearances for electric wires going under bridges:

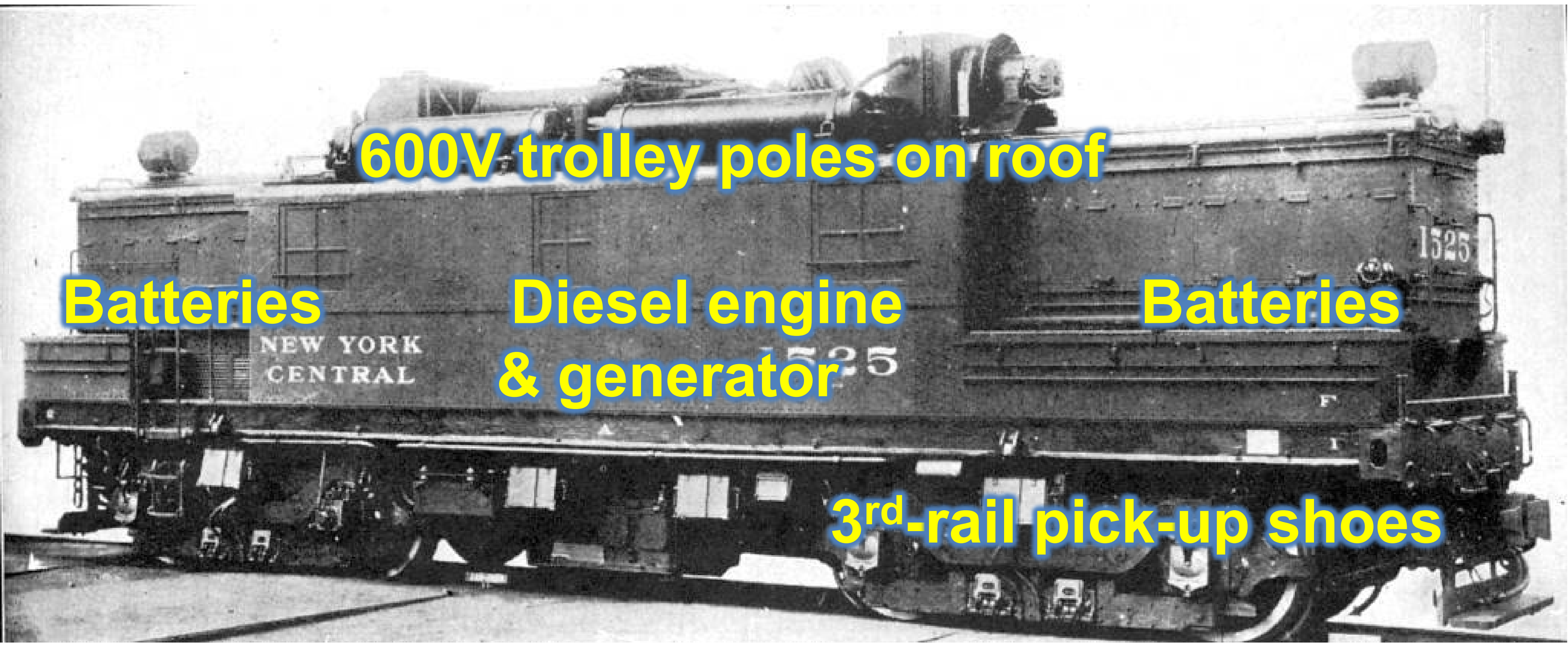
- **Under-cable support structures**
- **Conductor bars**
- **Insulating covers/coatings (combined with surge arresters)**
- **Neutral sections**

All-electric 999, prototype battery-electric switcher locomotive

Catenary-Battery Hybrid Electric Switcher Locomotive

Austrian Federal Railways ÖBB InnoShunt eHybrid prototype catenary-supercapacitor-battery switcher. Rebuild of Class 1063 electric locomotive by vehicle modernisation company TecSol

All-electric locomotive operation has been required, & hybrids used, in New York City since the 1920s



GE "three-power boxcab", 1928
New York Central #1525

Battery-catenary hybrid electric, 75-ton locomotives were introduced to the Utah Copper Company rail line in the late 1920s, capable of up to six hours of 'off wire' operating time.

Alstom Coradia iLint hydrogen-powered train

- Alstom's intended target market in Europe for the iLint trains on lightly-used, non-electrified lines.
- Range reported to be ~300 miles
- Max. propulsion power: 628 kW

  (compared to 25 MW for full-length U.S. freight train)

Photo: R. Frampe, 2018

Alstom Coradia iLint hydrogen-powered train

In 2022, the EVB regional railroad in Lower Saxony, Germany was the first in the world to introduce a fleet of hydrogen-powered trains

- **Reliability problems**
- **Massive cost overruns**
- **Half of the promised range on a full tank of hydrogen**
- **A major cost factor was that (supply/demand/market speculation) the price of hydrogen skyrocketed just as these trains were introduced. In this case, the hydrogen was coming from Russian gas.**

- **Lower Saxony's public transportation authority recently announced that no more hydrogen trains will be pursued, and that the remainder of the diesel fleet will be replaced with electric trains that use batteries combined with overhead wires.**

- **Another state in Germany, Baden-Württemberg, has come to the same conclusion after an extensive study.**

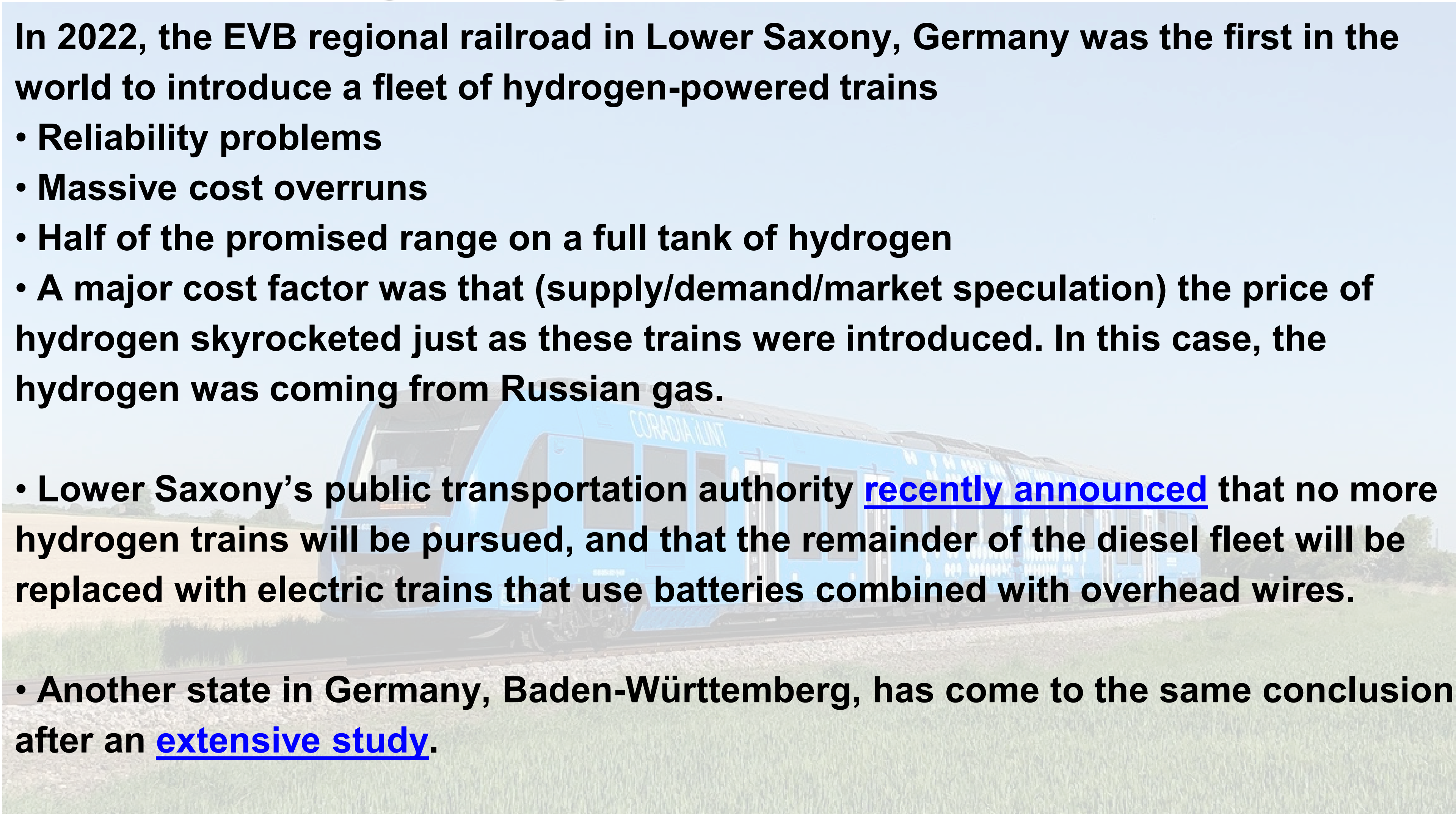


Photo: R. Frampe, 2018

Stadler hydrogen-powered FLIRT

Stadler's hydrogen-powered Flirt trainset, built for use in California's San Bernardino County Transportation Authority, is on display at InnoTrans in Berlin (Photo: Keith Fender Trains 9/21/22)

"Zero Emissions" Rolling Stock Cost comparison- All-Electric, Battery and Hydrogen:

Compared to a typical new electrical multiple unit (EMU) passenger train…

- ***Battery trains are about 2 times more expensive* than a standard EMU:**

~ $5 million per 'U.S.-length railcar'

[based on recent order of € 100 million for 11 'three-car' Alstom battery trains in Germany]

- ***Hydrogen trains are about 4 times more expensive* than a standard EMU:**

~$11 million per 'U.S.-length railcar'

[based on recent order of € 500 million for 27 'two-car' Alstom hydrogen trains in Germany]

“Zero Emissions” Infrastructure Cost Comparison- All-Electric, Battery and Hydrogen:

- **Battery and hydrogen trains also require costly infrastructure:**
  - **Battery-electric charging stations that require multi-MW of power**
  - **Hydrogen production plants, pipelines, massive storage tanks, and fueling stations (all have a lot of potential safety problems)**

• A recent report from the state of Baden Wurttemberg in Germany concluded that they will no longer consider hydrogen for rail propulsion as it is more expensive than battery or hard wire electrification by as much as 80%.

“The positives for hydrogen were: minor impacts upon introduction and during operation, and no changes required to the rail infrastructure.

But the negatives were: costly filling stations; low efficiency, high energy consumption and high cost; the possible need to increase the number of trains because the range would not be sufficient for a whole day of travel; limited availability of green hydrogen; and the need to continually resupply the hydrogen filling stations.”

Energy Efficiency

• A major part of the reduced operating cost of electric trains is the relatively low cost of electricity as a “fuel” for the amount of useful propulsion energy, and greater energy efficiency. The ‘wire-to-wheel’ electrical to mechanical propulsive energy efficiency of electric trains is typically greater than 95%.

• This is *three times greater* than the overall (or “roundtrip”) energy efficiency of diesel-powered trains.

• Battery trains are only about 80% as energy-efficient than all-electric trains using the overhead wire

• Hydrogen trains have the worst roundtrip energy efficiency:

It takes *3 to 4 times the amount of electricity* to produce renewable hydrogen, which would have the same useful train-propulsive energy as powering a train directly with renewable electricity directly.

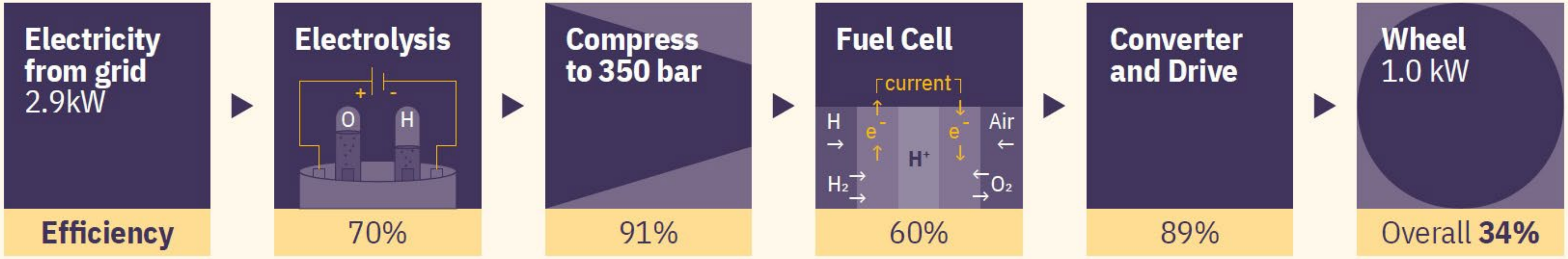


Figure 16 Typical overall efficiency of hydrogen trains

[from UK Railway Industry Association, *Why Rail Electrification?* report, 2021]

Onboard Energy Storage Density

	By Volume		By Weight	
	MJ/litre	Storage Volume (x diesel)	MJ/kg	Storage Weight (x diesel)
Diesel	36		43	
Hydrogen (at 700 bar)	4.8	7.5	71[2]	0.6
Hydrogen (at 350 bar)[1]	2.9	12.4	71[2]	0.6
Battery pack – current	1.7	21.2	0.7	61.3
Battery pack – 2035	2.6	13.8[3]	1.0[3]	42.9

[1] Does not take account of inefficient storage of cylindrical tanks
[2] This does not include weight of tank which would be of order of 750kg
[3] Expert prediction by Advanced Propulsion Centre

Figure 3a – Comparative energy densities of diesel, hydrogen, and batteries

[from UK Railway Industry Association, *Why Rail Electrification?* report, 2021]

Onboard Energy Storage Density

Electric trains are a future-proofed technology that is unique in offering potentially net-zero carbon high-powered transport because:

- The electricity they receive can be generated from any power source.
- Their power is limited only by the amount of energy they can collect from overhead line or third rail – in contrast self-powered traction is limited by the on-board power plant or battery size.
- They use electricity as it is needed and so do not have to store energy on board.
- The second law of thermodynamics states that whenever energy is converted from one state to another (e.g. heat to motion) useful energy is lost. Unlike other types of rail traction, this is not a problem for electric trains which collect electrical energy and feed into their electric motors without any energy conversion process.

No amount of research can change any of the above.

[from UK Railway Industry Association, *Why Rail Electrification?* report, 2021]

Range

- A train or locomotive powered by a hydrogen tank taking up the same amount of space as a typical on-board diesel tank could go only 1/12th the distance as a typical diesel-powered train

- … a battery-powered train less than 1/20th the distance.

- In the case of a hydrogen passenger train using compressed gas, a sizeable amount of space is taken by high pressure tanks, although hydrogen fuel cells alone cannot produce enough variable power to power a train directly. So a large and heavy battery pack is also needed onboard, in addition to the hydrogen tanks and fuel cells.

[from UK Railway Industry Association, *Why Rail Electrification?* report, 2021]

7.6. Alternative Traction Options

A number of energy storage technologies have been proposed as alternatives to electrification - in particular, battery and hydrogen. A 2020 study concluded that the overall feasibility of these technologies compared to electrification was as follows.

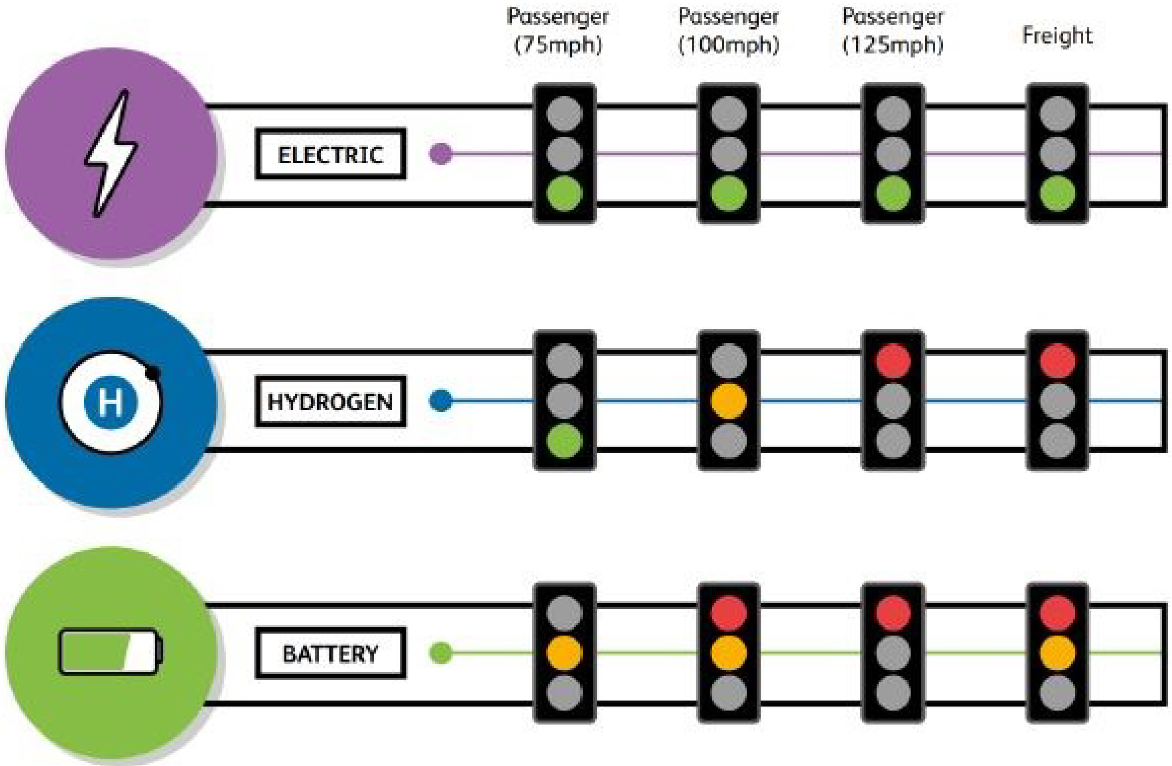


Figure 4: Technical abilities of non-diesel traction technologies[35]

[35] "Traction Decarbonisation Network Strategy - Interim Programme Business Case - Executive Summary"; Network Rail; July 2020; p4

Conclusion

Evidence does not support the view that electrification is unnecessary, thanks to hydrogen and battery systems improving rapidly: hydrogen trains are inherently less efficient than electric trains, due to the physical properties of the gas. Expert opinion predicts that battery capability might double by 2035. *Yet, whilst this might affect the hydrogen / battery traction mix required for decarbonisation, it is unlikely to change significantly the requirement for electrification.*

The laws of nature make electrification a future-proofed technology that is a good investment, offering large passenger, freight, and operational benefits. Furthermore, railways cannot achieve net-zero carbon emissions without a large-scale electrification programme.

[from UK Railway Industry Association, *Why Rail Electrification?* report, 2021]

Thank You