Technological Paradigms and Technological Trajectories. An Application to the case of British Steam Engineering, 1800-1850

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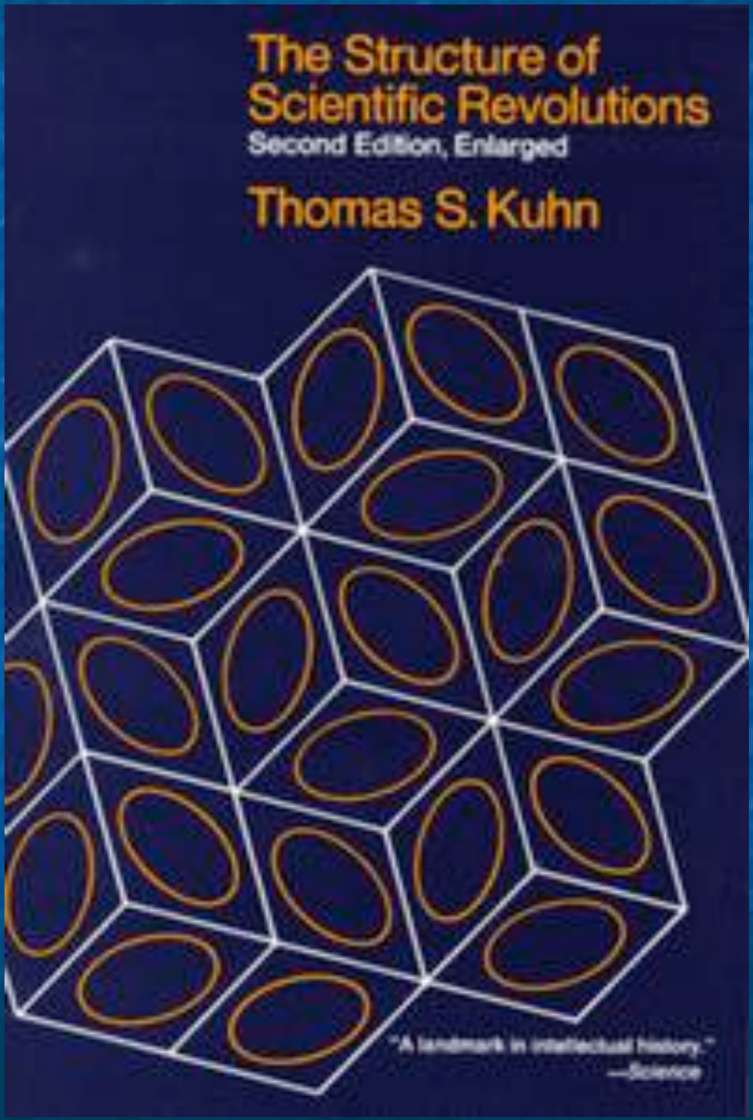
Aim of the talk

- Examine the potentialities of the paradigm/trajectory view of technological evolution (Dosi, 1982) for explaining patterns of technical change (our case will be steam engineering in Britain)
- Discuss an (economic) historian's approach to technology data

T.S. KUHN (1962), THE STRUCTURE OF SCIENTIFIC REVOLUTIONS



SCIENTIFIC PARADIGMS

“…accepted examples of actual scientific practice – examples which include law, theory, application, and instrumentation together –…. [they] provide models from which spring particular traditions of scientific research. These are the traditions which the historian describes under such rubric as ‘Ptomelaic astronomy’ (or ‘Copernican’) , ‘Aristotelian dynamics’ (or ‘Newtonian’), ‘corpuscular optics’ (or ‘wave optics’), and so on….” (Kuhn, 1962)

".....constellation of beliefs, values, techniques and so on shared by the members of a given [scientific] community" (Kuhn, 1969)

A reviewer counted at least 22 different definitions of the term "paradigm" in the book!!

TECHNOLOGICAL PARADIGMS

"…a 'technological paradigm'..[is a] 'model' and a 'pattern' of solution of *selected* technological problems, based on *selected* principles derived from natural sciences and on *selected* material technologies" (Dosi, 1982)

"A technological paradigm is both an *exemplar* – an artifact that is to be developed and improved (such a car, an integrated circuit, a lathe, each with particular technoeconomic characteristics) – and a *set of heuristics*…" (Dosi, 1988)

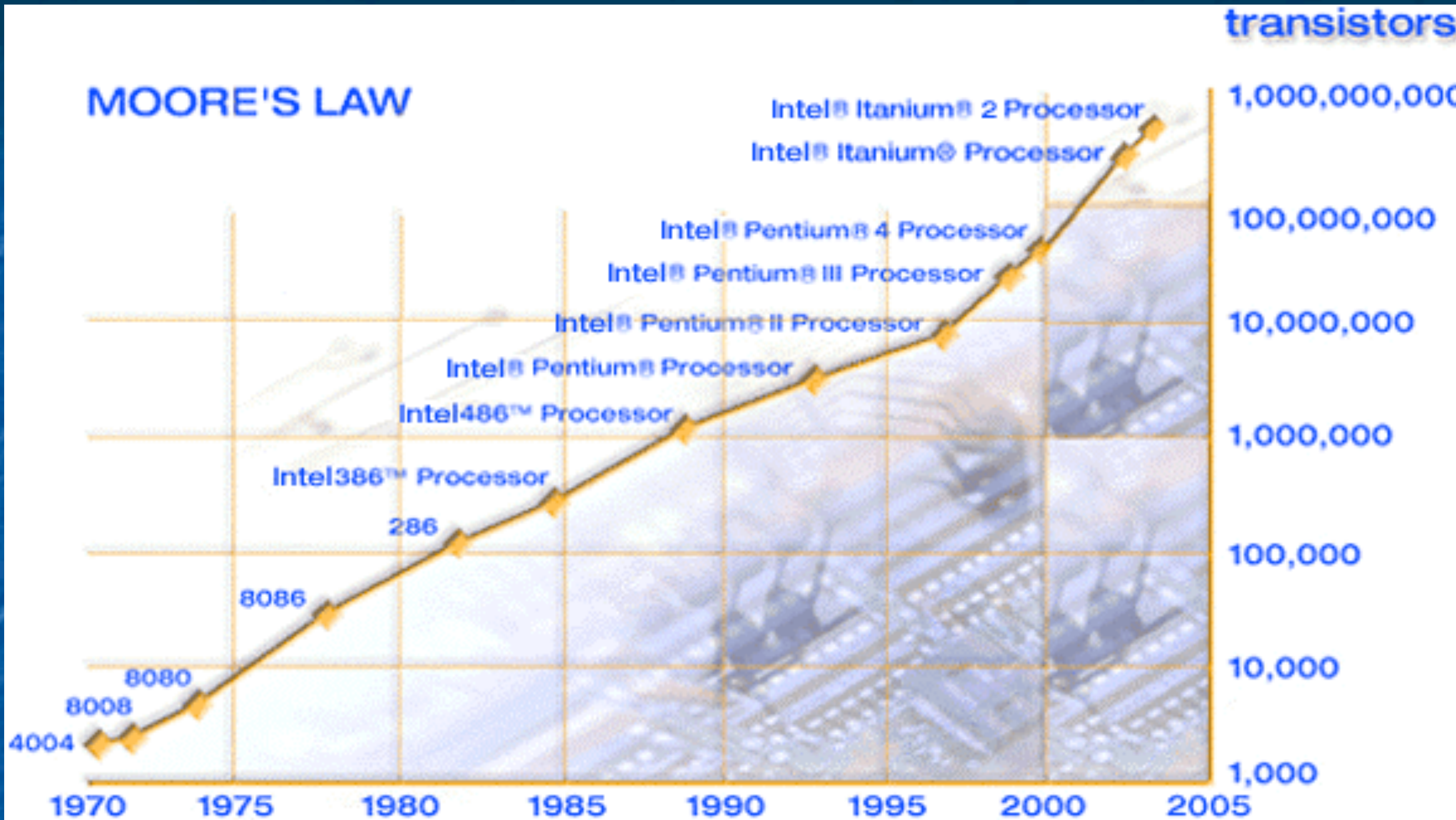
The role of heuristics

"More precisely, if the hypothesis of technological paradigm is to be of some use, one must be able to assess also in the field of technology the existence of something similar to a "positive heuristic" and a "negative heuristic". In other words a technological paradigm embodies strong prescriptions on the directions of technological change to pursue and those to neglect" (Dosi, 1982)

TECHNOLOGICAL TRAJECTORIES

"We will define a *technological trajectory* as the pattern of 'normal' problem solving activity on the ground of a technological paradigm" (Dosi, 1982).

"A technological trajectory…can be represented by the movement of multi-dimensional trade-offs among the technological variables which the paradigm defines as relevant. Progress can be defined as the improvement of these trade-offs" (Dosi, 1982)



Moore's Law: Number of transistors per integrated circuit (Source: INTEL, 2005)

Gordon Moore (1965), "Cramming more components onto Integrated Circuits", Electronics Magazine

Number of transistors in integrated circuits would double every 18 months

Example: A Paradigmatic Discontinuity
The Turbo-Jet Revolution

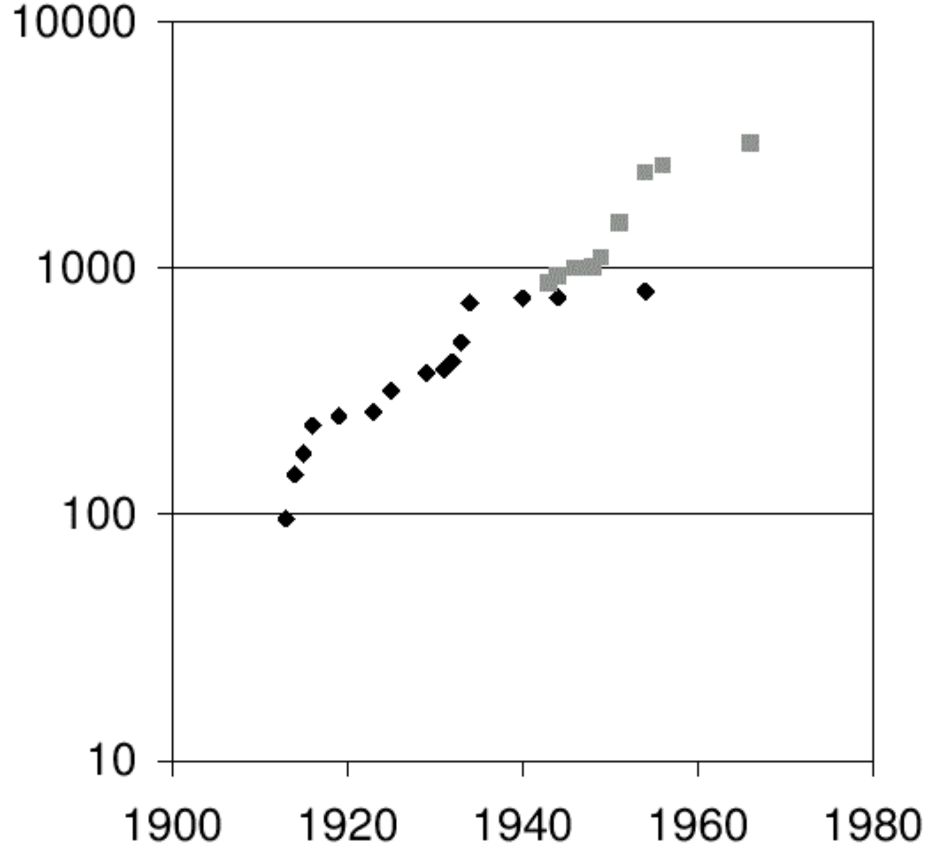
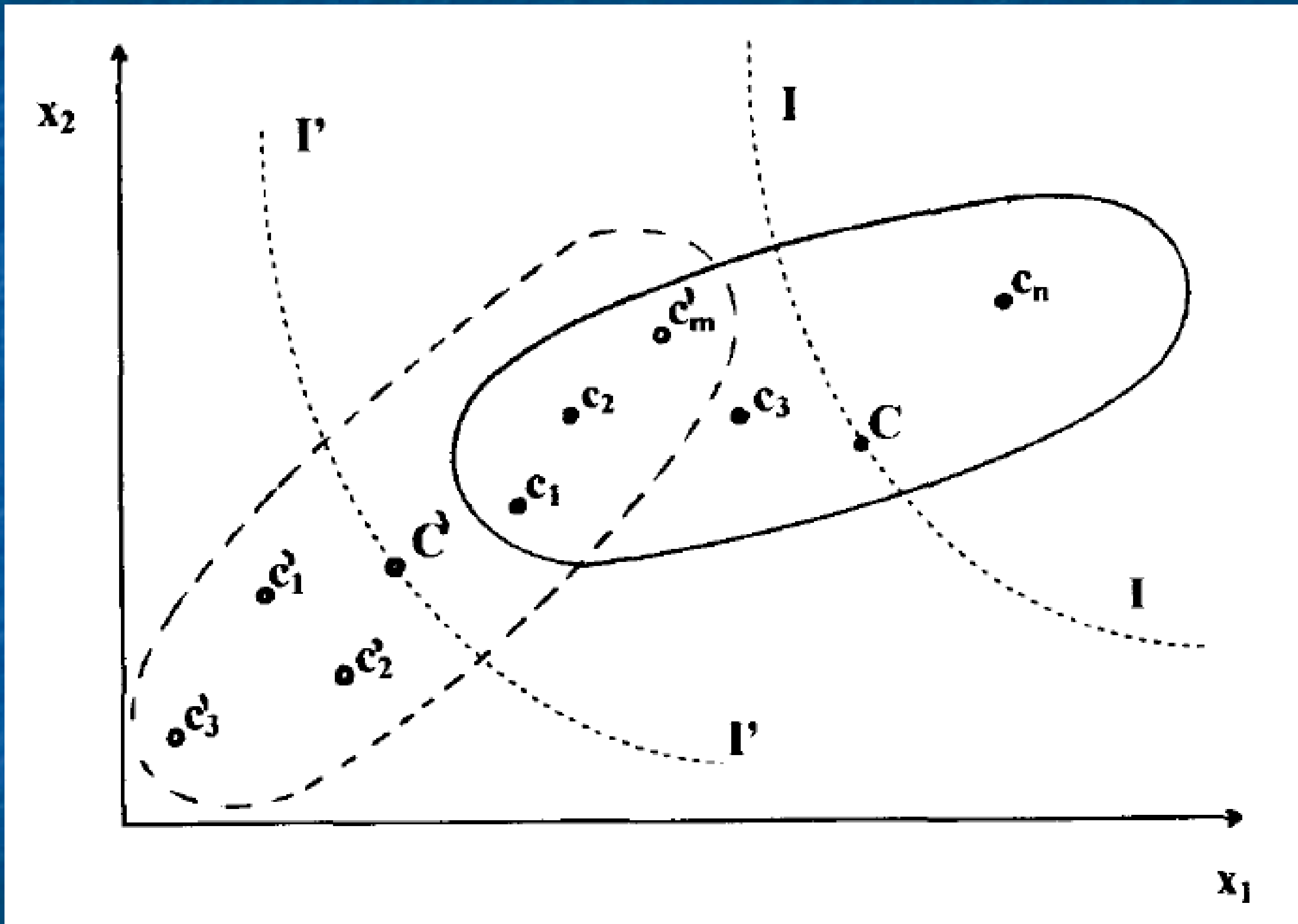


Figure 4.1. Maximum speed in km/h of propeller aircraft (diamonds) and jet aircraft (squares). Data taken from Jane's 1978)

Source: Frenken (2005)

Microheterogeneity and non substitution



Cimoli & Dosi (1995),

Technological performance of steam engines

Two indicators of fuel efficiency:

-Lbs. of coal per HP-hour
-Millions of lbs lifted one foot per bushel of coal ('duty')

Engine	Fuel Consumption (lbs. of coal per HP -hour)
Savery (1700 -1750)	30
Newcomen (1710 -1750)	20-30
Newcomen (Smeaton) (1770 -1780)	17
Watt (low pressure) (1800 -1840)	10-15
High Pressure (1850)	5

Source: Von Tunzelmann (1978)

The main question

Why we see a rapid diffusion and development of the high pressure expansive steam engine in Cornwall and a delayed adoption in other application sectors/locations ?

[Note that Cornish achievements were widely discussed in the contemporary engineering literature]

The Cornish Pumping Engine as a Case of Collective Invention (Nuvolari, 2004)

"Collective invention" concept introduced by Allen (1983)

Case study of blast furnaces in Cleveland (1850-1870)

"...[I]f a firm constructed a new plant of novel design and that plant proved to have lower costs than other plants, these facts were made available to other firms in the industry and to potential entrants. The next firm constructing a new plant build on the experience of the first by introducing and extending the design change that had proved profitable. The operating characteristics of the second plant would then also be made available to potential investors. In this way fruitful lines of technical advance were identified and pursued"

Work performed by the following Steam-Engines, drawing Ores ... in March, 1823.

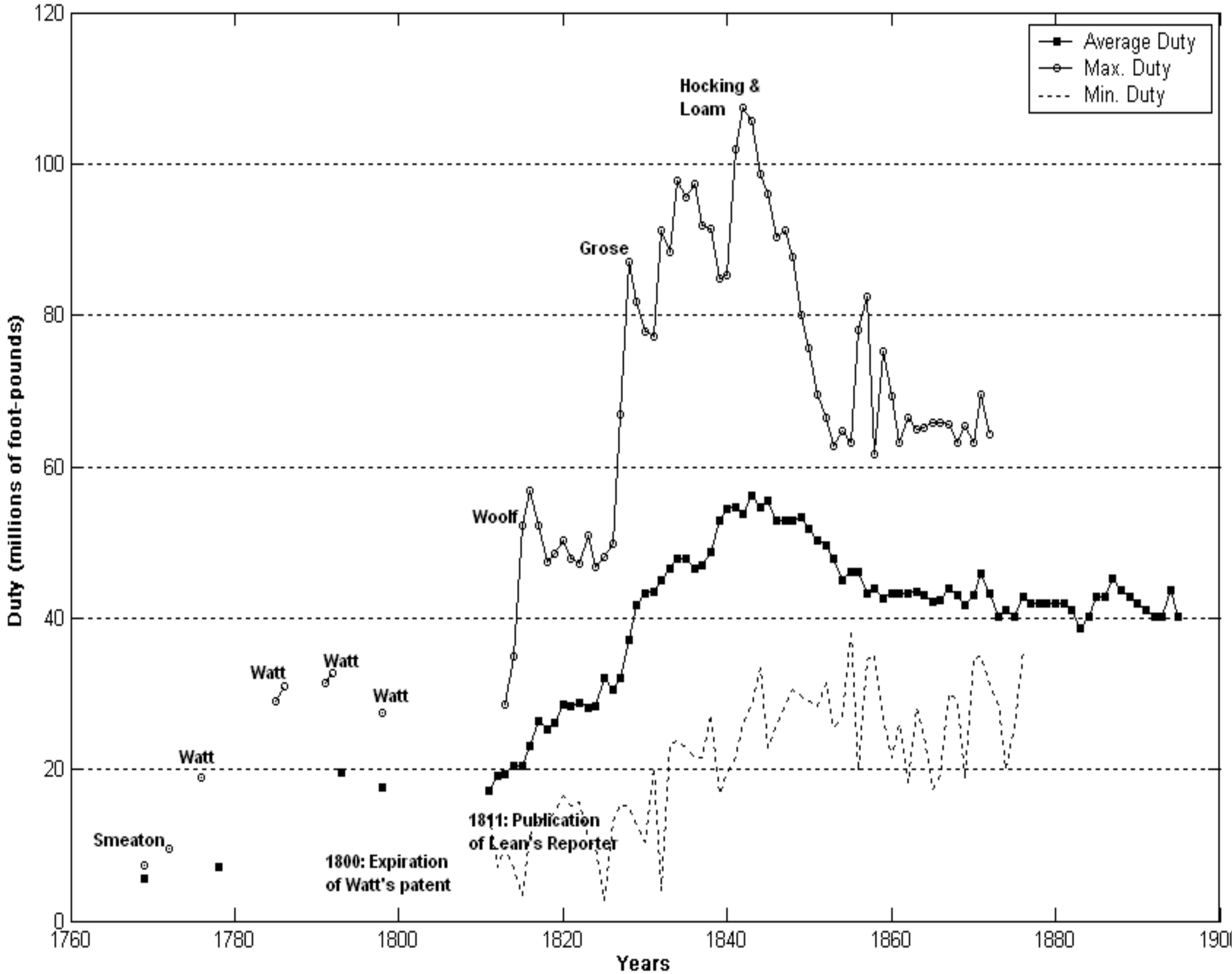
Work performed by the following STEAM-ENGINES, in MAY, 1823.

MINES.	ENGINES, and the diameters of the cylinders.	Load per square inch, on the piston. Lbs.	Length of the stroke, in the cylinder. Ft. ins.	No. of lifts.	Depth. Fms. ft.	Diameter of the pumps. Inches.	Time.	Consumption of coal, in bushels.	Number of strokes.	Length of the stroke, in the pumps. Ft. ins.	Load, in pounds.	Pounds lifted one foot high, by consuming a bushel of coal.	Number of strokes, per minute.	REMARKS, AND ENGINEERS' NAMES.
DOLCOATH ..	76 inches, single.	11 . 5	9 0	1 9 3	2 0 179 1 23 3	8⅛ 12 13	April 28th. to May 27th.	3043	256000	7 6	64860	40,987,278	6,1	Drawing perpendicularly, 179 fathoms, and on the underlay, 33 fathoms. Main beam over the cylinder. Five balance bobs under ground, and one at the surface. GRIBBLE.
DITTO	Strav-Park, 64 inches, single.	8 0	8 0	1 3 2 1 3 1 1 1	6 0 60 5 43 0 18 0 49 0 2 0 5 3 10 0	11⅛ 11¼ 11 9⅛ 7 6 8½ 6	ditto	1251	182800	5 6 3 9	37739 736	30,733,268	4,38	Drawing perpendicularly, 110 fms. and on the underlay, 24 fms. Main beam over the cylinder. Two balance bobs under ground, and one at the surface. 180 fms. of horizontal rods, at the surface, and 132 fms. of dry rods, under ground. JEFFREE.
TIN-CROFT .	66 inches, single.	8 4	9 0	1 1 1 1 1 1 1 1	36 4 24 3 21 5 21 1 5 0 3 3 4 0 12 0	14⅛ 13⅛ 11 10 5 7 9 6	ditto	2466	345540	7 0 5 0	25638 1270	34,990,759	8,26	Drawing perpendicularly, 104 fathoms, and on the underlay, 12 fathoms. Main beam over the cylinder. One bob at the surface, and one under ground. GRIBBLE.
WHEAL CHARLOTTE	36 inches, single.	3 9	9 0	1 1 1	45 0 23 0 1 3	6 7 6	May 8th. to June 4th.	201	67840	6 3	5728	12,082,945	1,7	Drawing all the load perpendicularly, with horizontal rods. SIMS.
WHEAL VOR	Pearce's, 63 inches, double.	17 0	8 0	1 4 3 1 1 1 1 1	2 0 83 0 69 3 20 0 9 3 10 0 10 0 4 0	10 13 14 6 12½ 15 10½ 9	May 3rd. to June 5th.	6837	412060	6 3	68100	25,689,897	8,30	Drawing perpendicularly, 87 fms. and on the underlay, 70 fms. Main beam over the cylinder. Five bobs, and 55 fms. of horizontal rods, under ground. SIMS AND RICHARDS.
DITTO	Woolf's, 53 inches, single, gt. cylinder; 27 inches, single, small cylinder.	19 6	8 9	1 1 2 3 1	3 0 25 3 59 1 56 3 5 3	10 12½ 13 14 6½	ditto	5080	431180	7 3	52341	32,208,380	9,0	Drawing perpendicularly, 131 fathoms, and on the underlay, 20 fms. Main beam over the cylinder. Two bobs under ground, and one at the surface. SIMS AND RICHARDS.
				1	2 3	8½								Drawing perpendicularly, 65 fms. and on

Geographical distribution of British steam engine patents, 1698-1852

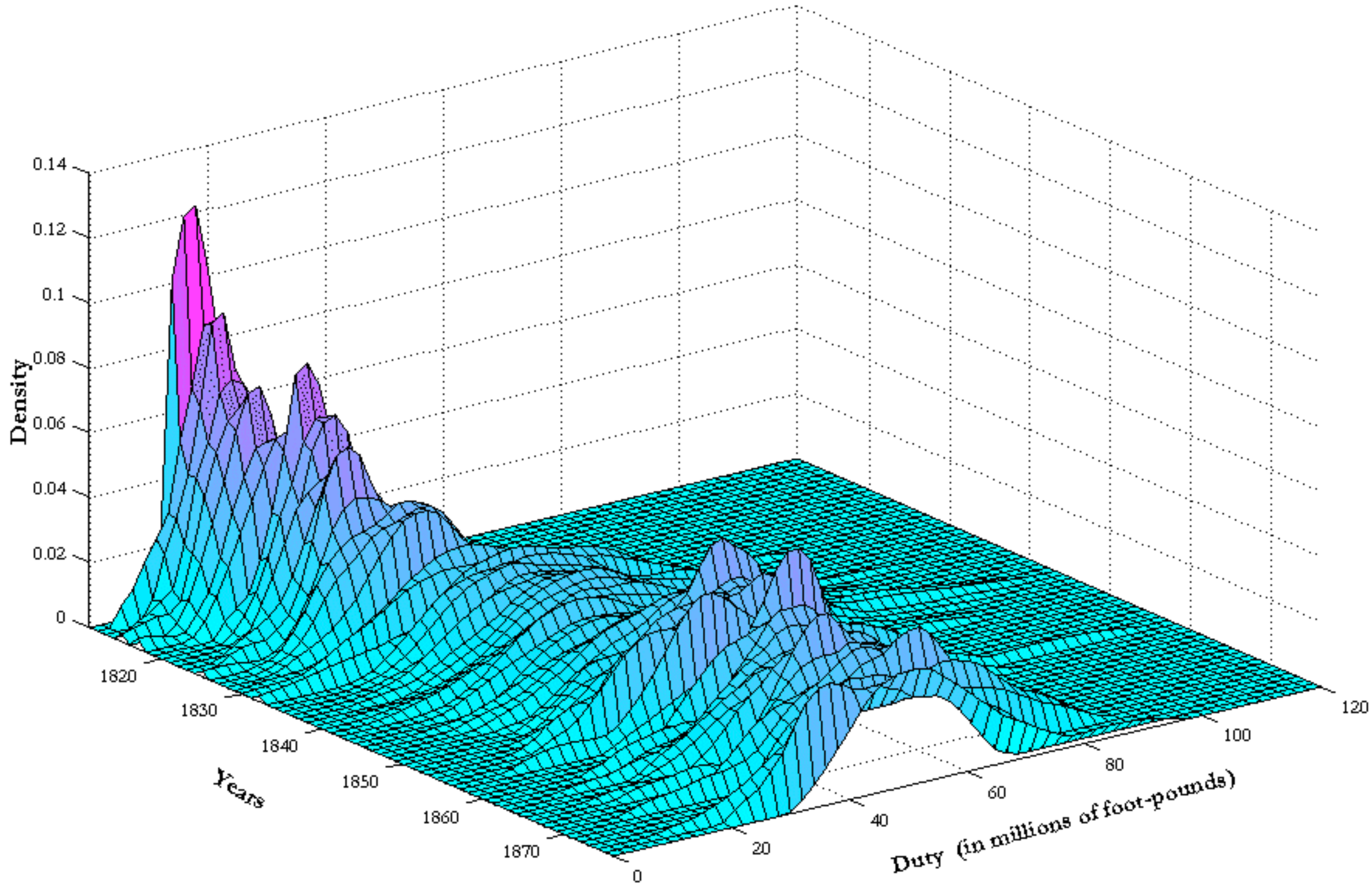
County	N. of Patents 1698-1852	(%) 1698-1852	N. of Patents 1698-1812	(%) 1698-1812	N. of Patents 1813-1852	(%) 1813-1852
Cornwall	17	1.50	8	6.25	9	0.89
Cornwall*	21	1.85	12	9.38	9	0.89
Derby	11	0.97	1	0.78	10	0.99
Durham	13	1.15	0	0.00	13	1.29
Gloucester	20	1.76	8	6.25	12	1.19
Kent	31	2.73	1	0.78	30	2.98
Lancashire	145	12.78	5	3.91	140	13.90
London	395	34.80	40	31.25	355	35.25
Northumberland	22	1.94	2	1.56	20	1.99
Nottingham	13	1.15	1	0.78	12	1.19
Scotland	47	4.14	6	4.69	41	4.07
Stafford	27	2.38	5	3.91	22	2.18
Surrey	88	7.75	10	7.81	78	7.75
Wales	12	1.06	1	0.78	11	1.09
Warwick	58	5.11	8	6.25	50	4.97
York	63	5.55	11	8.59	52	5.16
Others	152	13.39	9	7.03	143	14.20
Total	**1135**	**100**	**128**	**100**	**1007**	**100**

Source: Nuvolari (2004)

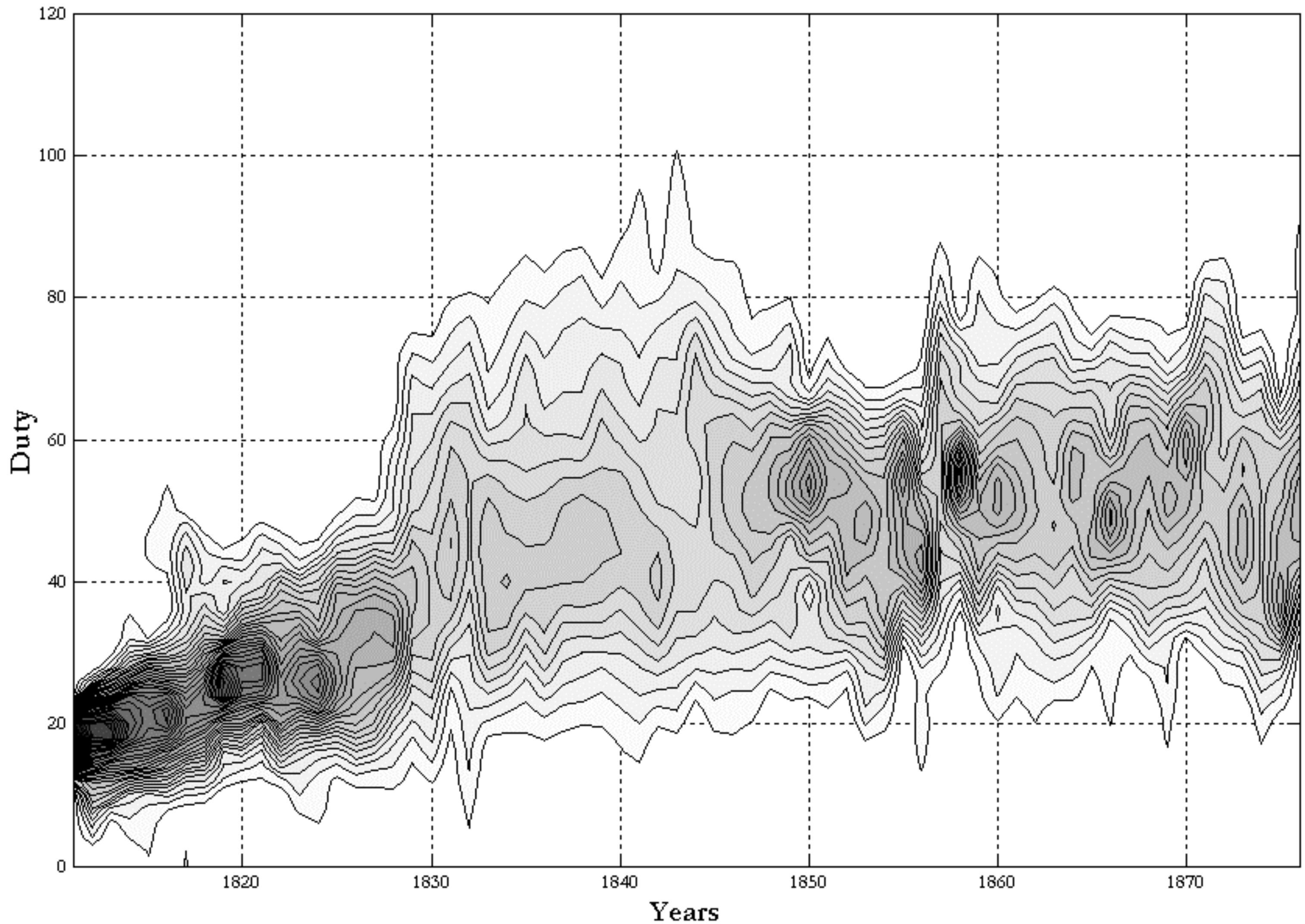


Average Duty
Max. Duty
Min. Duty
Hocking & Loam
Grose
Woolf
Watt
Watt
Watt
Watt
Smeaton
1800: Expiration of Watt's patent
1811: Publication of Lean's Reporter
Duty (millions of foot-pounds)
Years
0
20
40
60
80
100
120
1760
1780
1800
1820
1840
1860
1880
1900

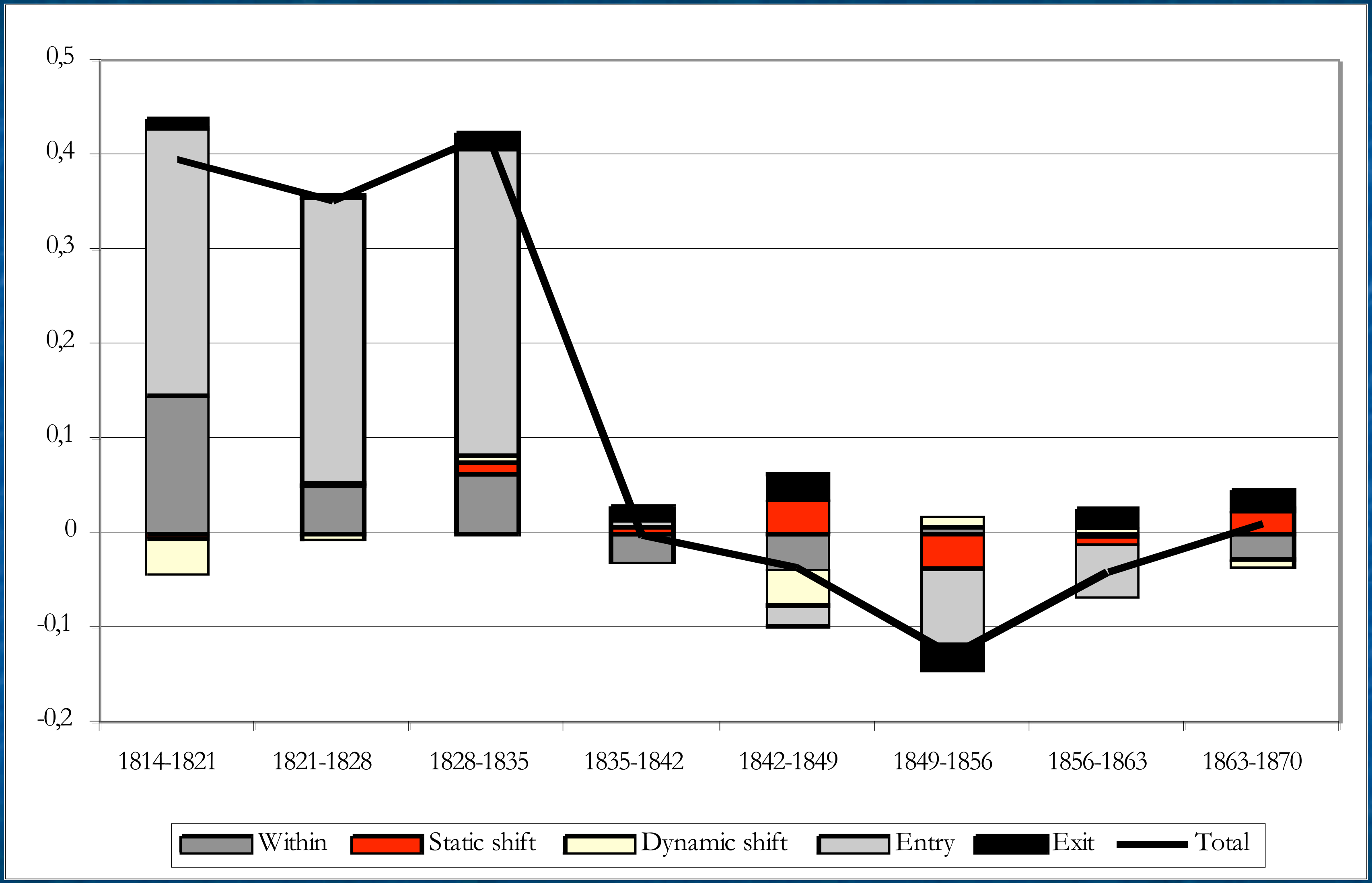
Kernel density of duty, 1811-1876



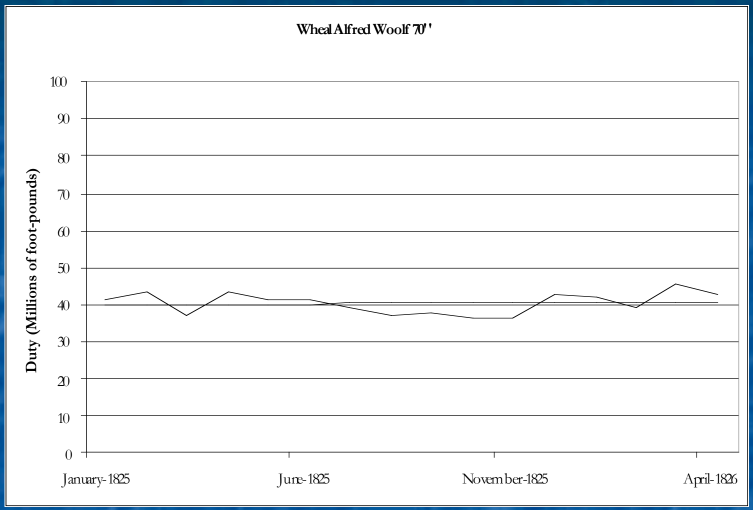
Kernel density of duty, 1811-1876

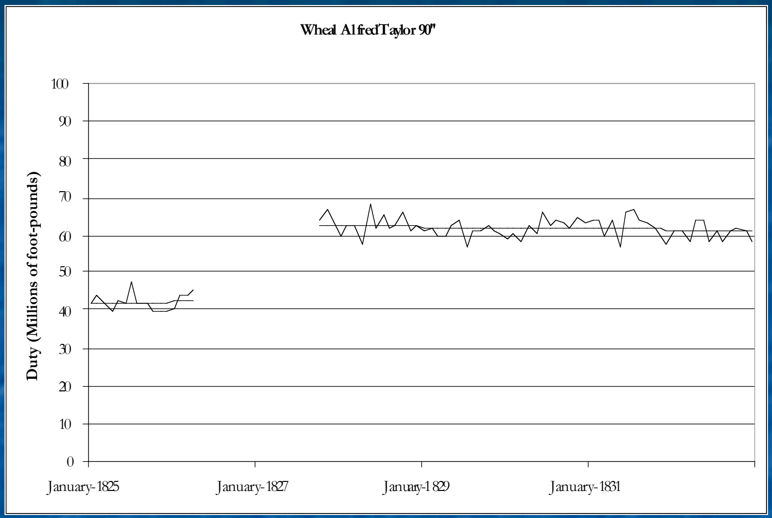


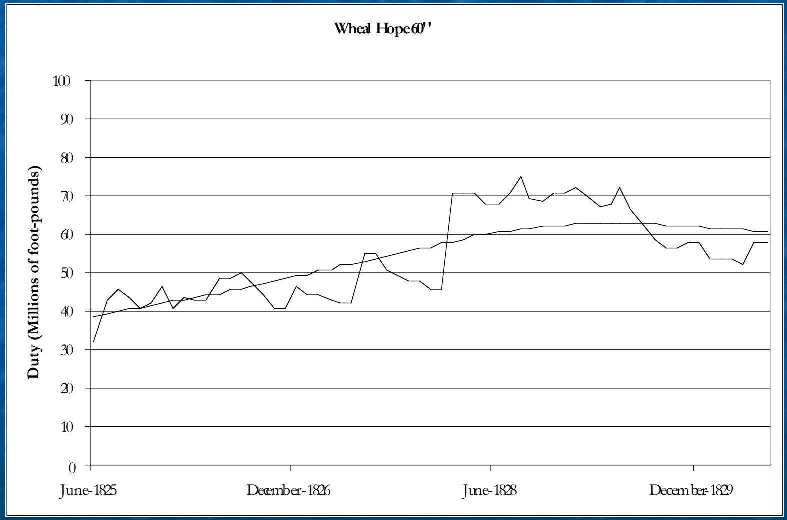
Decomposition of average duty growth.

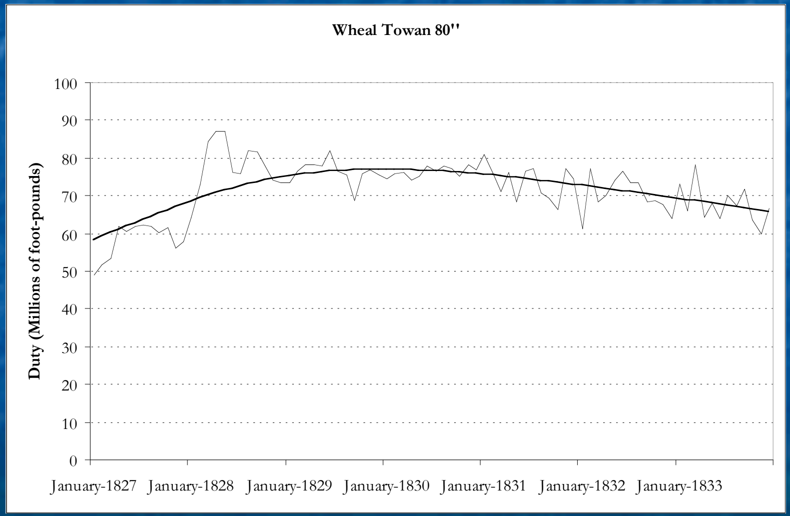


Learning in Cornish Steam engineering

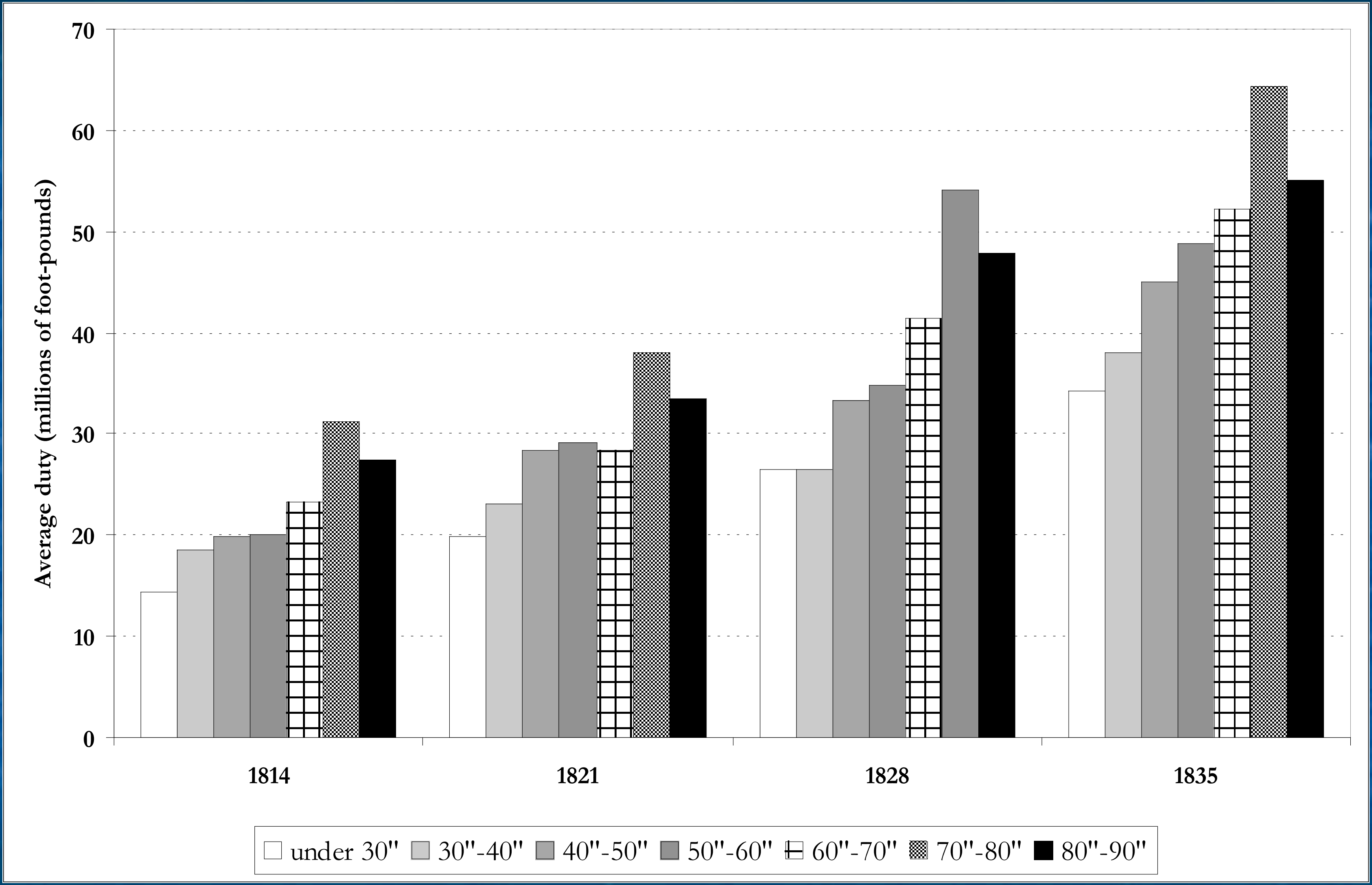






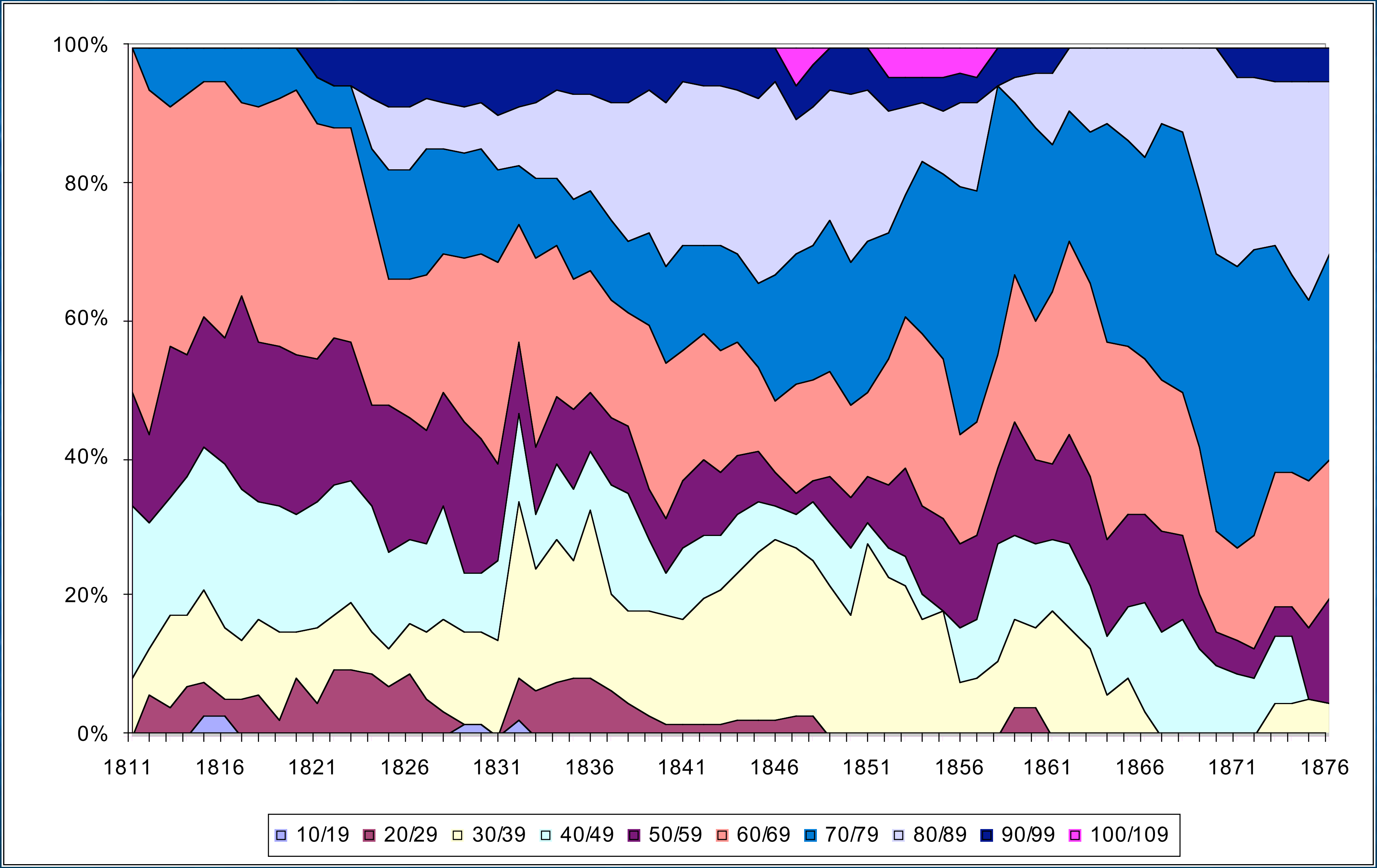


Learning in Cornish Steam engineering



Average duty of steam engines of various sizes.
Source: Lean, *Historical Statement...*, 1839

Learning in Cornish Steam engineering



Distribution of cylinder diameters (in inches), 1811-1876

Different choice of technique: Contemporary assessments

"widespread and culpable state of apathy as to the consumption of fuel…in the great manufacturing district of the North" (J. Farey, 1838)

"For a great number of years a strong prejudice existed against the use of high pressure and it required more than ordinary care in effecting the changes which have been introduced: it had to be done cautiously, almost insidiously…." (W. Fairbairn, 1849)

"The engine power of this district (Lancashire) lay under the incubus of timid and prejudiced traditions for nearly forty years, but now we are happily emancipated…." (J.Nasmyth, 1852)

Different choice of technique: Contemporary assessments

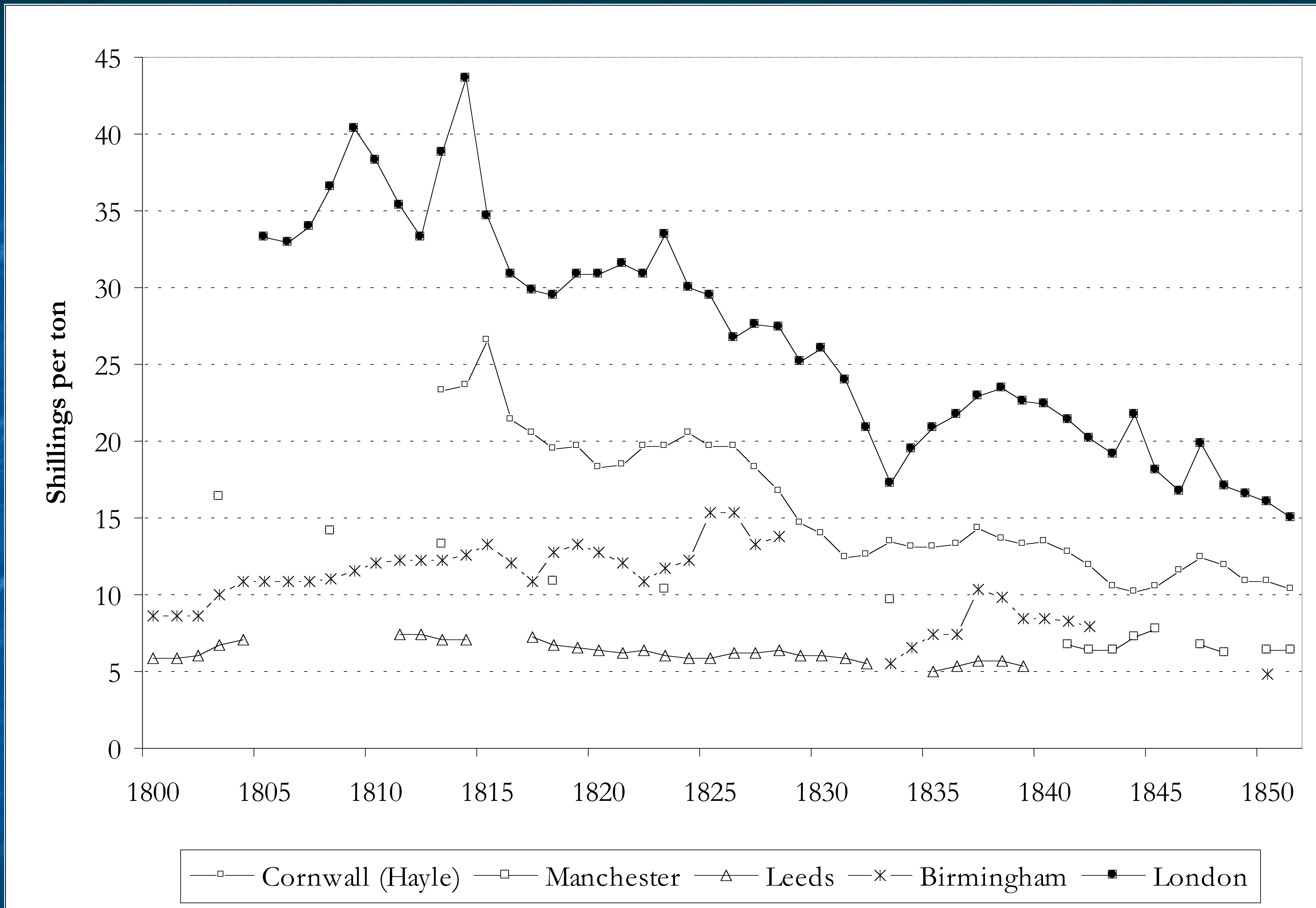
"If the statements given to the public by the Cornish engineers, whose sincerity I cannot doubt, are correct, I dare to trust to call Nature to account for the undue favouritism she confers upon our Cornish friends by enabling them to perform results that the London, Manchester and Birmingham engineers cannot approach….Upon what principle, permit me to ask, can the Cornish engineers perform so much more than all other engines. Strong should be the evidence that ought to outweigh or cancel the laws of Nature…..." (Palmer,1838)

"…the duty reported are gross exaggerations…there is nothing in the Cornish system of management that can profitably imitated by Lancashire engineers" (Armstrong, 1839

Possible Interpretations

- Entrepreneurial failure: delay in the adoption of high pressure (although we should not forget the uncertainty surrounding the decision). The contemporary debate was couched in these terms
- Rational choice: different choice of technique reflect different factor price configurations
- Technological bottleneck: adoption of high pressure required adaptations to specific application contexts (von Tunzelmann, 1978, chap 4)

Our interpretation focuses on the role of engineering *heuristics* in the different application sectors (consistent with the evidence)



Coal prices: 1800-1850

Some simple economics of steam power

Installation of a new engine:
Entrepreneur is indifferent between adopting a high pressure and a low pressure engine if

$$K_H(i+d)+C_H\cdot H\cdot p_c = K_L(i+d)+C_L\cdot H\cdot p_c$$

K_H, K_L = capital costs per HP for the high/low pressure engine,
C_H, C_L = consumption of coal per HP -hour for the high/low pressure engine
i = interest rate,
d = depreciation rate,
H = amount of working hours in the year
p_c = price of coal

Threshold coal price $$p_c = \frac{(K_H - K_L)(i+d)}{(C_L - C_H)H}$$

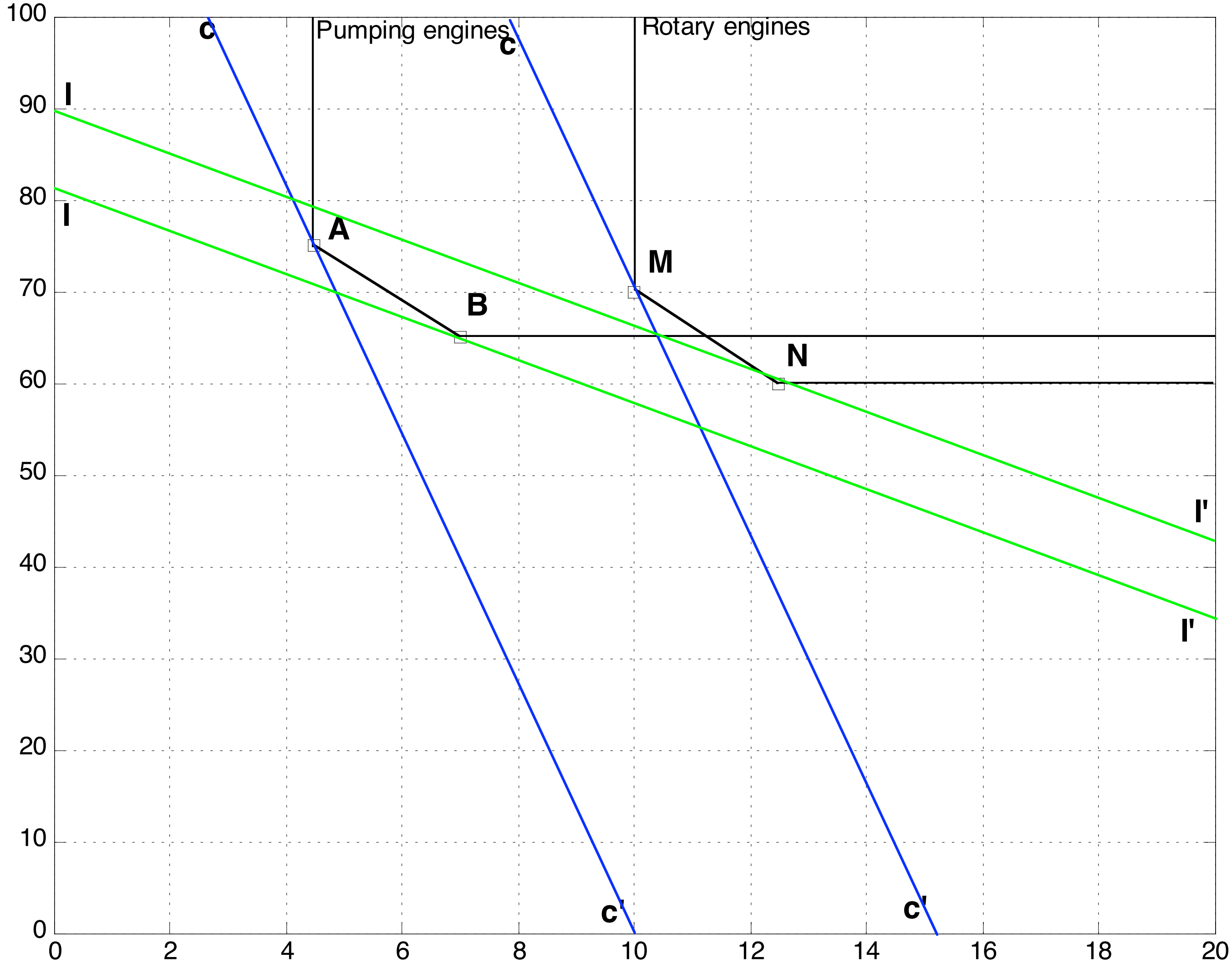
Profitability of a high pressure engine for pumping applications, late 1830s (source: T. Wicksteed, 1841)

	Cornish	Boulton & Watt	Coal price (s. per ton)	Coal price (s per ton.)
Duty (millions of foot - pounds)	90.809	40.049		
Coal Consumption (lbs per HP -hour)	2.05	4.65		
HP	135	71.50		
Total costs (£)	7600	(-)		
Cost per HP (£)	56.30	(45)		
Cost per HP per annum (£)	5.63	4.50		
Threshold coal price for replacing an already working engine (s. per ton)				
(4500 hrs.)			21.58	
(5000 hrs.)			19.42	
(5500 hrs.)			17.65	
(6000 hrs.)			16.18	
(6500 hrs.)			14.94	
Threshold coal price for a new engine (s. per ton)				
(4000 hrs.)				4.33
(5000 hrs.)				3.54
(6000 hrs.)				3.00

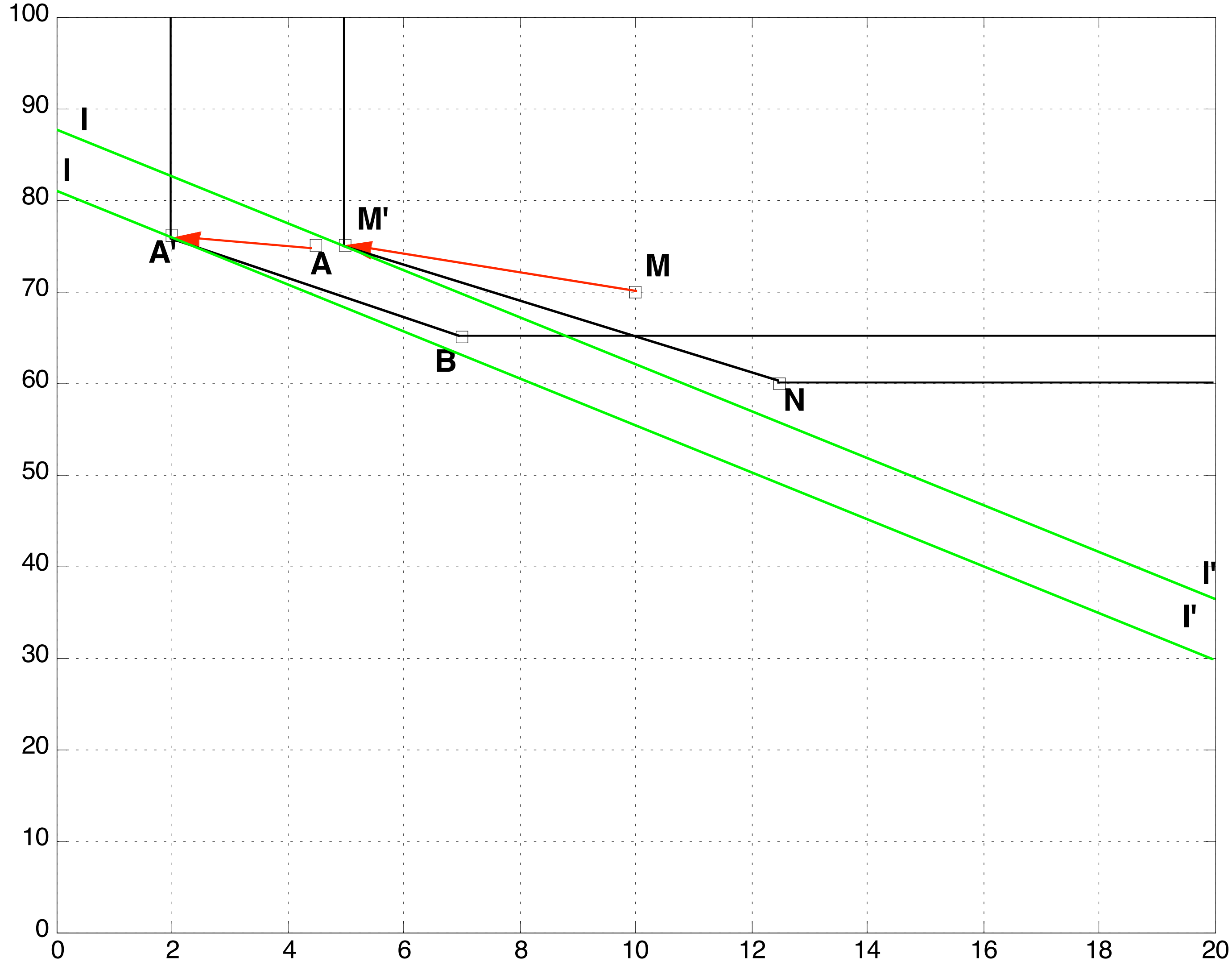
Profitability of a high pressure engine for rotary applications, late 1830s (source: B. Hick, 1841)

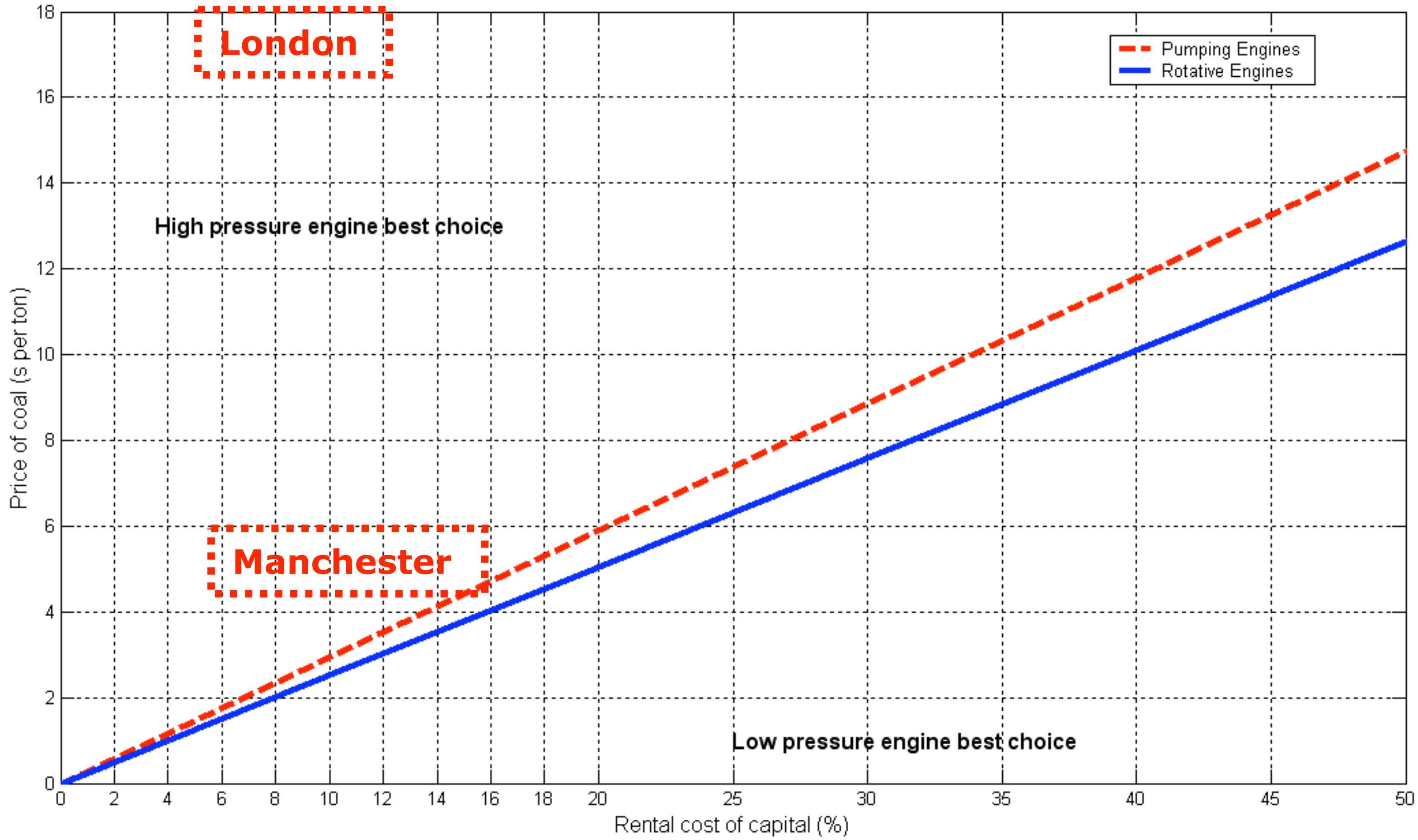
	Low pressure condensing engine			Woolf compound			Threshold coal price, new engine (s per ton.)	Threshold coal price, existing engine (s per ton)
Coal consumption (lbs per HP hour)	14			5				
HP	**Engine (£)**	**Boiler (£)**	**Capital costs per HP p. a. (£)**	**Engine (£)**	**Boiler (£)**	**Capital cost per HP p.a. (£)**		
6	330	50	8.33	335	65	8.88	0.71	11.63
10	435	65	6.58	450	100	7.38	1.05	9.66
12	480	80	6.17	510	120	7.06	1.17	9.25
16	550	100	5.39	620	150	6.48	1.43	8.49
20	630	120	4.99	720	180	6.08	1.42	7.96
25	710	150	4.60	800	220	5.54	1.23	7.26
30	770	180	4.26	870	260	5.14	1.16	6.74
40	960	240	4.05	1130	320	4.93	1.15	6.46
50	1170	280	3.91	1350	400	4.78	1.14	6.25

A David(-Habakkuk) interpretation: Technical Choice around 1815



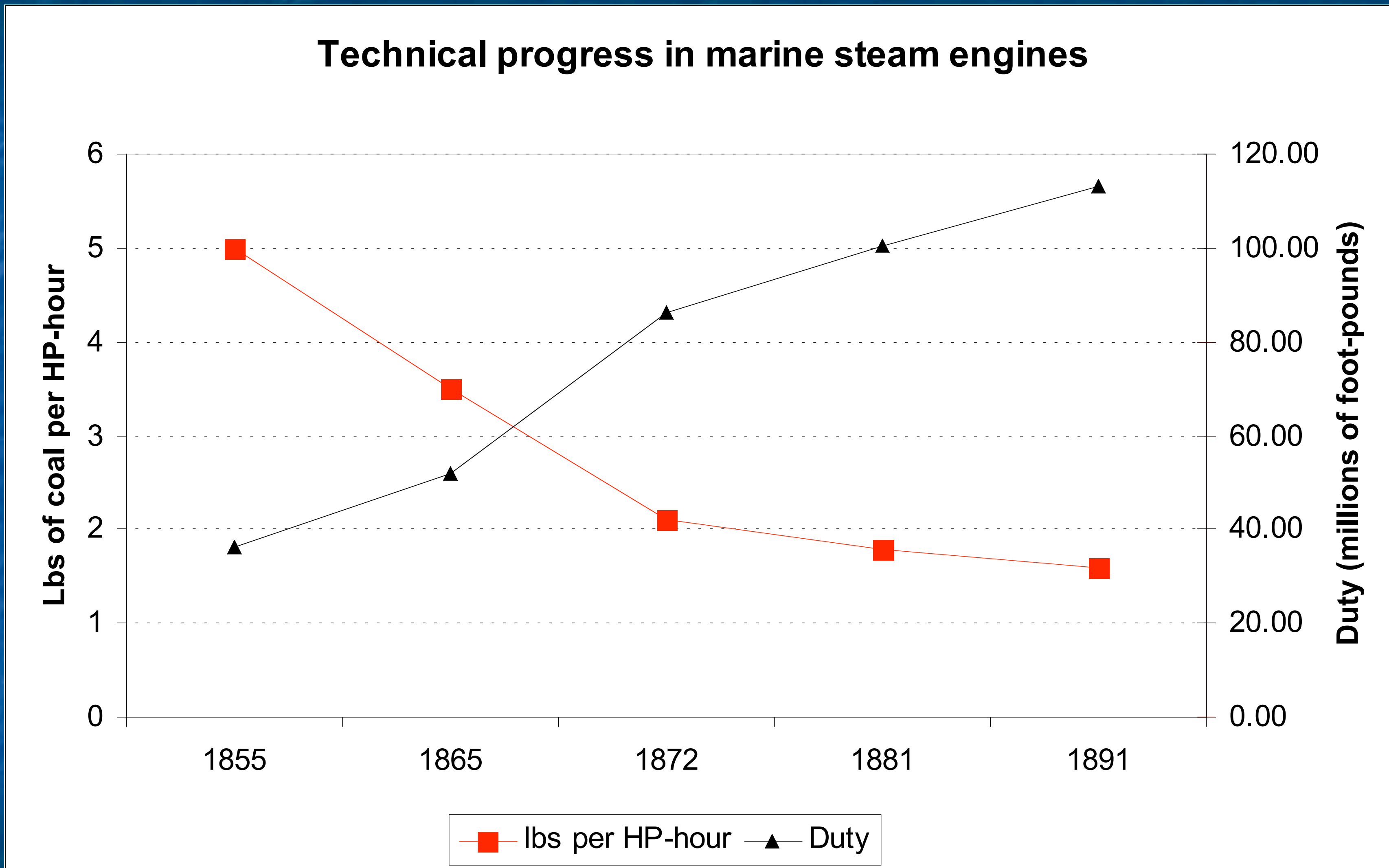
A David-Habakkuk interpretation: Technical Choice in the late 1830s





London
Manchester
Pumping Engines
Rotative Engines
High pressure engine best choice
Low pressure engine best choice
Price of coal (s per ton)
Rental cost of capital (%)
0
2
4
6
8
10
12
14
16
18
0
2
4
6
8
10
12
14
16
18
20
25
30
35
40
45
50

Technical progress in marine steam engines



Source: Harley (1971)

Conclusions

- Steam engineering in 1800-1850 was characterized by a number of different application-specific 'knowledge bases' (technological paradigms)
- Innovations reflected many peculiarities and specificities of application contexts
- Uneven rates of technical progress across applications
- To understand patterns of technical change we should reconstructed the set of heuristics.

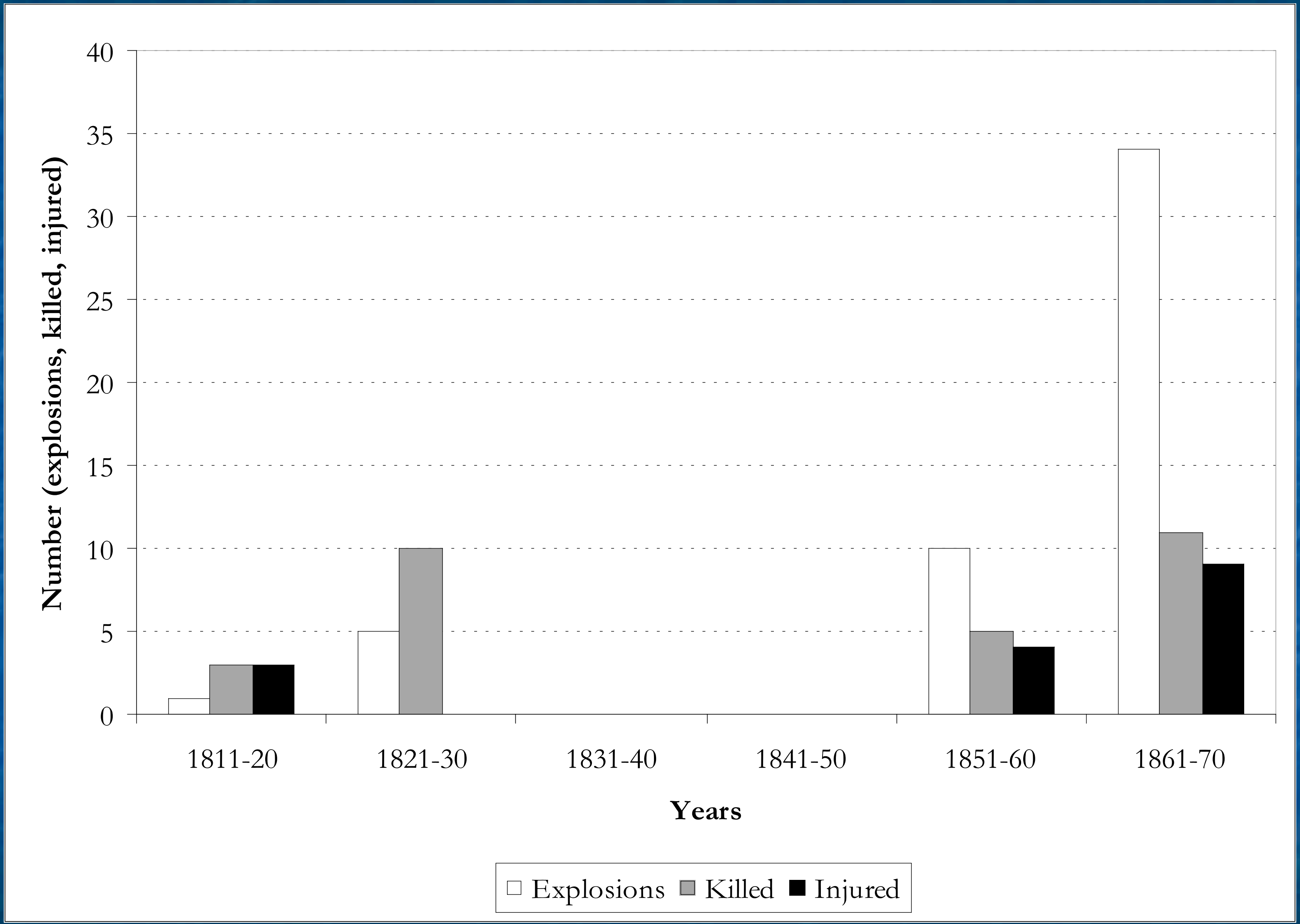
References

- G. Dosi (1982),'Technological paradigms and trajectories', Research Policy, Vol. 11, pp. 147-162.
- M. Cimoli and G. Dosi (1995), 'Technological paradigms, patterns of learning and development', Journal of Evolutionary Economics, Vol. 5, pp. 243-268
- A. Nuvolari and B. Verspagen (2008),'Technical Choice, Innovation and British Steam Engineering, 1800-1850', Economic History Review, forthcoming.

Technical progress in steam engineering, 1800-1850

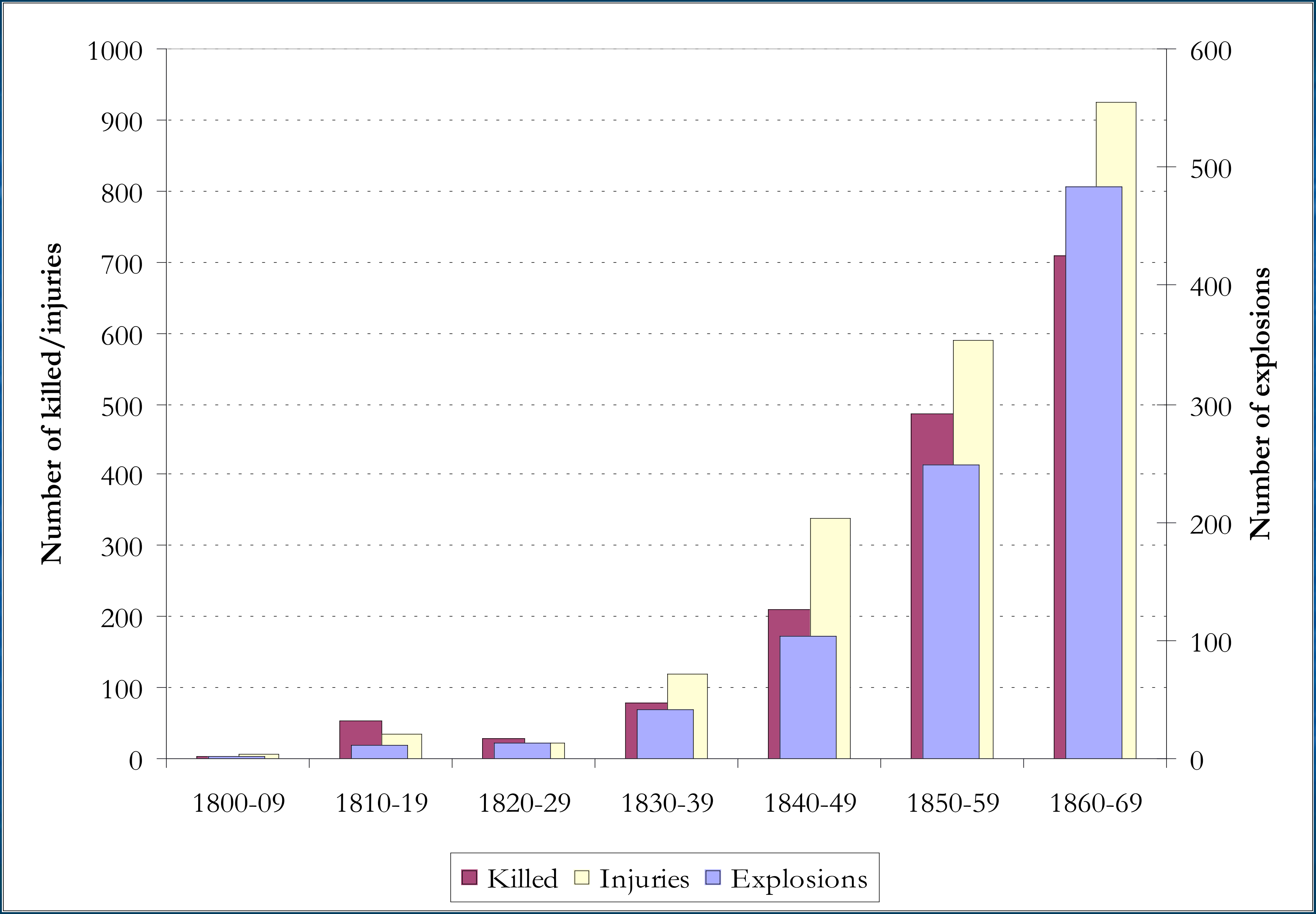
	Mining (Cornwall)		**Waterworks**		**Industrial (Manchester)**		**Marine**		**Locomotive**	
	Coal cons. (lbs per HP-hour)	Pressure (psi)	Coal cons. (lbs per HP-hour)	Pressure (psi)	Coal cons. (lbs per HP-hour)	Pressure (psi)	Coal cons. (lbs per HP-hour)	Pressure (psi)	Coal cons. (lbs per HP-hour)	Pressure (psi)
1800					15	6				
1810	3.3	40								
1820			5	14						
1830	2.5	45						5	3	50
1840	2	50	5	14	12	8		10		
1850	2	50					4	40		90
1860							2.5			

NUMBER OF BOILER EXPLOSIONS IN CORNWALL, 1811-1869



Source: Marten (1870)

NUMBER OF BOILER EXPLOSIONS, BRITAIN 1800-1869



Pitwork of the engines reported

Year	Number of Engines	Pumping perpendicularly	(%)	Pumping perpendicularly, then diagonally	(%)	Pumping diagonally	(%)
1812	16	7	(43.75)	8	(50)	1	(6.25)
1822	51	32	(62.75)	18	(35.29)	1	(1.96)
1828	59	40	(67.8)	19	(32.2)	0	(0)
1834	62	44	(70.97)	17	(27.42)	1	(1.61)
1838	61	40	(65.57)	18	(29.51)	3	(4.92)
1840	62	35	(56.45)	24	(38.71)	3	(4.84)
1850	31	22	(70.97)	7	(22.58)	2	(6.45)
1855	22	11	(50)	10	(45.45)	1	(4.55)
1860	25	8	(32)	16	(64)	1	(4)
1868	24	7	(29.17)	16	(66.67)	1	(4.17)
1876	20	5	(25)	15	(75)	0	(0)