Environmental Effects of Transport Electrification: Evidence From the Indian Railways

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Motivation Short

Sits at the intersection of three motivations

- Under-investment in Public Transport Infrastructure
- Policy Impetus behind Transport Electrification
- Air Pollution

Motivation I - Struggling Public Transport & Transition

- Public Transport Infrastructure is neglected & under-invested.

- E.g.: Indian Railways under-investment in safety and modern signaling
- Coupled with weak revenues
  - Metros in the US (Kearney et al., 2015)
  - Public Transport Corporations (Bus operators) in India (MoRTH, 2019)
  - Europe - public transport haven - not an exception post-COVID (Jenelius and Cebecauer, 2020; Marra et al., 2022)
- Consequences
  - Pollution
  - Overcrowding -> harassment & exit of women
  - Accidents

- The spectre of Green Transition

Motivation I - Struggling Public Transport & Transition

- Transition imposes new demands on stressed budgets

- Acquire new vehicles or retrofit existing ones, Create enabling infrastructure, and Monitor fuel and power consumption efficiency

- Estimated costs - **?? - No reliable estimates for even a case-study in the literature**
- What we know:
  - At present, electric *rolling stock* costs more than diesel rolling stock
  - Technology is improving, path uncertainty higher than in electricity technology
  - Hysteresis

- Electrification

Motivation II - Electrification & Its Unknowns

- Massive policy push for transport electrification
- Policy Buckets
  - Subsidies for electric vehicles
  - Subsidies for R&D in the sector
  - Public R&D investments
  - Market-making mechanisms and commitments
- Key policy unknown - technology adoption
- Demonstrated benefits in real world remain few - most studies use modelling, laboratory settings, simulations. (Exception - country-level panels with low explanatory power)

Motivation III - Air Pollution

- Transport is a huge & growing contributor to global GHG and pollutant emissions
- Important pollutants (in order of transport sector's share to ambient levels) - CO, NO_x, particulate matter, ozone, SO_2 (Annadanam and Kota, 2019)
- Considerable policy action - carbon taxes, congestion taxes, odd-even (or driving restriction) rules (Davis, 2008; Gallego et al., 2013), fuel and performance standards, infrastructure provision (public transport, new/wider roads & highways)
- Mixed Effects of success
  - Taxes - extremely successful in developed countries.
  - Fuel Standards - well-studied, success depends on phase-out of older vehicles (Not as quick as one may think)
  - Driving Restrictions - very leaky.
  - Infrastructure - except new modes of PT (Gendron-Carrier et al., 2022), remains understudied.

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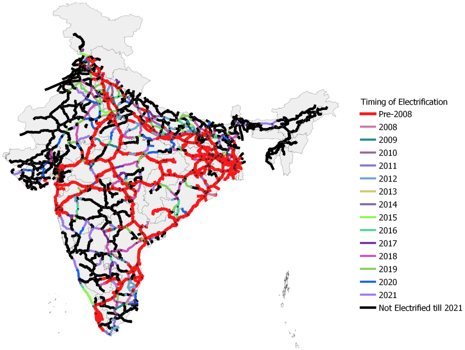
Contributions & Brief Preview

- Case Study of the Electrification of Indian Railways
- Extent of Electrification (under 30% tracks in 2010 -> 80% in 2019)



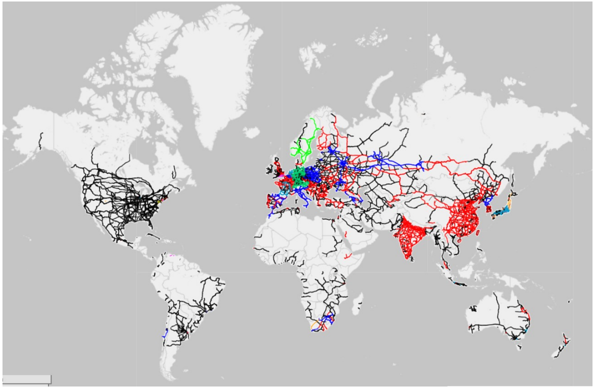
NOTE. Timing of Electrification of Indian Railway Tracks

Contributions & Brief Preview

- Bygone Issue??

Contributions & Brief Preview

- Bygone Issue??
- Extent of Electrification of Global Railways (IEA, 2017)



NOTE. Extent of Electrification of Railways Across the World

Contributions & Brief Preview

- Case Study of Electrification of Indian Railways - developing country context - new data, new detail
  - Digitized maps & list - dataset of year of electrification of majority route-kilometre in India
  - Utility - network effects
- Link route electrification to electric locomotive use
- Tentative Impacts of electrification on air pollution
- Move beyond PM2.5 - impacts for NO_x, CO
- Some Policy-centric simulations

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Basic Background - Indian Railways

- Indian Railways is a behemoth - 67000 kms of tracks, 1.5 million employees, 1% of country's GNP (Raghuram and Gangwar, 2009)
- Its environmental impact is under-studied - low incentives as no clear authority can regulate it
- Huge railway electrification drive - Rs. 1 lakh crore over a decade ($12 billion)
- Its impacts remain understudied.

Basic Background - Electrification

- Why Electrify?
  - Lower use of diesel (IR cuts its diesel use by half within the period of study) - less exposure to price volatility
  - Lower air pollution and emissions
  - Faster Speeds
  - *Sparks Effects*

Basic Background - Electrification

- Why Electrify?
  - Lower use of diesel (IR cuts its diesel use by half within the period of study) - less exposure to price volatility
  - Lower air pollution and emissions
  - Faster Speeds
  - *Sparks Effects*
- How does Electrification work?

NOTE. Process of Electrification

Sample Construction

- Not tracks, but Trains and Stations
- Goal: Measure pollutant concentration in a buffer of 2km around 612 junction railway stations
- & its evolution with changes in electrification in incoming train traffic.
- Two samples - national (2010-2019), Bengaluru (2016-2019)
- Panel of railway stations linked to trains arriving with varying degrees of electrification over time.

Data - Outcomes (PM2.5)

- Source: (Dey et al., 2020)
- Brief description - Remotely sensed (and calibrated) 1kmX1km PM2.5 concentration across country at monthly frequency (2000-2019) [Several caveats may arise during the course of the talk]

Table Summary Statistics, Air Pollution (2010-2019)*

Characteristic	N	Mean	SD
Average PM2.5	73440	69.1	37.9
Average PM2.5, Largest Zones			
NR Zone	9720	80.1	39.9
WR Zone	8040	61.6	23.5
ECR Zone	6840	82.5	47.4
SCR Zone	6120	54.7	24.3
SR Zone	5040	46.4	18.5

Data - Outcomes (Other Pollutants)

- Source: CPCB Air Quality Monitoring Stations (AQS)
- Brief description - Two AQS - City Railway Station (CRS), BTM Layout - at different distances from railways that report daily frequencies of many pollutants (2016-2019). Values imputed for completion
- CRS located at 0.2 kilometres from the railway station, BTM at 8 kilometre (also the AQS which is farthest away from railway stations/tracks in the city)
- Is SBC a good station to use?
  - 140 trains daily, one of the busiest stations in South India
  - One of only 2 railway stations with an AQS within 1 kilometre, only 32 stations have AQS within 5 kilometres.
  - The other station is Allahabad. Not used for 2 reasons - (a) variation, (b) data quality

Summary Statistics - Bengaluru Sample

Table Pollutant Concentration, Bengaluru Sample (2016-2019)

Characteristic	N	Mean	SD
CRS Air Quality Monitoring Station			
CO (mg/m^3)	1461	1.3	0.8
NO($\mu g/m^3$)	1461	18.4	16.8
NO_2($\mu g/m^3$)	1461	42.9	24.0
NO_x(ppb)	1461	41.3	29.7
BTM Air Quality Monitoring Station			
CO(mg/m^3)	1461	0.8	2.6
NO($\mu g/m^3$)	1461	6.2	16.5
NO_2($\mu g/m^3$)	1461	21.5	19.1
NO_x(ppb)	1461	18.5	16.6

Data - Electrification (General)

- Source:

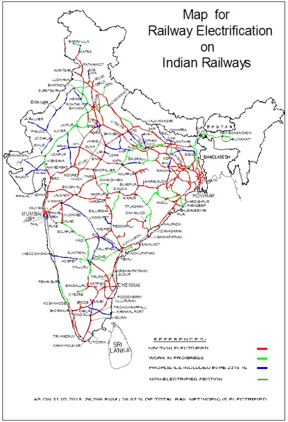


Figure IR Electrification Map, 2010

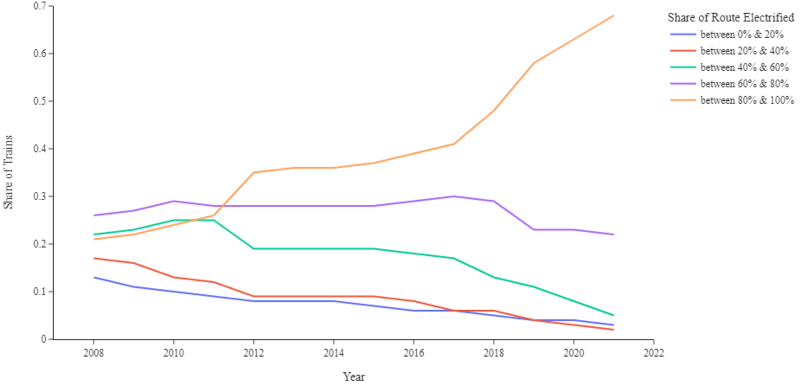
III Sections Opened for Electric Traction After Inspection by Commissioner of Railway Safety in 2014-2015.

S.No.	Section	Railway	State	RKM
1	Vellore-Villupuram	SR	Tamil Nadu	150
2	Pathankot-Jammu Tawi	NR	Punjab and Jammu & Kashmir	100
3	Barabanki-Gonda	NER	Uttar Pradesh	88
4	Chhapra-Siwan-Thawe	NER	Bihar	88
5	Khurja-Meerut	NR	Uttar Pradesh	84
6	Virudunagar-Vanchi Maniyachchi-Tirunelveli, including Vanchi Maniyachchi-Tuticorin	SR	Tamil Nadu	143
7	Hajipur-Muzaffarpur-Bachhwara	ECR	Bihar	140
8	Kachujor-Sainthia	ER	West Bengal	22
9	Siwan –Bhatni	NER	Bihar and Uttar Pradesh	50
10	Vizianagaram-Garudaballi	ECoR	Odisha	13
11	Mathura-Alwar	NCR	Uttar Pradesh & Rajasthan	123
12	Kanpur Anwarganj-Kalyanpur	NER	Uttar Pradesh	10
13	Shoranur-Kozhikkode (Excluding)	SR	Kerala	84
14	Manmad-Puntamba-Shirdi	CR	Maharashtra	81
15	Total			1,176

Figure Railway Tracks *electrified* in 2014-15

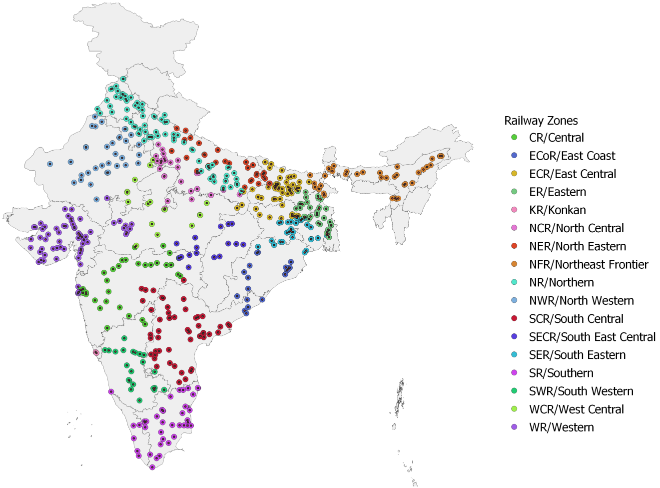
Data - Electrification (Trains)

- Aggregate track electrification to train routes - sample of **1942**** trains plying in 2016-17
- Y-axis - share of Trains with electrification level given by index, x-axis - year



Data - Electrification (Stations)

- Sample of 612 junction railway stations



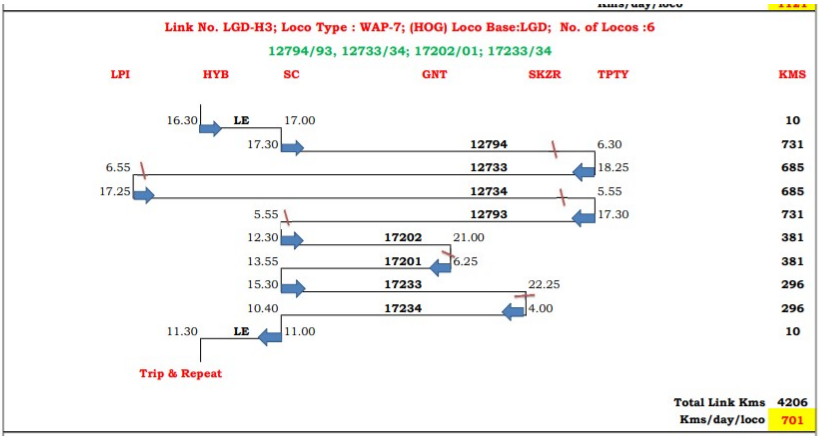
Data - Electrification (Stations)

Table Summary Statistics, Sample Railway Stations

Characteristic	(1) N	(2) Mean	(3) SD
Number of Arriving Trains	612	96.2	76.9
Share of Trains >80% Electrified (2008)	612	0.16	0.24
Share of Trains >80% Electrified (2021)	612	0.44	0.34

Data - Use of Electric Locomotives (2012)

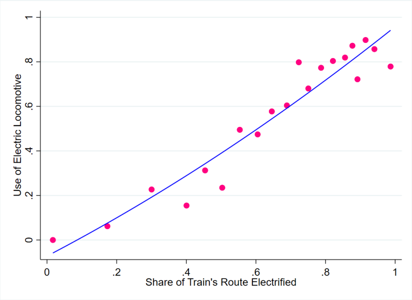
- Source: *Electric* Loco-Link Diagrams



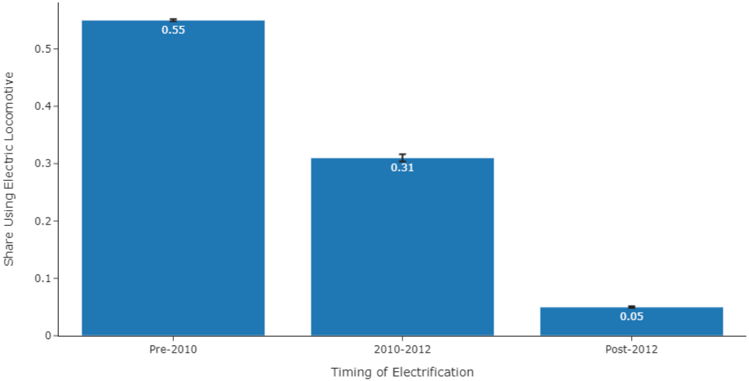
NOTE. Sample Loco Link Diagram

Data - Use of Electric Locomotives (2012)

- Source: Focus on 1942 trains***
- 55.7% were using electric locomotive at some point in their route in 2012.
- Over-optimistic take
- y-axis: share of trains using electric locomotive, x-axis=route electrification



Data - Use of Electric Locomotives (2012)



NOTE. Electric Track Usage by Year of Electrification

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Models

- PM2.5

$$Y_{smt} = \lambda_s + \lambda_{mt} + \lambda_s * t + \sum_{i=1}^{i=4} \beta_i * N_{st,i*20 \leq x < (i+1)*20} + X_{smt} + \epsilon_{smt}$$

- Other Pollutants

$$Y_{qdwmt} = \lambda_q + \lambda_{mt} + \sum_{i=1}^{i=4} \beta_i * N_{wt,i*20 \leq x < (i+1)*20} +$$

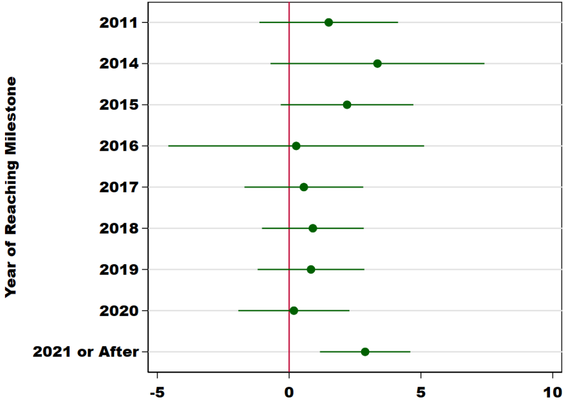
$$NearStation_q * \sum_{i=1}^{i=4} \gamma_i * N_{wt,i*20 \leq x < (i+1)*20} + W_{dmt} + \epsilon_{qdmt}$$

Threats to Identification

- Focus on PM2.5 as a ’continuous difference-in-differences’
- Address Parallel Trends and Selection on Gains
- Neither of them are testable on their own, but we show some evidence to suggest that our data is conducive to estimation using methods that require these assumptions

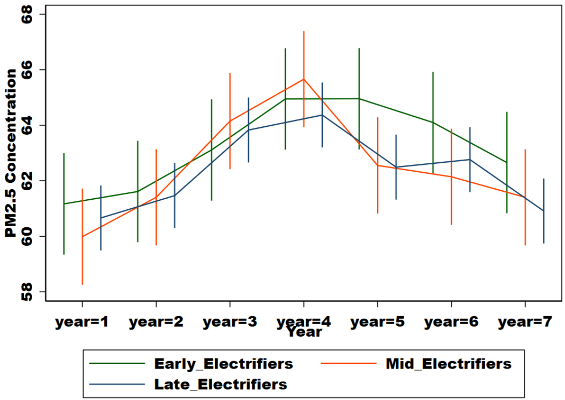
Parallel Pre-Trends

- Use data on PM2.5 concentration from **2000-2008****
- Classify stations according to their speed of traffic electrification - number of years post-2010 for a majority of their trains to reach 80% electrification bracket.
- Difference in Levels



Parallel Pre-Trends

-
- Club them into early electrifiers (reached milestone pre-2011 - 22.6%), mid-electrified (reached there in 4-8 years, 23.2%, and the rest 54.2%)



NOTE. PM2.5 Trends by Speed Buckets

Selection on Gains

- Callaway et al. (2021) argues that conditional ATTs should be same - different from parallel trends
- observations receiving different dosages should expect to respond similarly to alternative dosage of treatment
- Arguments:
  - Different stations - notably those with different levels of electrified train traffic - would respond similarly to addition of new electric trains.
  - May not be true for shares of local pollution, as they would depend on the background air pollution in the area
  - Key difference between plying new electric trains through the station and raising the share of route-electrification of incoming trains

Selection on Gains

Table Determinants of the Use of Electric Locomotives (N=55,380)

$N_{20 \leq x < 40}$	-0.02	0.01	-0.00
	(0.016)	(0.014)	(0.011)
$N_{40 \leq x < 60}$	-0.02**	-0.02**	-0.02**
	(0.007)	(0.006)	(0.007)
$N_{60 \leq x < 80}$	0.02**	0.01	0.01
	(0.006)	(0.006)	(0.005)
$N_{80 \leq x < 100}$	0.02***	0.02***	0.00
	(0.004)	(0.004)	(0.002)
Share Route Elec.		0.65***	0.53***
		(0.041)	(0.038)
Stn. Controls			Yes
R-squared	0.13	0.19	0.26

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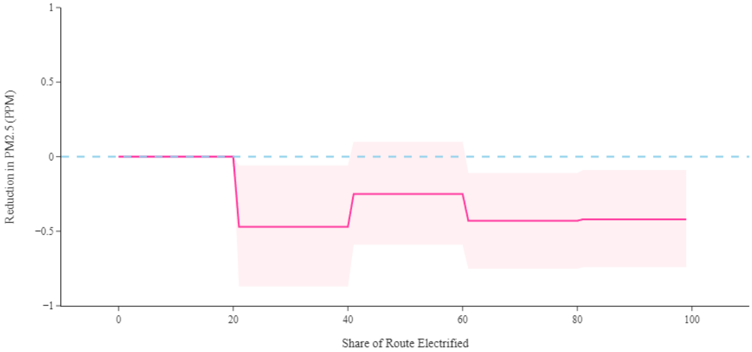
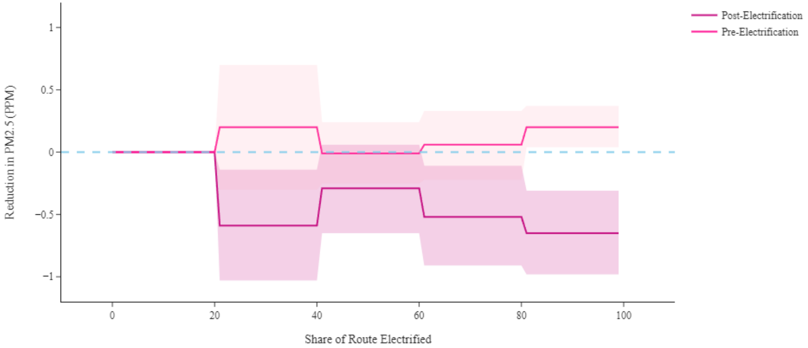
Results PM2.5 -1



NOTE. Estimated Effects of Electrification on PM2.5

Results PM2.5 -2



NOTE. Estimated Effects of Electrification on PM2.5

Results Other Pollutants -1

Standard Errors - 95% confidence intervals, two-way clustering at day-of-weekXyear & stationXmonth level.

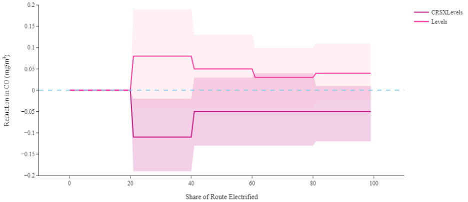


Figure Effect of Electrification on *CO* (Bengaluru Sample)

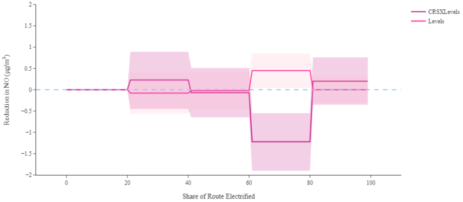


Figure Effect of Electrification on *NO* (Bengaluru Sample)

Results Other Pollutants -2

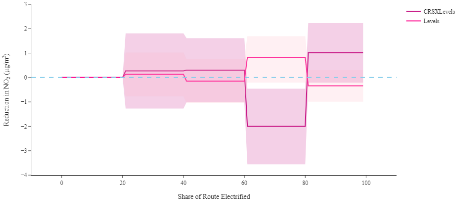


Figure Effect of Electrification on NO_2 (Bengaluru Sample)

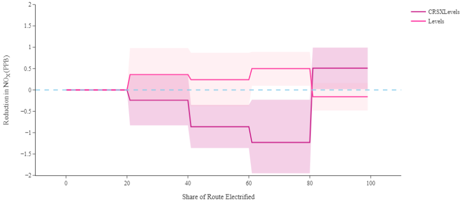


Figure Effect of Electrification on NO_x (Bengaluru Sample)

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Potential Ways to Address Policy Concerns

- Should Diesel Engines be phased out?
  - Current policy requires IR to use diesel locomotives for at least 15 years after acquiring, the last ones purchased in 2015.
  - Decommissioning seen as a loss to exchequer, but benefits of retention may outweigh costs.
- Should other countries electrify their railways?
  - Electrification seen an expensive, especially not useful in light of underfunded infrastructure discussed earlier
  - Alternative engines - "diesel-electric" locomotives exist
  - Is there an economic case for electrification in the US & Africa?
- Valuing Dual-mode locomotives - still undergoing trials in India

Some Takeaways

- What happens when we electrify? A case study on process & outcomes
- Accelerated electrification in Indian Railways from 30% to 90% in 2023
- Electrification prompted use of electric locomotives, but inefficiencies existed - low use of electric locomotives, delay in phase-out
- Electrification leads to reductions in local air pollution across pollutants
- Provides key parameters for a benefit-cost analysis of the policy

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