Modeling the Economics of Modern Options for Mainline Freight Railway Electrification

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TRAIN
TEXAS RAILWAY ANALYSIS & INNOVATION NODE

TEXAS
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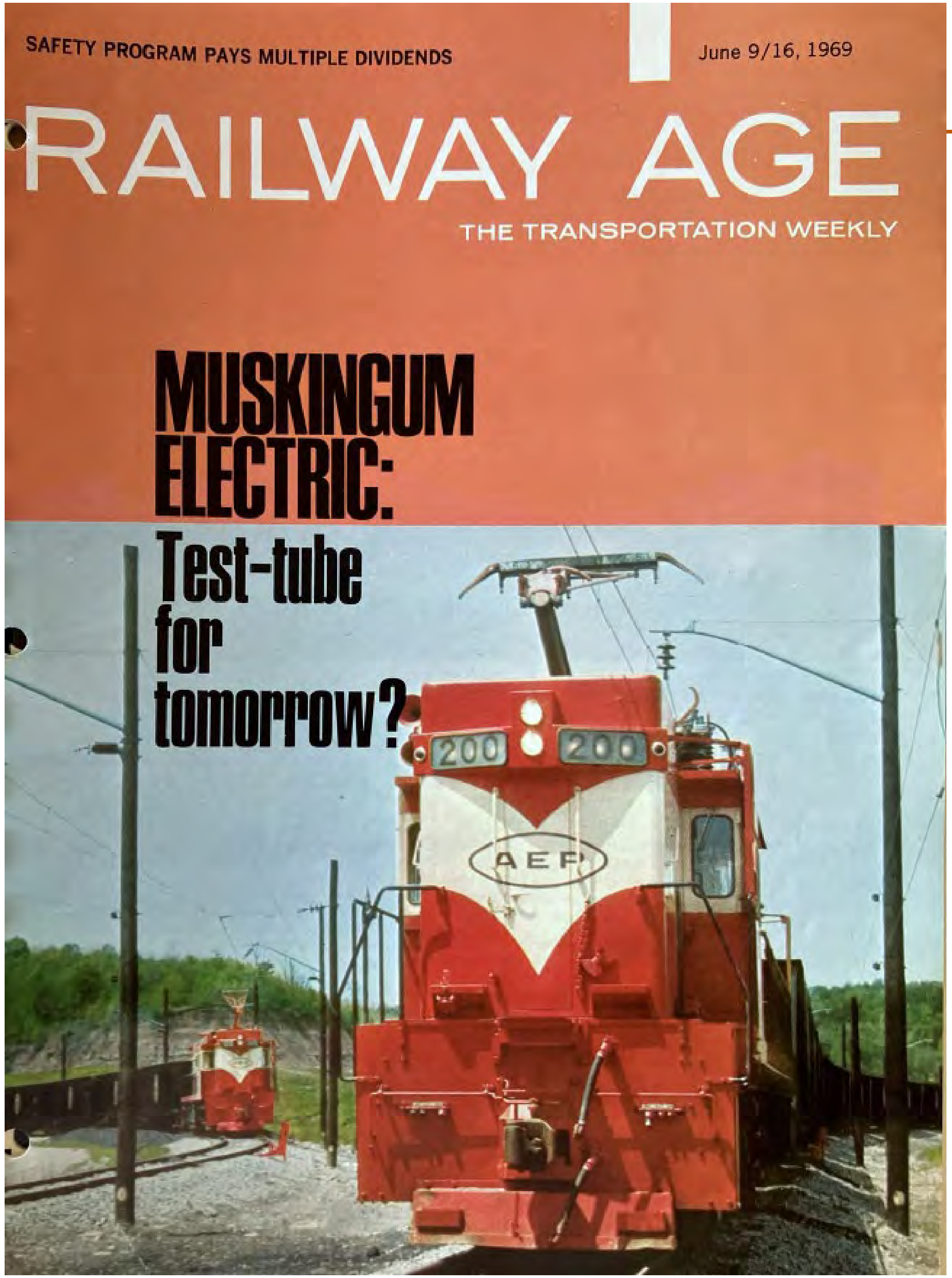


Railroad of Tomorrow c.1969

- Muskingum Electric, *Railway Age*, June 1969

- Unit Trains ✓ *Ubiquitous*
- Automated ✗ *Two-person crews*
- **Electrified** ? *Not yet for mainline freight, but in the future?*

Project Objectives

- Holistic understanding of the primary technical and economic barriers to freight railway electrification

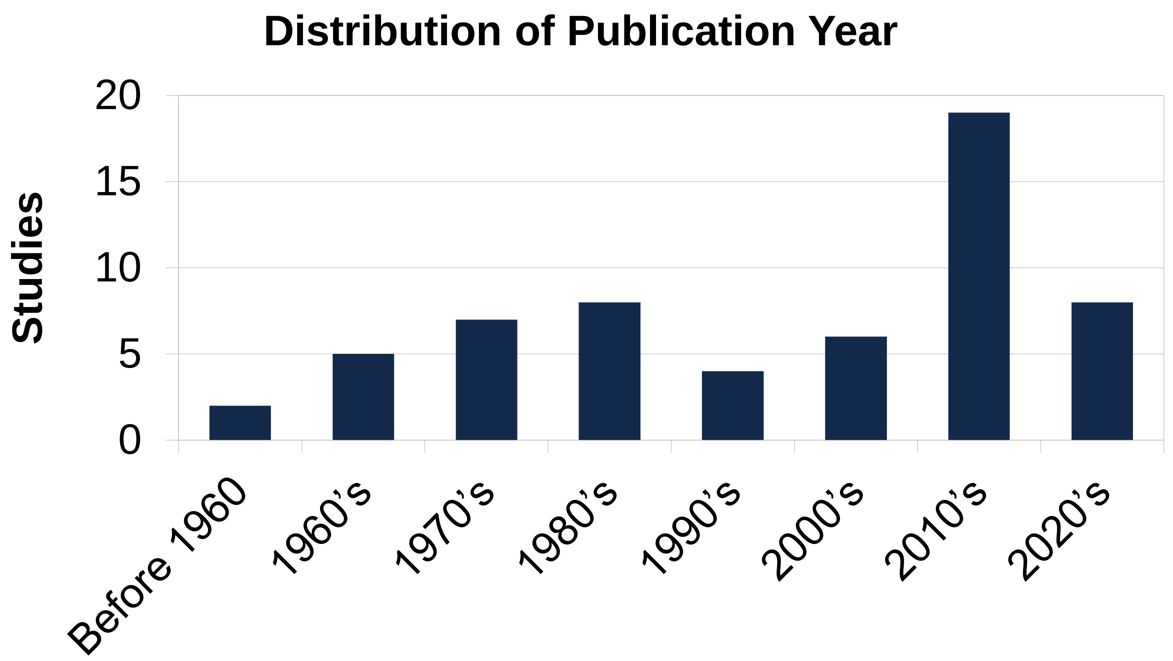
- Identify innovative technologies and approaches to electrified freight rail operations and implementation that will:
  - Improve benefits,
  - Reduce cost and risk, and
  - Eliminate or lessen operational limitations and impacts

- New risk-based framework for evaluating the sensitivity of electrification decisions to cost uncertainty, considering:
  - Current railroad operating situation
  - Carbon-focused environmental decision context

→ **CURRENT Model for economic analysis of rail electrification**

Review of Previous Electrification Studies

- Reviewed 53 studies, reports and papers on railway electrification
  - Focus on Class 1 Railroad and FRA studies from the 1960s through early 1980s
  - Also utility and manufacturer studies



- **Key common themes:**
  - **Primary barriers are economic and institutional**
  - **Technical barriers only related to limited North American experience**

- Many electrification proposals entered advanced stages of engineering design
  - But do not appear to have reached advanced stages of contractual negotiations

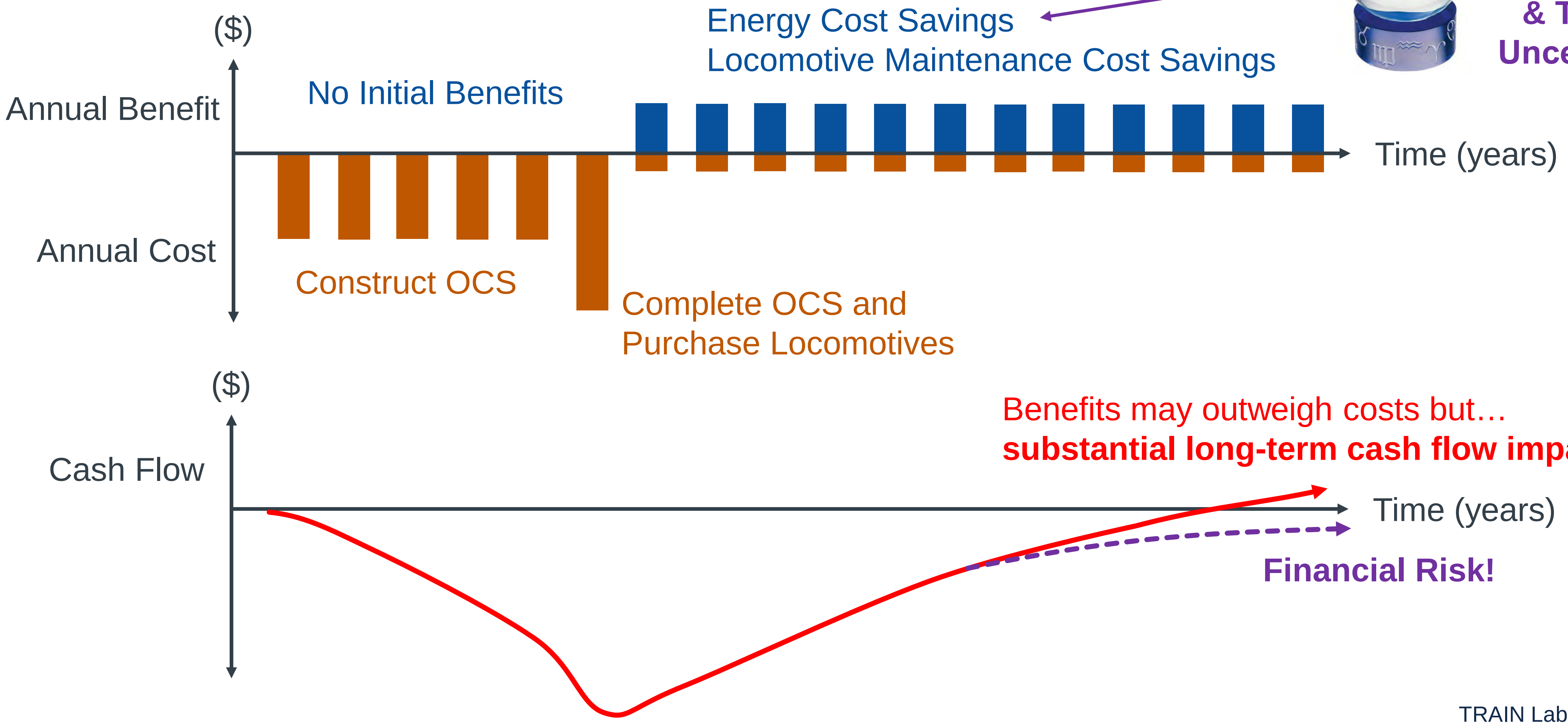
Southern Pacific Electrification Odyssey 1964-74

- 1966: Portland - Klamath Falls, OR
  - Utility offers low-cost power *at night*
- 1967: Roseville, CA - Sparks, NV
  - *Inadequate power supply*
- 1968: Bakersfield - Los Angeles, CA
  - Railroad ROW for transmission access
  - *No long-term electricity rate structure*
- 1969-74: Colton, CA - El Paso, TX
  - Partnership with five utilities
  - Large uncertainty in signal and clearance costs → **risk!**
  - *Terminated by 1974 freight traffic recession*

Economic Barriers to Traditional Electrification

- Typical pattern of capital investment and operating benefits

Future
Energy Cost
& Traffic
Uncertainty



What About BC Rail?

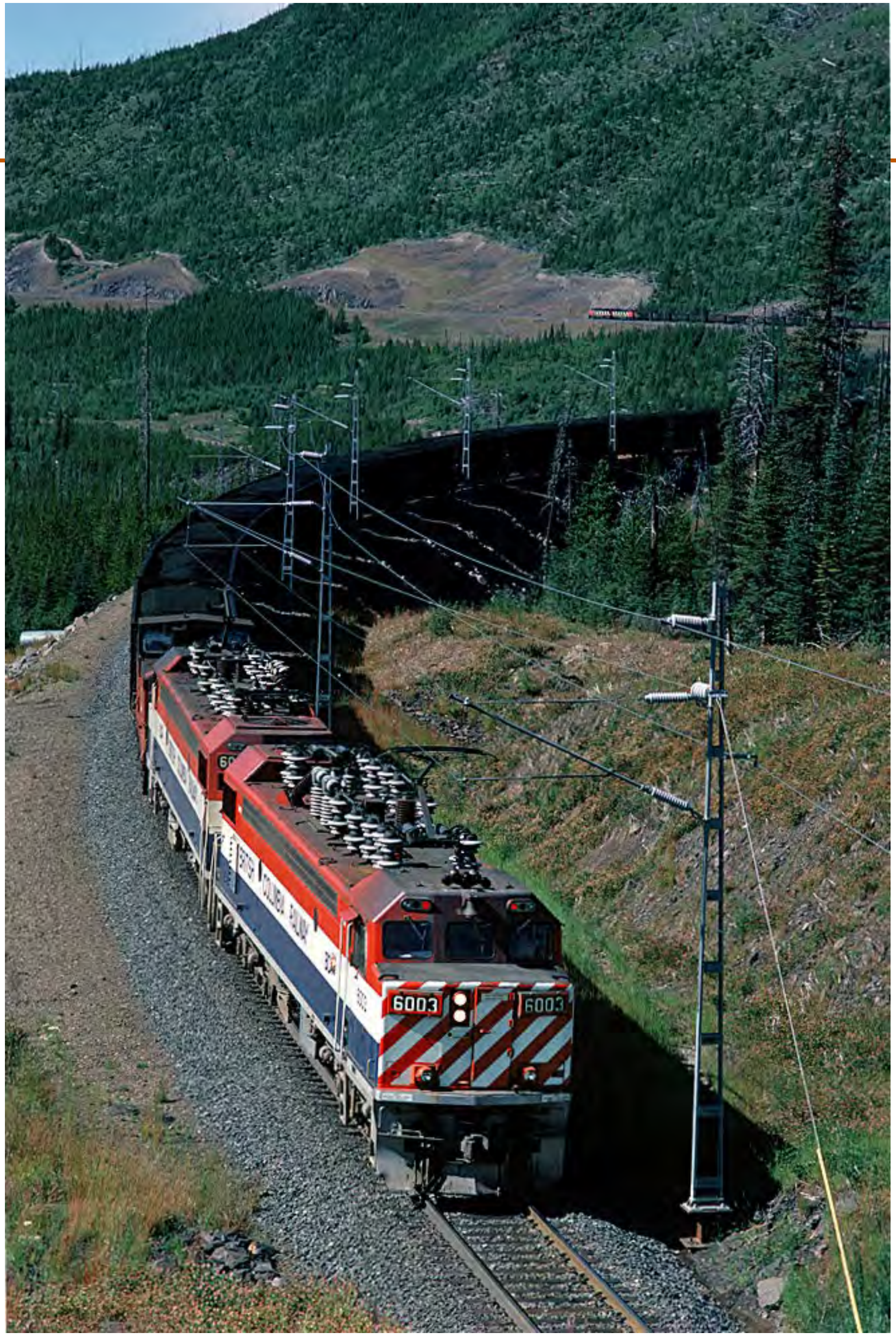
- Electrified new 81-mile route in 1983

- Constructed to access new coal mines
  - Guaranteed 15-year shipping contract

- OCS was low incremental cost compared to ventilating two tunnels (~3 miles total)
  - Electrical supply established for mine
  - Same substations for ventilation or OCS

- New line required locomotive purchase regardless of technology
  - 7 electric vs. 11 diesel-electric

- Partial support from Federal/Provincial Conservation and Renewable Energy Grant



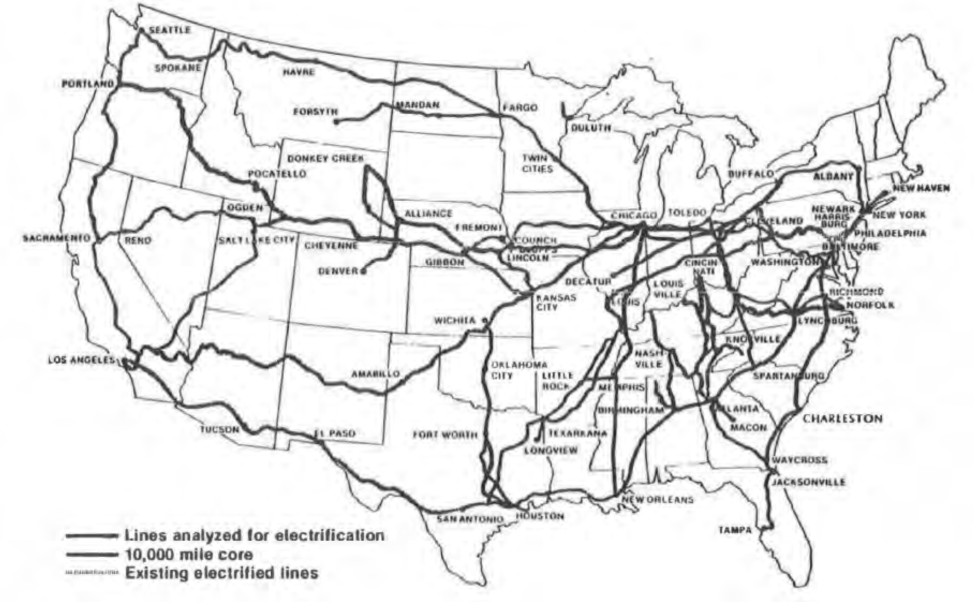
Reducing Financial Risk through Partnerships

- Railroads and FRA explored different electrification financing models
  - Reduce initial capital investment from private railroads
  - Spread risk and guarantee loans

- Separate entity to finance, construct and operate OCS → **Assume risk of OCS ownership**
  - Proposed partnerships:
    - Catenary Associates (SP and five utilities in 1970)
    - Railroad Electrification Management Cooperation (Southern, L&N and TVA in 1980)
    - FRA-Railroad "Joint Venture" (1983 Volpe study)

- Railroad roles:
  - Purchase and maintain electric locomotives
  - Pay an OCS use fee per kWh

- OCS could be transferred to railroad once initial investment recovered



Power by the Hour

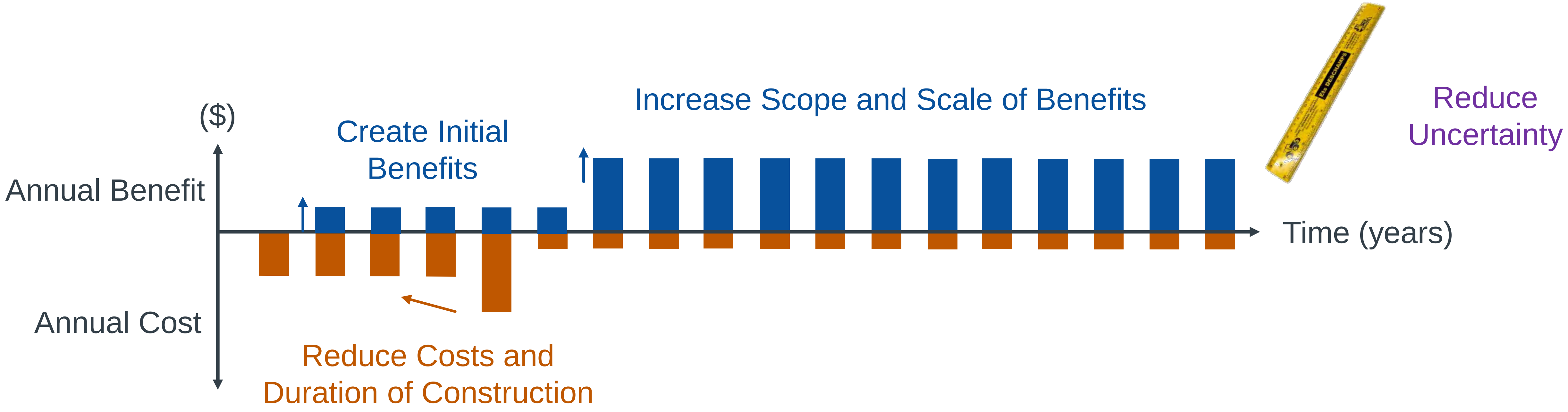
- Adopted by Burlington Northern from 1986 through the early 1990s

- **Only pay for the electricity generated by the diesel-electric locomotive, not its capital cost**
  - Locomotives leased and maintained by third party
    - Oakway – EMD
    - LMX - GE

- Motivated locomotive manufacturers to improve
  - Reliability and availability
  - Locomotive efficiency

Addressing Economic Barriers

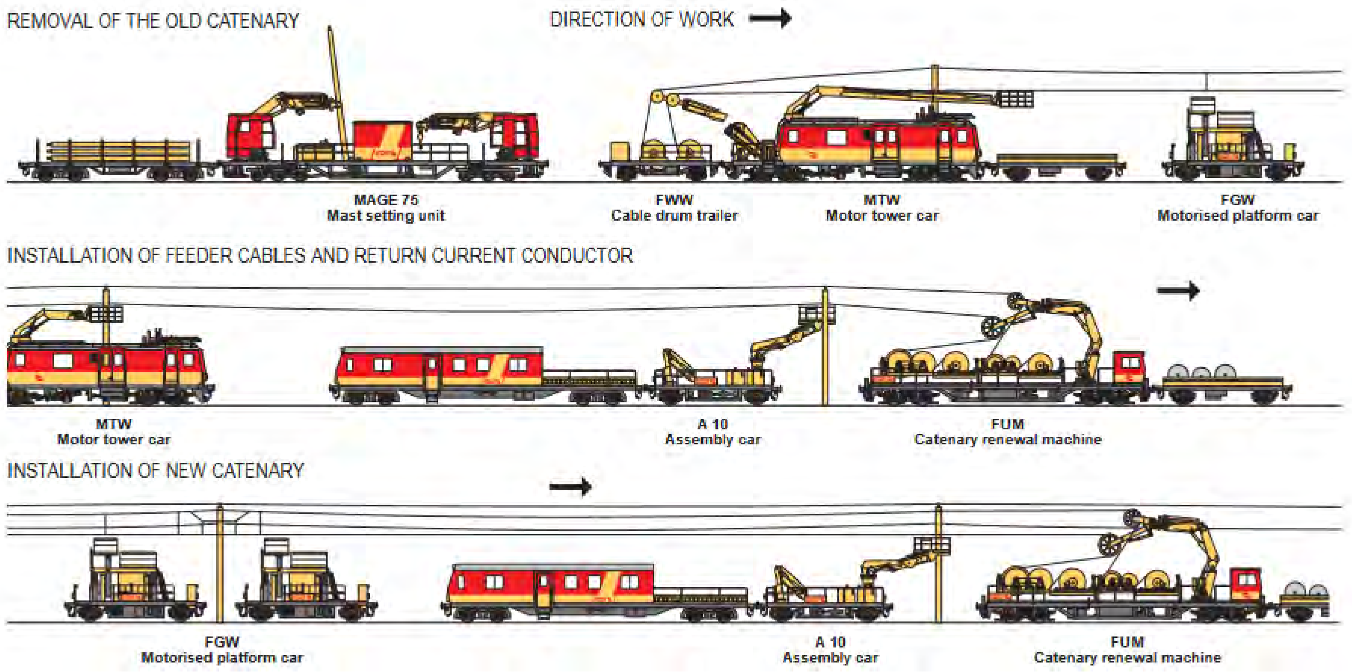
- How can we improve the cost and benefit structure of freight rail electrification?



- **Need to identify innovative technologies and approaches to electrified freight rail operations and implementation that produce these affects**

Addressing Barriers: Technologies and Strategies

- Methods to streamline catenary construction and reduce costs
  - Electrical efficiency improvements and different voltages
  - Design improvements
  - New construction techniques
  - Alternatives to OCS



- Locomotive technologies

- Intermittent (or discontinuous) electrification

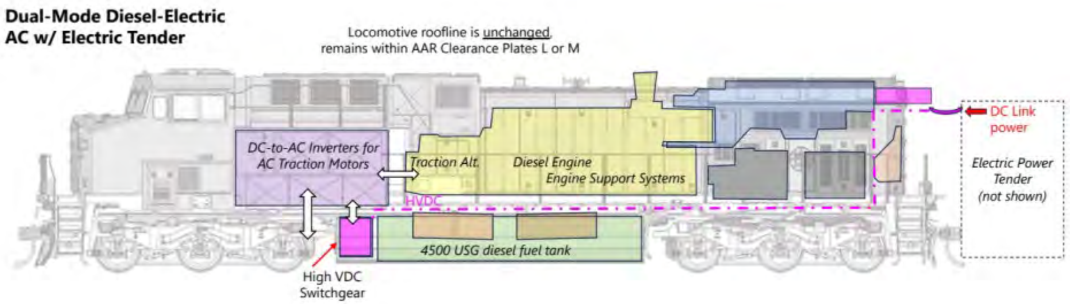
- Implementation strategies
  - Design-build, DBOM and PPPs
  - Mechanisms to monetize emissions reductions
  - Utility partnerships to share right-of-way

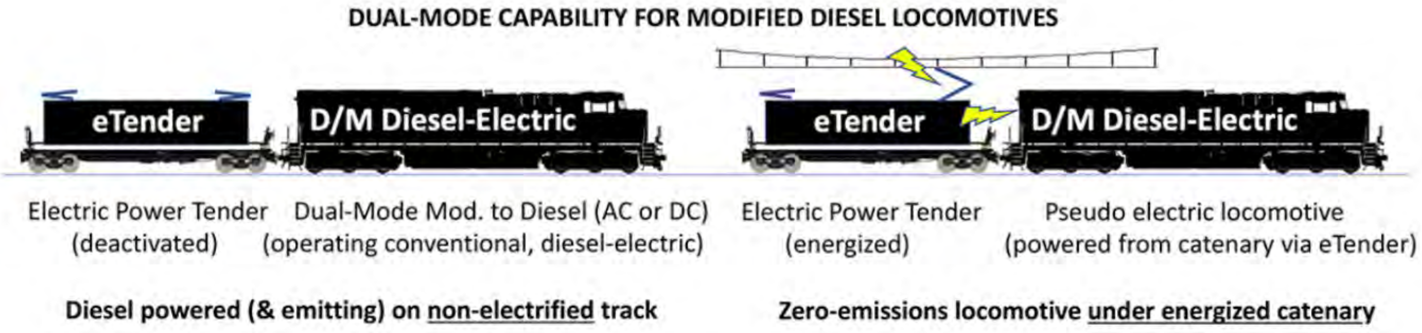
Dual-Mode Locomotives and Electric Power Tenders

- Traditional OCS with electric locomotives dictates an “All or Nothing” approach

- Convert AC traction platform to dual-mode
  - Supplement with “Electric Power Tender” equipped with pantograph to maintain full diesel capability
  - May also have battery capability
  - Adds complexity to crowded platform
  - Maintenance and training

- Benefits to electrification economics
  - Reduce capital costs compared to new straight electrics
  - Accrue project benefits sooner
  - Motor through gaps in OCS
  - Avoid locomotive changes



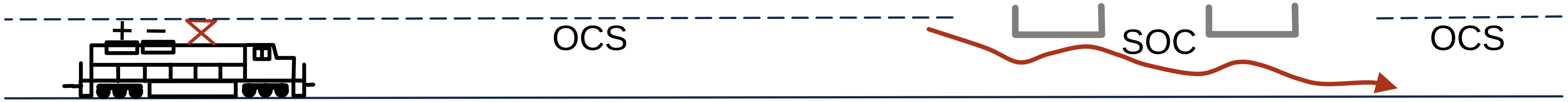


Intermittent Electrification

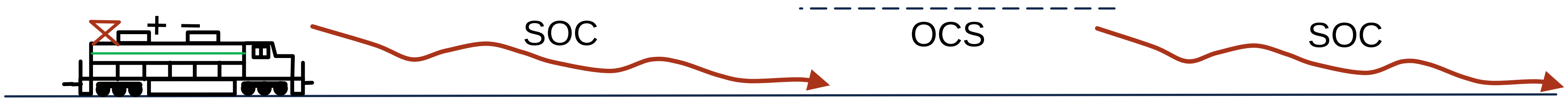
- Infrastructure cost is often used to quickly dismiss electrification with traditional OCS
  - Batteries and dual-mode locos help
- Need to balance extent of OCS with required last-mile battery size
- Unique solutions for route topography and extent of clearance constraints → optimization!

- Traditional Electrification – Capital Intensive

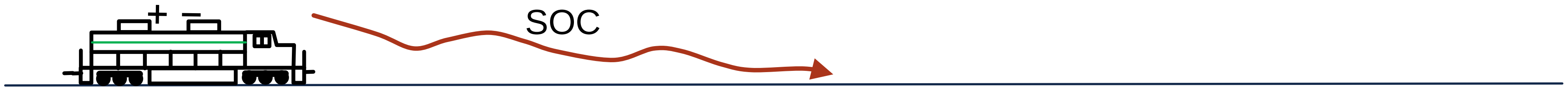
- Battery-Assisted Discontinuous Electrification



- BEL with Periodic Range-Extending Electrification



- BEL Alone – Limited Range



Social Benefits of Freight Rail Decarbonization

- Impact of diesel emissions on planet and population can be monetized
- Cost of carbon and health impacts assigned by EPA and USDOT

- Estimated social cost of emissions for **one hour** of locomotive operations at full 4,400 hp

Locomotive	NO_x	HC	$PM_{2.5}$	CO_2	Total
Tier 0	$28	$20	$1320		**$1920**
Tier 1	$28	$19	$1320		**$1920**
Tier 2	$16	$11	$740	$552	**$1320**
Tier 3	$5	$5	$329		**$894**
Tier 4	$1	$2	$62		**$617**

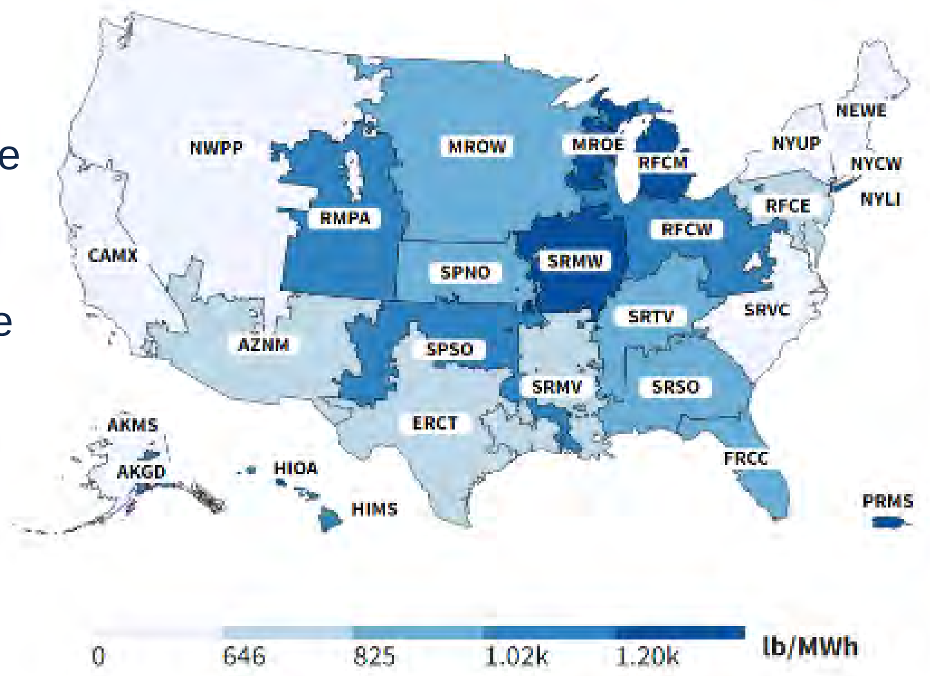
- **Need mechanisms to capture and transfer this value to railroads**

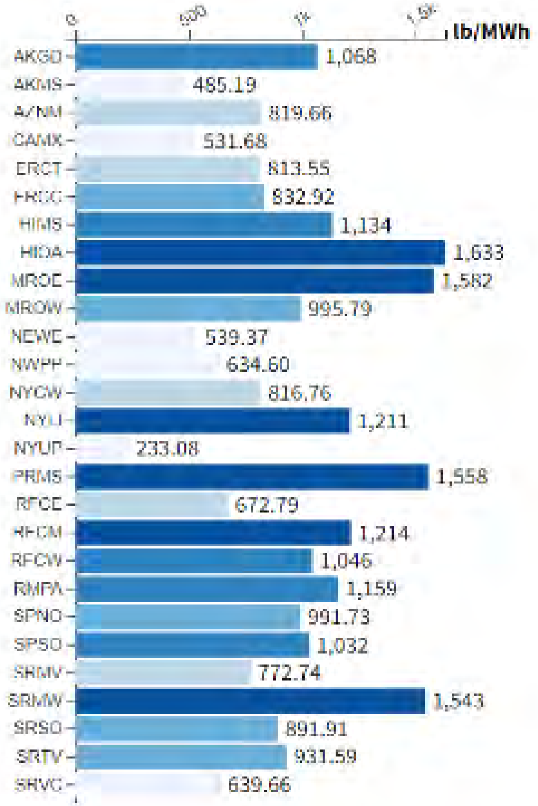
Source of Electricity: How Green is Your Energy?

- Overall emissions of OCS tied to local electrical grid generation mix
- Regional electric grid average CO_2 intensity
  - Can vary by time of day and location within each territory

More CO_2 intense

Less CO_2 intense





Partnerships with Utilities

- Electrical transmission grid expansion needed to connect renewable energy sources with demand
  - $100 billion investment
- Railroad ROW offers utilities advantages
  - One property owner instead of hundreds!
- SOO Green Project with CPKC
  - 250-mile HVDC line from Mason City, IA to Chicago, IL on railroad right-of-way
- Leverage utility co-location to support costs of batteries and/or OCS
  - Revenue from leases
  - Reduced grid connection cost
  - Reduced or guaranteed electricity rates

The New York Times

Energy Dept. Pours Billions Into Power Grids but Warns It's Not Enough

America's electric grids may need to expand by two-thirds by 2035 to handle future growth in clean energy, the agency said. The nation isn't on track.

CPKC

SOO Green HVDC LINK

New Context for Freight Rail Electrification

Then	Now
Cost of diesel fuel vs. electricity?	Most economical way to decarbonize?
Utilities want to sell more low-cost electricity produced from coal and nuclear sources	Utilities need new grid connections to handle increasing demand for renewable sources
Oil crisis and fossil fuel security	Diversity of energy sources
Local smog pollution and noise	Public health and climate change
“All or nothing” with OCS	Alternative locomotive technologies and improved battery storage density

- **Need to model new approaches to freight rail electrification in this context**

CURRENT Model

- **Costs, Uncertainties, and Risks of Rail Electrification with New Technologies (CURRENT)**

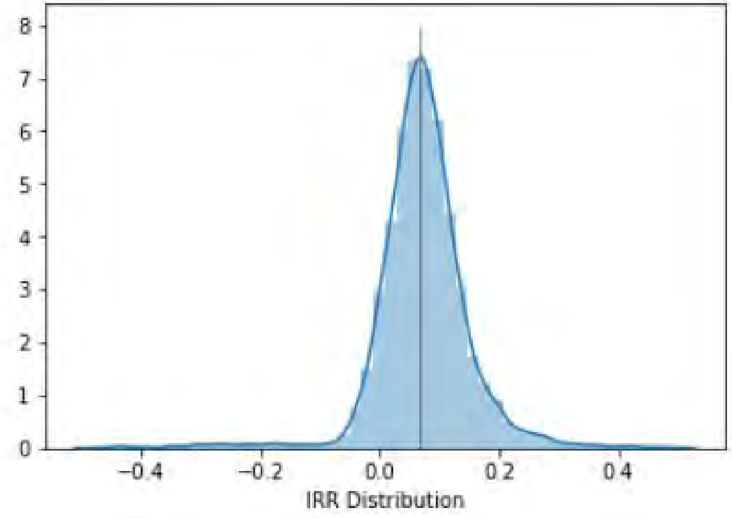
- Framework developed to analyze many different electrification strategies along any given railway corridor
  - **Train Performance Function in Python** uses a mass strap model to estimate energy consumption for different types of electrification
  - **Benefit-cost analysis model in Microsoft Excel** incorporates fifteen categories of costs and benefits to provide rates of return from private and public perspectives
  - **Risk assessment via Monte Carlo simulation** of the BCA using ARGO Excel plug-in

- Key Inputs
  - Route Data
  - Traffic Data
  - Unit Costs and Other Parameters

- Key Outputs
  - Capital Costs
  - Maintenance Costs
  - Energy Costs
  - Emissions
  - Overall NPV, Rate of Return and B/C Ratio
  - Distribution of Rate of Return

Monte Carlo Risk/Uncertainty Analysis of IRR

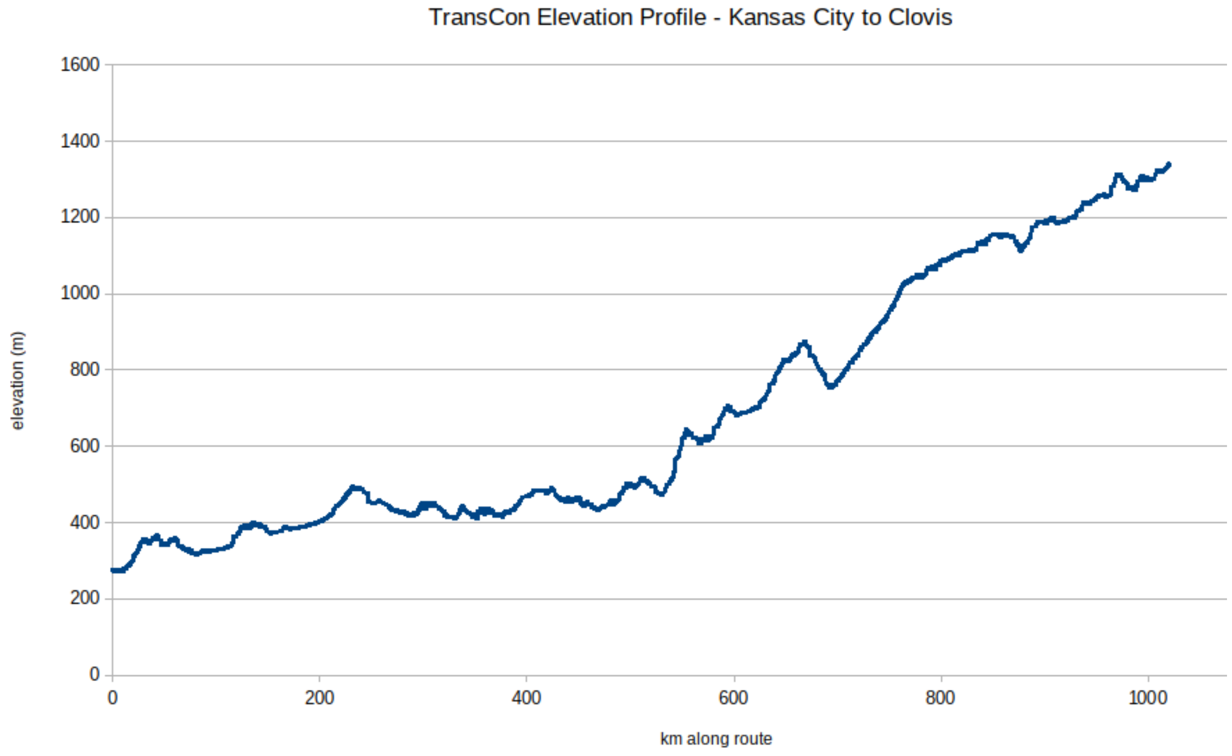
- Implemented in Excel using ARGO
  - Free Monte Carlo simulation plug-in
  - Developed by Booz Allen Hamilton
  - Repeats economics calculations 1,000+ times using input distributions to create distribution of output metrics
  - User can select between normal, triangular and uniform input distributions for each parameter
- Partial example of simulation input:



Variable		Unit	Default Value	Distribution	Confidence Level	Normal Distributions Mean	Standard Deviation	normal distribution
Catenary		$1000/km						
	Single Track	$1000/km	403	Normal	95%	403	125	474
	Double Track	$1000/km	737	Normal	95%	737	228	722
	Along Bridge Deck	$/m	1 474	Normal	95%	1 474	188	1 800
Substations		ea ($1000)	7 094	Normal	95%	7 094	2 758	6 100
Substation Spacing		km/substation	50	Normal	95%	50	5	52
Transmission		$1000/km	49	Normal	95%	49	19	69
Public Works*		Lump						
	Track Lowering	ea	50 000	Normal	95%	62 500	19 133	13 593
	Bridge Raising	ea	3 000 000	Normal	95%	3 250 000	892 874	2 557 836
	Tunnel Reconstruction	linear m	300 000	Normal	95%	250 000	51 021	264 568
	Bridge Reconstruction	linear m	100 000	Normal	95%	125 000	38 266	73 124
Signaling and Communications		$1000/km	947	Normal	95%	947	424	1 047
OCS Construction per year		km	250	Normal	95%	250	26	246
Days of Mobilization for a new segment		days	7	Normal	95%	9	3	10
OCS maintenance		$ per km	7 652	Normal	95%	7 652	1 301	7 734
Substation maintenance		ea	73 662	Normal	95%	73 662	12 528	70 973

Mainline Corridor Case Study

- Double-track mainline corridor with dense traffic
  - ~1,020 km (635 miles) from Kansas City, KS (Argentine) to Clovis, NM on BNSF
  - Long route requires multiple years of OCS implementation
  - Strong potential value as a utility corridor to connect wind and solar to midwest



- Representative Traffic Parameters
  - 60 trains per day
    - Intermodal: 150 platforms
    - Bulk: 125 cars, 286k GRL
    - Manifest: 77 loads, 38 empty (286 GRL)
  - 3 or 4 locomotives per train

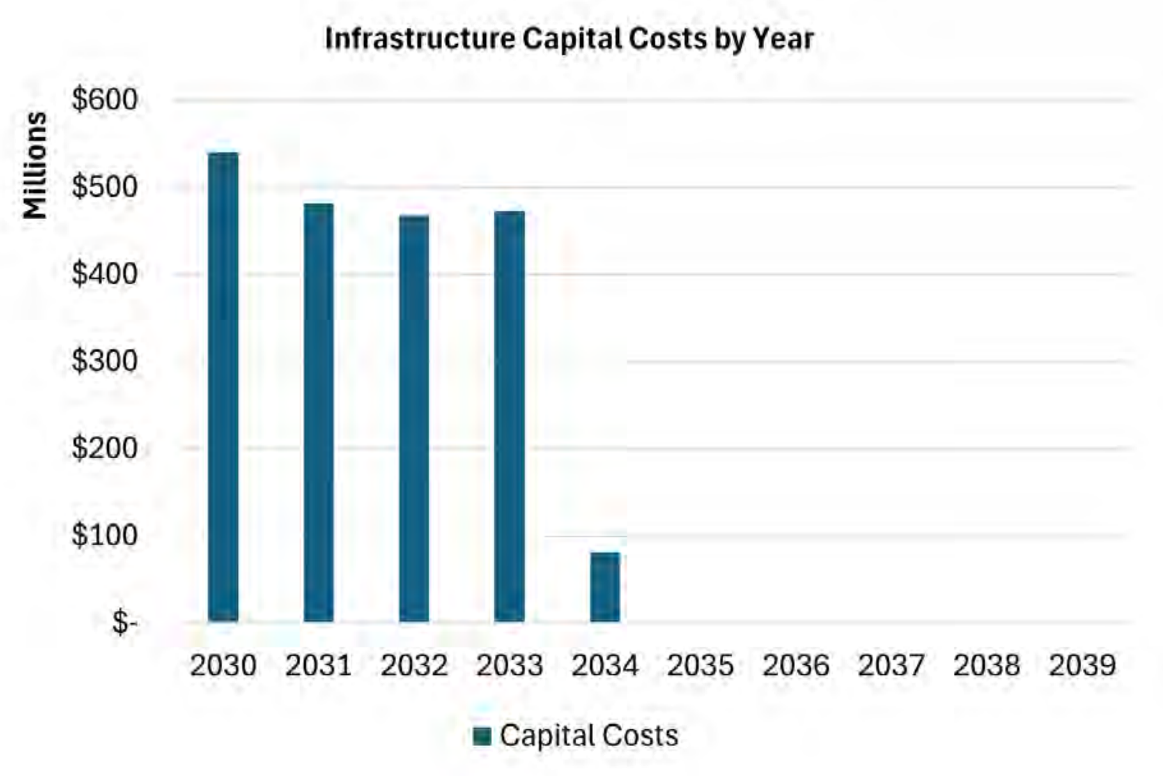
Mainline Case Study Scenarios

- **Analyzed four electrification scenarios:**
  - Full conventional OCS electrification
  - OCS with short gaps at public works and last-mile batteries
  - Progressive electrification via dual-mode locomotives
  - Intermittent electrification via battery tenders and OCS recharging segments

- **Each scenario considered from four different perspectives:**
  - Private railroad investment
  - Private investment with utility ROW sharing for transmission lines
  - Private investment with ROW sharing and public support to monetize diesel health/climate costs
  - Public project perspective

Mainline Case Study: Conventional OCS Costs

- Signaling & Communication is the largest expense, highlighting the need for more research in this area, particularly related to PTC compatibility
- Public Works cost shows the potential savings for intermittent electrification

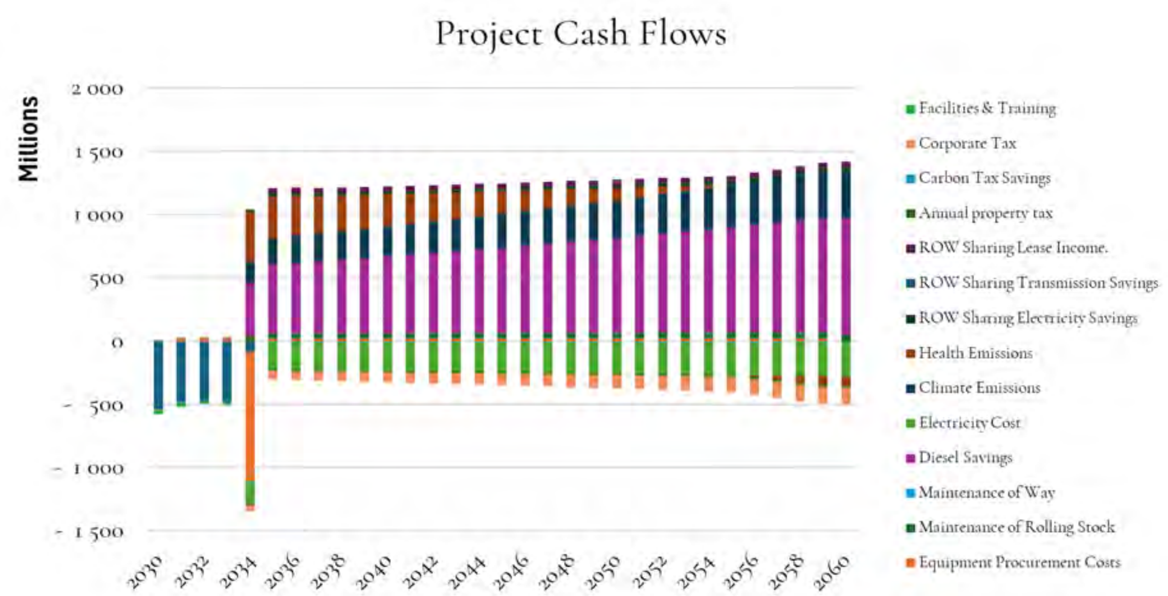


OCS Subtotals ($ millions)

Catenary	754
Substations	149
Transmission	25
Public Works	149
Signaling & Communication	969
Total	**$2,046**

Mainline Case Study: Conventional OCS Economics

- Conventional electrification produces positive returns, but requires significant upfront investment that creates a negative position unattractive to private railroad investment
- Utility partnerships improve economics
- Public support might be necessary to bring-about private investment



Perspective	Net Present Value ($ millions)			Internal Rate of Return	Benefit-Cost Ratio		
Discount Rate:	3%	7%	18%		3%	7%	18%
Purely Private RR Investment	1320	48	-1170	7.2%	1.4	1.0	0.5
Private Investment with ROW Sharing	2060	538	-975	9.3%	1.7	1.2	0.6
Private investment w/ ROW sharing and public support	7870	4440	643	22.9%	3.7	2.7	1.3
Public Perspective	8280	4700	728	23.5%	4.0	2.8	1.3

Mainline Case Study: Economics of Modern Options

- **OCS with Short Gaps**
  - Electric locomotives have last-mile battery
  - Motor through breaks in OCS located at clearance constraints
  - Assumed to **avoid all public works costs**
    - ~$150 million in capital saved

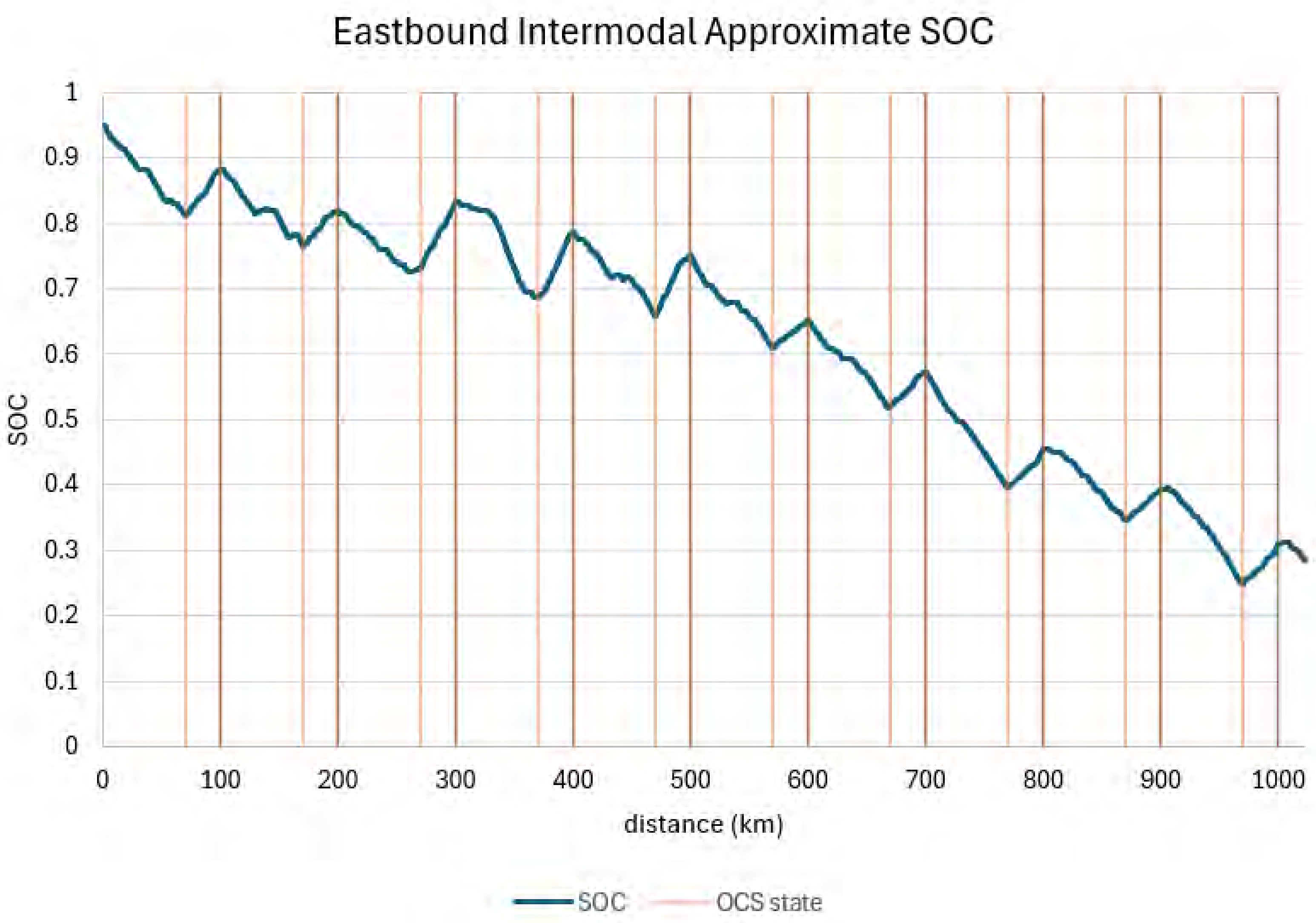
Perspective	Net Present Value ($ millions)			Internal Rate of Return
Discount Rate:	3%	7%	18%	
Private RR Investment	1410	147	-1070	7.7%
Private with ROW Sharing	2160	637	-871	9.8%
Private w/ ROW sharing and public	7960	4540	747	24.1%
Public Perspective	8370	4800	830	24.6%

- **Progressive Electrification with Dual-Mode Locomotives**
  - Use modified diesel-electrics mated with electric power tender
  - Assume same gaps as above
  - Start electrified operations as the OCS infrastructure is built in the initial years
  - **Create initial benefits** and avoid traditional “all or nothing” OCS cashflows

Perspective	Net Present Value ($ millions)			Internal Rate of Return
Discount Rate:	3%	7%	18%	
Private RR Investment	1410	213	-962	8.1%
Private with ROW Sharing	2180	720	-755	10.5%
Private w/ ROW sharing and public	8410	5020	1190	29.1%
Public Perspective	8810	5280	1280	29.8%

Mainline Case Study: Intermittent Electrification

- Ratio of OCS to battery operations?
- Locomotive consist
  - 4 × 8 MWh BEL
  - 4 × 9.6 MWh battery tender
- Split power between traction and in-motion battery charging as appropriate
- Initial test of 24 MW OCS power at 30% coverage → unsustainable

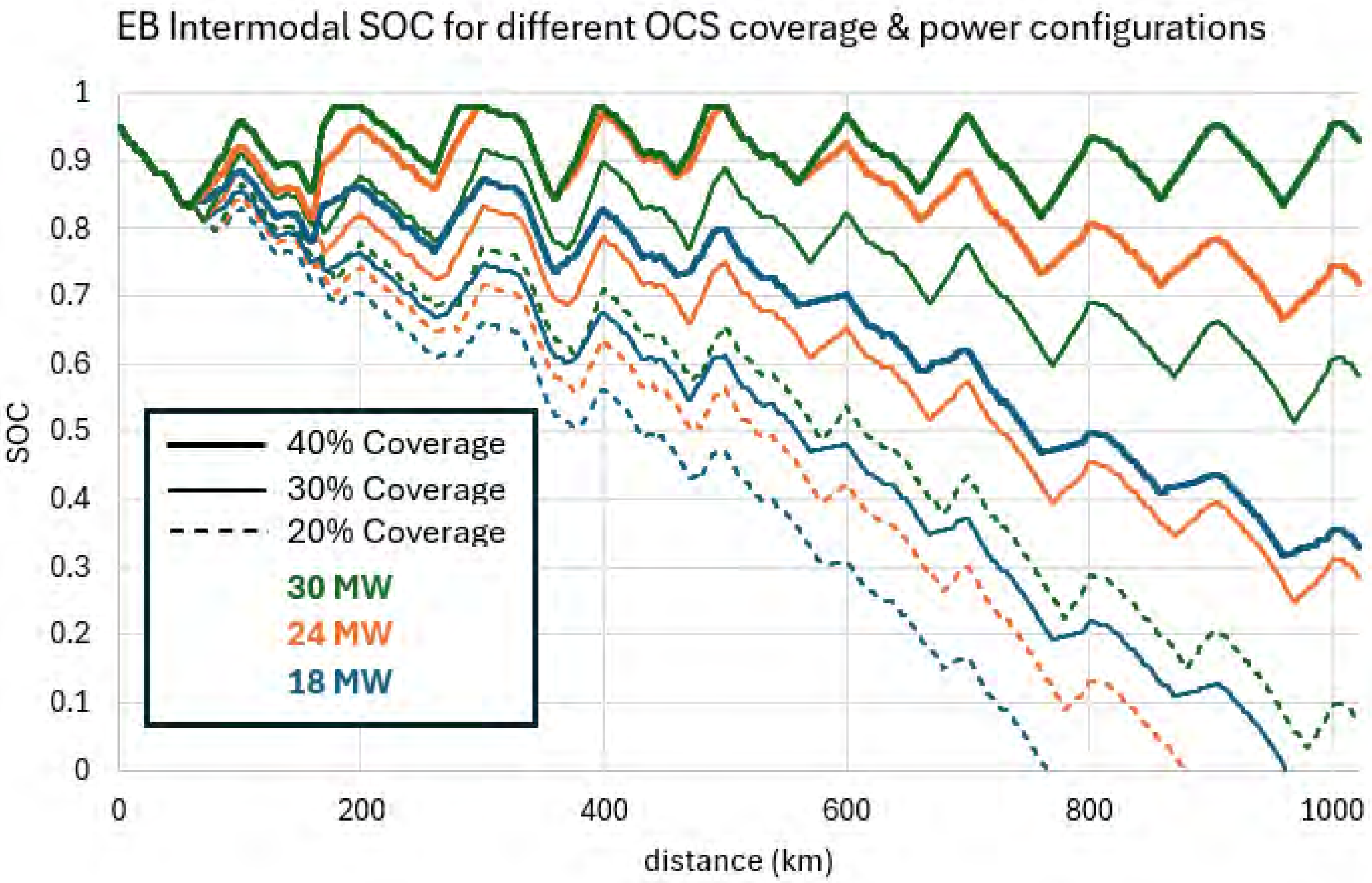


Mainline Case Study: Intermittent Electrification

- 30 MW OCS at 40% coverage proved sustainable
  → room for further optimization
- Substantial reduction in OCS cost in exchange for battery storage capacity costs

OCS Subtotals ($ millions)

Catenary	85
Substations	142
Transmission	12
Public Works	0
Signaling & Communication	291
Total	**$530**



(was $2,046 for conventional OCS)

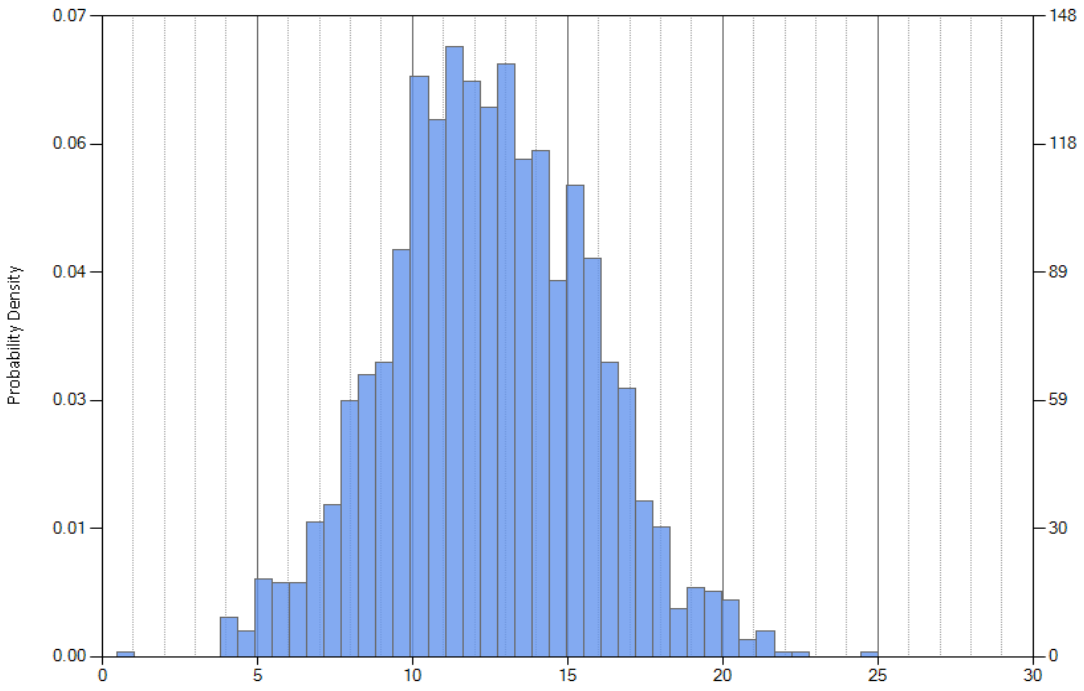
Mainline Case Study: Intermittent Electrification

- Economics and cashflow are improved but still create substantial negative position
- Public support might still be necessary to stimulate private investment
  - Attractive rates of return if public benefits can be monetized
  - However, much uncertainty in battery costs and lifespan

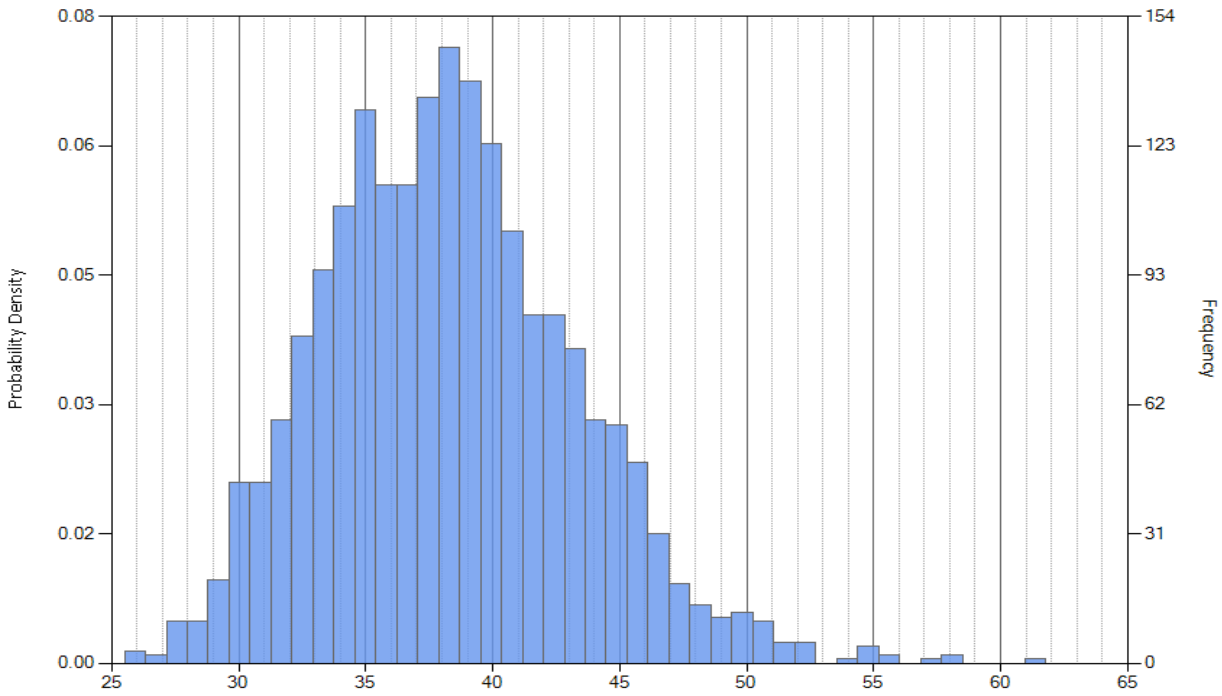
Perspective	**Net Present Value ($ millions)**			**Internal Rate of Return**	**Benefit-Cost Ratio**		
Discount Rate:	3%	7%	18%		3%	7%	18%
Purely Private RR Investment	1530	279	-1060	8.3%	1.5	1.1	0.6
Private Investment with ROW Sharing	2310	806	-835	10.6%	1.8	1.3	0.7
Private investment w/ ROW sharing and public support	9530	6020	1850	35.7%	4.2	3.2	1.8
Public Perspective	9890	6270	1980	36.9%	4.4	3.3	1.8

Intermittent Electrification Scenario – Uncertainty/Risk

Private Rate of Return



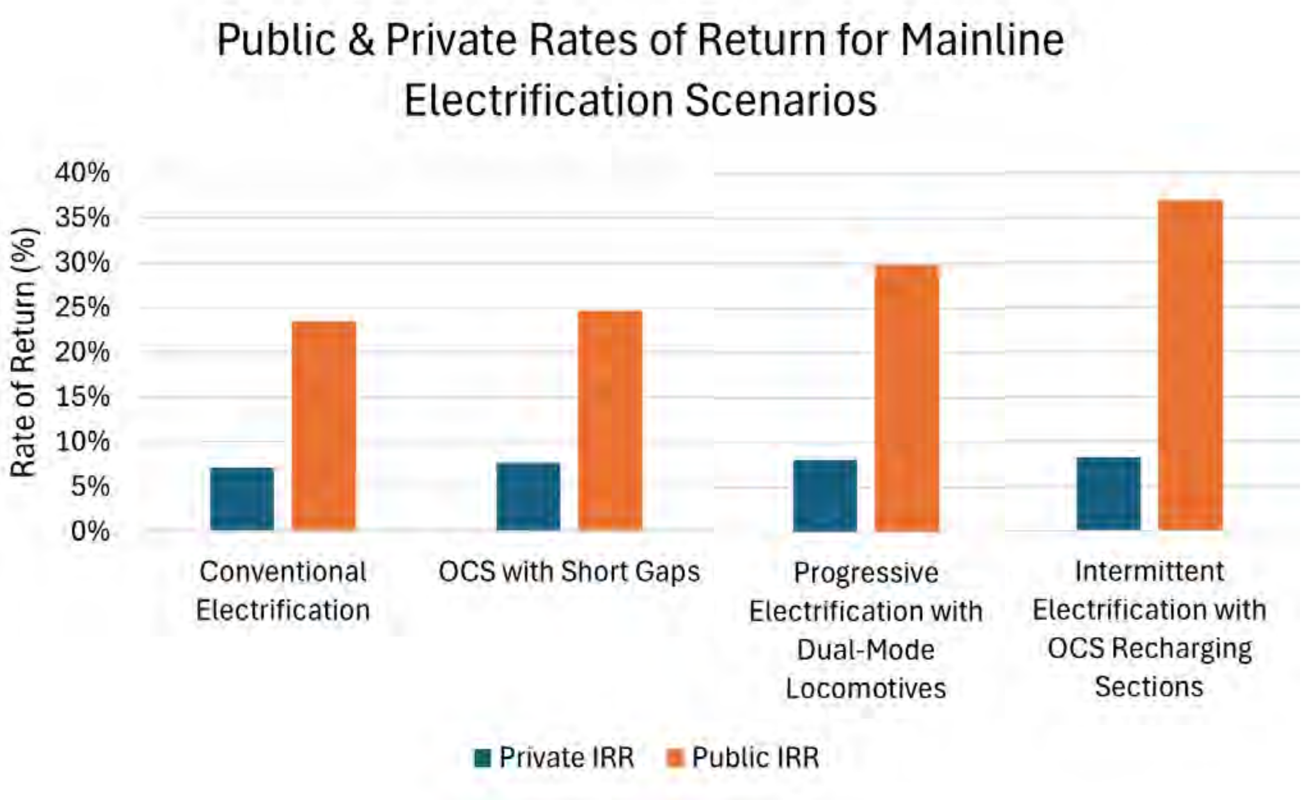
Public Rate of Return



Mainline Case Study: Scenario Comparison

- Each of the technologies tested improved project economic performance
- Some internalization of public benefits might be necessary to bring about large enough returns for investment

Scenario	Private Internal Rate of Return	Public Internal Rate of Return
Conventional Electrification	7.2%	23.5%
OCS with Short Gaps	7.7%	24.6%
Progressive Electrification with Dual-Mode Locomotives	8.1%	29.8%
Intermittent Electrification with OCS Recharging Sections	8.3%	36.9%



Summary

- Barriers to traditional freight rail electrification are **economic and institutional**

- Key methods to improve the economics by reducing initial private capital outlay:
  - **Dual-mode locomotives**, and progressive and/or **intermittent OCS schemes**
  - **Utility partnerships** for transmission on railroad ROW in exchange for lease payments or favorable electrical rates plus low-cost grid connections
  - **Public partnerships** to monetize the climate and health benefits via infrastructure investment

- Even with these technologies and partnerships, current understanding of costs and benefits leads to **large uncertainty** in benefit/cost ratio and rate of return → **Risk!**
  - **CURRENT Model** can help practitioners understand and quantify this risk
  - Railroad-utility-public partnerships can help **spread inherent risk of future energy prices**
  - **Further research and demonstration projects** on dual-mode locomotive costs and efficiency, and potential impact of OCS on PTC systems, will help reduce uncertainty and risk

Thank you for your attention!

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