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Accessibility and the choice of network investments in the London Underground

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Abstract: In 1863, the Metropolitan Railway of what came to be known as the London Underground successfully opened as the world's first subway. Its high ridership spawned interest in additional links. Entrepreneurs secured funding and then proposed new lines to Parliament for approval, though only some were actually approved. While putative rail barons may have conducted some economic analysis, the final decision lay with Parliament, which did not have modern transportation, economic, or geographic analysis tools available. How good were the decisions that Parliament made in approving Underground lines? This paper explores the role accessibility played in the decision to approve or reject proposed early London Tube schemes. It finds that maximizing accessibility to population (highly correlated with revenue and ridership) per expenditure largely explains Parliamentary approvals and rejections.

1 Introduction

The advent of modern steam railways occurred in 1825 with the opening of the Stockton and Darlington Railway in England. By 1836, the London and Greenwich Railway was the first line to reach the capital. To preserve the cohesion of the City of London, which would have been lost if every intercity line had entered the regional core at grade or in a trench, the 1846 Royal Commission on Railway Termini established a moratorium on intercity railway lines entering the City of London and areas immediately west (see Figure 1).

Yet Londoners demanded a solution for the street congestion, and concern arose that businesses would locate elsewhere. A commission was established to examine alternatives, out of which came a charter in 1853 for the North Metropolitan Railway (later renamed the Metropolitan Railway), which is most well-known for moving passengers but also moved freight. The period leading up to the opening of the Metropolitan Railway was dominated by intercity rail growth. In 1829, only 82 kilometers of track had been laid in the UK. This figure would grow to 24,800 kilometers by 1871 (British Railways Board 1966).

Traveling underground provided a dedicated right-of-way, allowing people to traverse London more quickly than at grade. When the Metropolitan Railway of what became the London Underground opened for service in 1863, its intent was to ease connections between key intercity termini across the northern edge of developed London. It also made it much easier for people making intracity trips to travel across London at a time of large population growth. Previous research has shown that both surface railways and the London Underground codeveloped with local land use in a process of mutual causation (Levinson 2008a,b).

The Metropolitan Railway opened to immediate success. More than 40,000 trips were taken on the first day (January 10, 1863). At the beginning, trips ran every 15 minutes from 08:00–20:00, and every 20 minutes from 06:00–08:00 and 20:00–24:00. The travel time from Paddington to Farringdon was 18 minutes—almost the same as today.

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In the early years of the Metropolitan Railway, many thought the enormous levels of ridership were too good to be true and dubbed it "curiosity traffic" (British Railways Board 1966). Future years would prove the opposite, however, and ridership would grow beyond the expectations of optimists.

The overwhelming success of the Metropolitan Railway begat many other proposals, some of them constructed and others confined to the archives (Badsey-Ellis 2005). Over the first 50 years of the London Underground, more than 100 proposals failed due to a lack of funding, insufficient plans, or Parliamentary rejection. The construction of the Underground imposed complex relationships between transport and land use, considering both physical (Darroch 2014) and travel behavioral aspects.

Accessibility has been demonstrated to be a significant factor affecting travel demand and land use (El-Geneidy and Levinson 2006; Gutiérrez 2001; Gutiérrez and Urbano 1996; Hansen 1959; Iacono et al. 2008; Krizek 2005; Kwan and Weber 2008; Levinson 1998; Levinson and Krizek 2005; Miller 1999). This study explores the relationship between accessibility and network investment. While funding is a project cornerstone, the decision to construct a line is influenced by many factors.

This study tests whether accessibility (the ease of reaching destinations) (Batty et al. 2000; El-Geneidy and Levinson 2006; Farber et al. 2013; Hansen 1959; Huang and Levinson 2012; Iacono et al. 2008, 2010; Ingram 1971; Kwan 2000; Levine et al. 2012; Levinson and Parthasarathi 2012; Levinson 1998; Levinson and Krizek 2005; Liu and Zhu 2004; Miller 1991, 1999, 2005; Miller and Wu 2000; Novak and Sullivan 2013; Owen et al. 2012; Pirie 1979; Vickerman et al. 1999; Wu and Miller 2001) explains network growth (which lines are built) (Bettencourt and West 2010; Bettencourt et al. 2007; Erath et al. 2009; Levinson and Karamalaputi 2003; Levinson et al. 2012; Levinson 2012; Roth et al. 2012; Southworth and Ben-Joseph 2003; Xie and Levinson 2011). Geurs and Wee (Geurs and Van Wee 2004) have defined four basic measures that accessibility analyses can cover: 1) location, 2) people, 3) infrastructure, and 4) utility. This study focuses on the first two.

The networks used in this study are those of the first few decades of the London Underground. As such, the change or proposed change in each network is limited, often a change in one link or line on the Underground network. We hypothesize that the proposals with the greatest accessibility impact for the lowest cost will be chosen for construction. One reason for this is, as we show, that accessibility largely explains ridership and thus revenue.

This paper starts by describing the data and networks used. The process for merging the networks is then described. Assumptions regarding travel speeds are stated. Locational accessibility methods are shown, calculating the accessibility for every network from every 200-meter by 200-meter cell in London. The accessibility calculations are weighted by population. It is shown that accessibility correlates with ridership, which itself correlates with revenue. Person-weighted accessibility (PWA) is used to compare proposals for new Underground lines. An estimated cost per kilometer from 1885 removes bias from the quotes given to Parliament. The accessibility results explain the decisions made to construct new lines on the network.

2 Data

2.1 Population data

Census data has been collected in the UK since 1801, and much of it was digitized by the Vision of Britain project. However, as geographic boundaries continuously changed, the lowest administrative district at which a consistent digital population set has been made publicly available from 1801 to the present is at the level of borough. London is divided into 32 boroughs plus the City of London, with populations ranging from 150,000–300,000 (excluding the job-heavy City) and areas ranging from 15 to 150 km^2) (Greater London Council and Office for National Statistics n.d.). The Great Britain Historical GIS Project (which releases data to the public via the Vision of Britain website) recoded UK censuses conducted prior to the establishment of current boundaries to give totals for current districts. The population dataset comprises six decennial censuses (1861–1911) for 33 areas. Historical data on employment by borough is unavailable for this period, though that data is likely also an important explanatory factor.

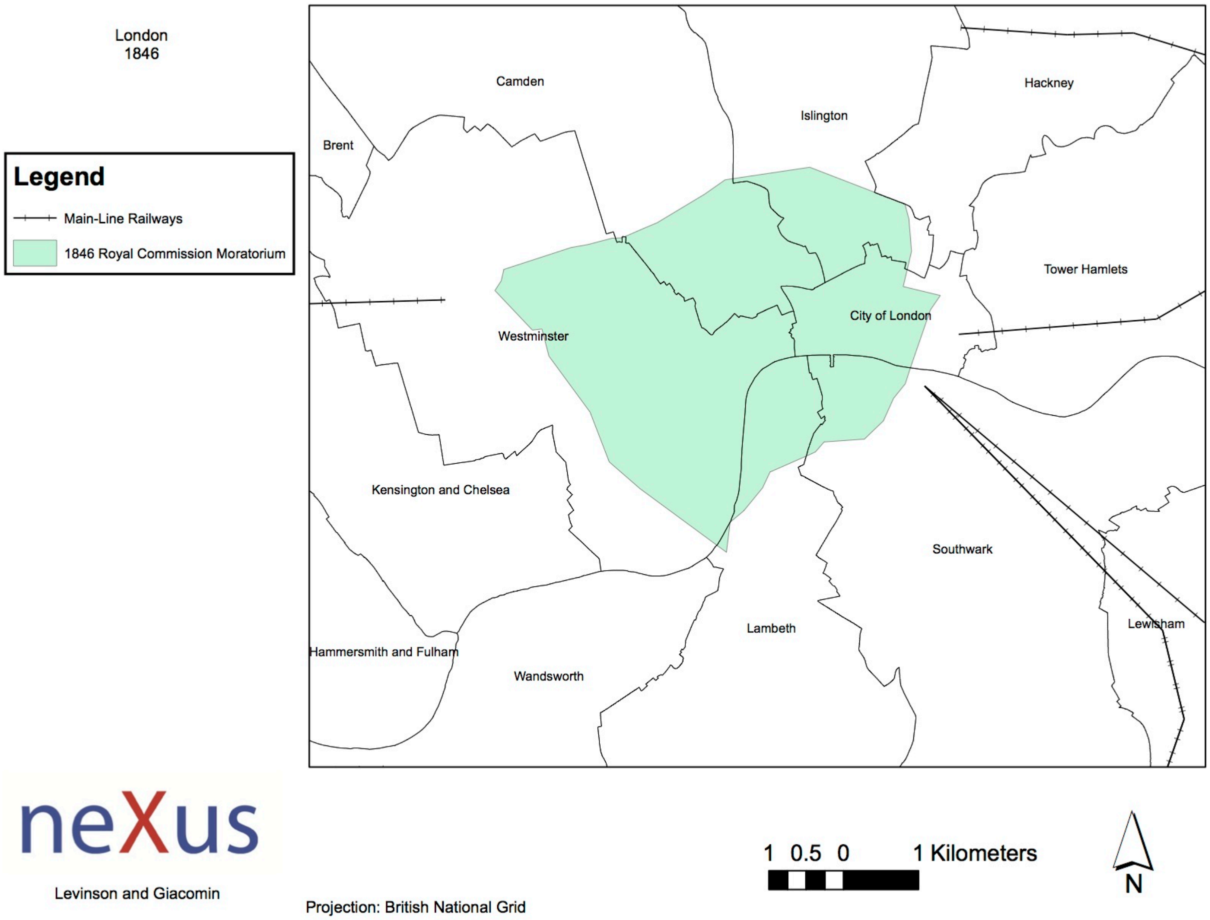

Figure 1: Royal Commission limits of 1846.

2.2 Network data

While the focus of this analysis is on the incremental accessibility offered by proposed Underground railway lines, those lines exist in the context of a network where people may walk or take existing rail lines to their destinations. In other research, straight-line or network distance has been used to model walking. Because network distances are longer than Euclidean distances (but not uniformly so), this research uses a pedestrian network to represent travel costs between origins and destinations, between origins and stations, and between stations and destinations. To our knowledge, no complete digitized pedestrian network exists for 19th-century London, but most of the links that existed then are present today. Certainly more links are present today, but areas then without links were also areas without much population at the time, minimizing the bias that an assumption of the street network as background would produce. An Open Street Map network file for modern day London was used as the background pedestrian network (Public 2013). The file was used throughout every study year and network. The speed on this pedestrian network was assumed to be 5 km $\cdot h^{-1}$.

For every study year, the existing Underground railway network was included as well as any lines currently under construction. Including lines under construction is important because it helps identify what proposers would have known about the future of the network and what would have guided investment decisions. A time penalty of two minutes was used to represent a transfer between the walking network and the London Underground network. The transfer could only occur at London Underground stations. The speed on the Underground network was assumed to be $12km \cdot h^{-1}$. The initial timetable for the Metropolitan Railway showed a travel speed of $20km \cdot h^{-1}$ including stops; however, this does not include access and egress times (which we aim to represent with the two-minute penalty) or wait times (about half the headway of 10 minutes in the peak and 15 or 20 minutes off-peak). Accessibility does not include monetary costs for tickets.

Intercity and other surface railway data were included for the year of each study (Borley 1982; Brown 2012). Like the London Underground, surface railway data for the study year were included in the network. A time penalty of two minutes was used to represent a transfer between the walking network and the surface rail network. Transfers could only occur at surface rail stations. The same time penalty was used for transfers between the Underground network and the walking network. As with the Underground, the speed on the rail network (within the urbanized area of London) was assumed to be $12 km \cdot h^{-1}$; in-vehicle speeds were obviously higher.

2.3 Proposed lines

For every proposed line, details were taken from the book *London's Lost Tube Schemes* (Badsey-Ellis 2005) and digitized based on available information. In many cases, straight lines were drawn between stations. Since the lines were never built, the accuracy of the spatial representation is lower than that of London Underground lines today. These are detailed in Giacomin (2014).

For each year with proposals, a base network is analyzed that included an example walking network (2012 London road network), surface rail lines that existed in the study year, and existing and under-construction Underground lines. The proposals are then compared in analysis. Some proposals resulted in slight changes to the network, perhaps an extension to an existing line. Others established entirely new routes, sometimes making significant changes to the network—especially early on.

3 Methodology

An accessibility analysis is conducted for every study year, staring with 1862—the year before the first line. In 1862, the network only includes the walking network and existing surface rail network. For each subsequent study year, the additional and/or proposed London Underground links would be added, as well as any new surface lines.

3.1 Population

This study assumes that the population is distributed homogeneously within each borough, as no more detailed analysis can be made with available data. To measure accessibility, cells are generated as 200-meter by 200-meter squares. The cell is assigned the population density of the borough in which the centroid fell. If the centroid of a cell fell outside of London, it was omitted from analysis. The remaining cells numbered 39,858. Maps of population density by borough can be found in Levinson (2008b).

The centroids are then snapped to the network. Occasionally points would snap to an isolated part of the network. In this case, the isolated part of the network would be re-snapped to the nearest part of the larger network. Specifically, the points are snapped to the walking network only. It is not logical to snap them to any other mode since it is not typical to begin or end a trip at subway or rail stations. The same cells were used to measure accessibility for every change (or proposed change) in the network. The population of each cell is given by the equation below:

$$P_i = \frac{k_i}{k_b} P_b \tag{1}$$

where k_b = the area of borough b,
k_i is the area of cell i,
P_b is the population of borough b.
From these P_i is obtained, the population within cell i.

3.2 Locational accessibility

Accessibility was first defined by Hansen (1959). This study focuses on two forms, locational accessibility and person-weighted accessibility (PWA). Locational accessibility calculates reachable destinations from a location. PWA weights the accessibility of many locations based on the population of each. The primary benefit of PWA is that it reduces the analysis to one number, allowing for internetwork and intranetwork comparison. Locational accessibility provides a cartographical benefit. A map displaying locational accessibility information can help identify areas in need of more transportation services or where opportunities for development intensity exist.

This study measures accessibility retroactively in London in the 19th century with a focus on the modes of walking and underground rail service. Previous studies examining accessibility for nonmotorized modes include Achuthan et al. (2007); Iacono et al. (2010); Ulmer (2003). This study uses walking accessibility as a base level for transport.

Locational accessibility bears particular relevance to planning. Maps of accessibility impacts allow planners to effectively understand the impact of transit development. Since such information was not available in 19th-century London, the effectiveness of central planning in London, had it existed, is debatable. Odlyzko (2014a) notes that central planning at the time may have actually decreased the efficiency of the intercity rail network in Britain.

The performance measure of accessibility is proposed as a factor explaining which proposed Tube schemes were most likely to be approved by Parliament. A cumulative opportunities accessibility is used, measuring the number of people that can be reached from a point within 30 minutes of travel time by walking, national rail, or Underground line.

In measuring accessibility for each cell centroid, an OD cost matrix is created for every network. For the other cell centroids that can be reached, populations are summed providing the cumulative opportunities for that cell centroid. These values are represented in Figure 10. Locational accessibility is shown by the equation below:

$$A_{i,T} = \sum_{j=1}^{J} P_j f(C_{ij}) \tag{2}$$

where $A_{i,T}$ = cumulative opportunities from a cell centroid (i) to every other cell centroid (j) reachable in time T,

C_{ij} = generalized (real) time or cost from cell i to cell j,

$f(C_{ij}) = 1$ if $C_{ij} < T$ and 0 otherwise.

In this study, a value of T=30min was used unless otherwise noted.

Using a 30-minute threshold for commutes will include a majority of commutes actually experienced today. Data for commute times is unavailable for 19th-century London. However, there is evidence for the travel time budget hypothesis (Levinson and Kumar 1995; Levinson 1999; Levinson and Wu 2005; Zahavi and Talvitie 1980), which would support using a 30-minute threshold. A sensitivity analysis for time thresholds is included in Giacomin (2014).

3.3 Person-weighted accessibility

While locational accessibility provides a cartographical benefit, its use is limited in quantitative analysis. With limited funds, planners must decide between an array of options. Such a decision may be to add a stop along a route or at the end of a route. Calculating person-weighted accessibility (PWA) allows for comparison when the options affect different populations. Once cost information is included on the two proposals, the more cost-effective option can be chosen.

Equation 3 calculates network-wide PWA. This measure increases with population at the origin and the population of destinations that can be reached within 30 minutes of each origin. It allows for comparison between proposed lines and implemented lines, as well as comparison across years.

Table 1: Open Trip Planner Analyst comparison (1863).

Headway	PWA
OTP - No Transit	$4.0844{*}10^{11}$
OTP - Scheduled: 20-min Peak	$4.1495{*}10^{11}$
OTP - Scheduled: 15-min Peak	$4.1630{*}10^{11}$
OTP - Scheduled: 1-min Peak	$5.0097{*}10^{11}$
ArcGIS - "0-min Headway"	$4.7221{*}10^{11}$

For the population of each sample point (that represents a cell), the population density was used to identify the weight assigned to each point. PWA is given as:

$$A_{pw,T} = \sum_{i=1}^{I} A_{i,T} P_i \tag{3}$$

where A_i is the opportunities of cell i, and P_i is the population within cell i (see Equation 1). We use a sum rather than an average because we posit total ridership is a function of total accessibility, and we want to be able to see the differences over time.

3.4 Historical GTFS comparison

Our analysis, using ArcGIS to compute accessibility, does not consider transit schedules in calculating accessibility. It thus assumes that when individuals arrive at stations (or transfer points), a transit vehicle will be immediately waiting for them. However, transit services are scheduled, so this likely overestimates the accessibility gain due to transit investments. This section uses a transit-based accessibility analysis to estimate the size of the error. Though it is more accurate, a disadvantage of this method is the higher data and computational burden. Many historical networks have missing data, and the creation of General Transit Feed Specification (GTFS) data was unfeasible, particularly for a large set of proposed but unbuilt routes. Comparing the two methods (with and without schedules) allows analysts to compare the accessibility impact of a network's ideal capacity (zero-wait) compared with actual or expected conditions.

For the original Metropolitan Railway line in 1863, a GTFS database was created manually (Antrim et al. 2013). The line ran at headways of 15 and 20 minutes, depending on the time of day. Open Trip Planner (OTP) Analyst was used to calculate the accessibility for every minute during the morning peak (Nair et al. 2013).

Table 1 compares the PWA from this study with the methods used in OTP Analyst for calculating accessibility. In OTP Analyst, accessibility is calculated for every 200-meter cell in London. This data was then weighted by the population of each cell to determine a PWA for every minute. Figure 2 shows an overlay of 20-minute and 15-minute headways on the Metropolitan Railway. The peak accessibility for the 20-minute headway (which occurred during the intervals 06:00–08:00 and 20:00–24:00) is slightly higher than the lowest accessibility during the 15-minute headway (occurring 08:00–20:00). The time axis begins at 0:00 to identify when service of that type begins.

3.5 Costs

The task of estimating the cost of a project is complex. Furthermore, there is pressure to underestimate costs since the primary goal is to win a project. Once construction has begun, it becomes nearly impossible to switch companies, at which point providing additional funding is easier than switching contractors. These issues were at play in 19th-century London. Flyvbjerg et al. (2004) ask the question of cost overrun in public works projects. They find that the time period between the decision to build and the beginning of construction is particularly influential in cost escalation. The longer construction is postponed, the more the costs escalate. Unfortunately, the data for London in the 1800s is sparse and varies in form. As such, a cost estimate from the time is used. Land values changed dramatically

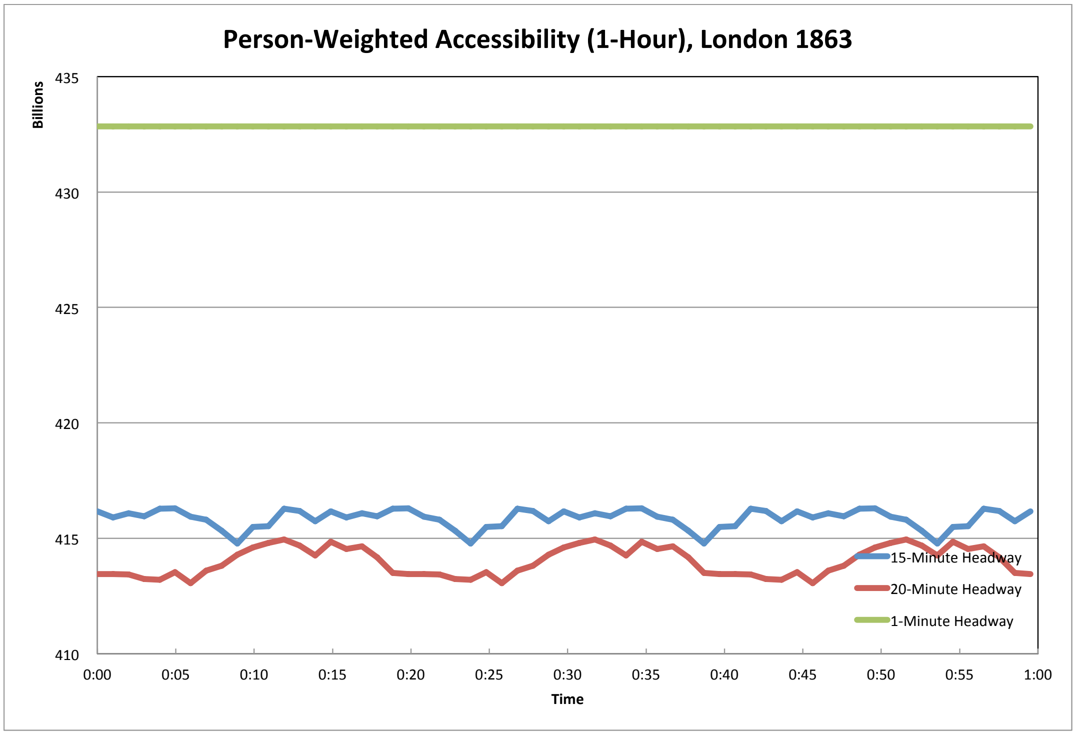

Figure 2: Metropolitan Railway person-weighted accessibility by headway.

over the first decades of London Underground construction. These underground lines were the first of their kind in the world, adding to uncertainty about construction costs.

The cost model in Equation 4 is based on the estimate given in the era (Baker 1885) that a typical double-track line cost £208,000 per mile (£174,000 per km). Over the period from 1863 to 1910, inflation fluctuated, but the overall inflation was around 0 percent (Office for National Statistics 1860-1900). As such, inflation data was omitted from the analysis.

$$E = 174,000 * L \tag{4}$$

where L = length of the proposed line in km.

Figure 3 shows how the estimated costs compare to the proposed costs of unbuilt lines. Since the model cost is based on an estimate from the time, it is likely that the estimate was relatively close to actual values. Figure 3 concurs.

4 Results

4.1 Metropolitan Railway: ridership and revenue

The Metropolitan Railway opened to ridership levels much higher than expected. Demand forecasting has always been prone to error. Many late-20th-century urban rail projects in the U.S. overestimated ridership, and, as a result,

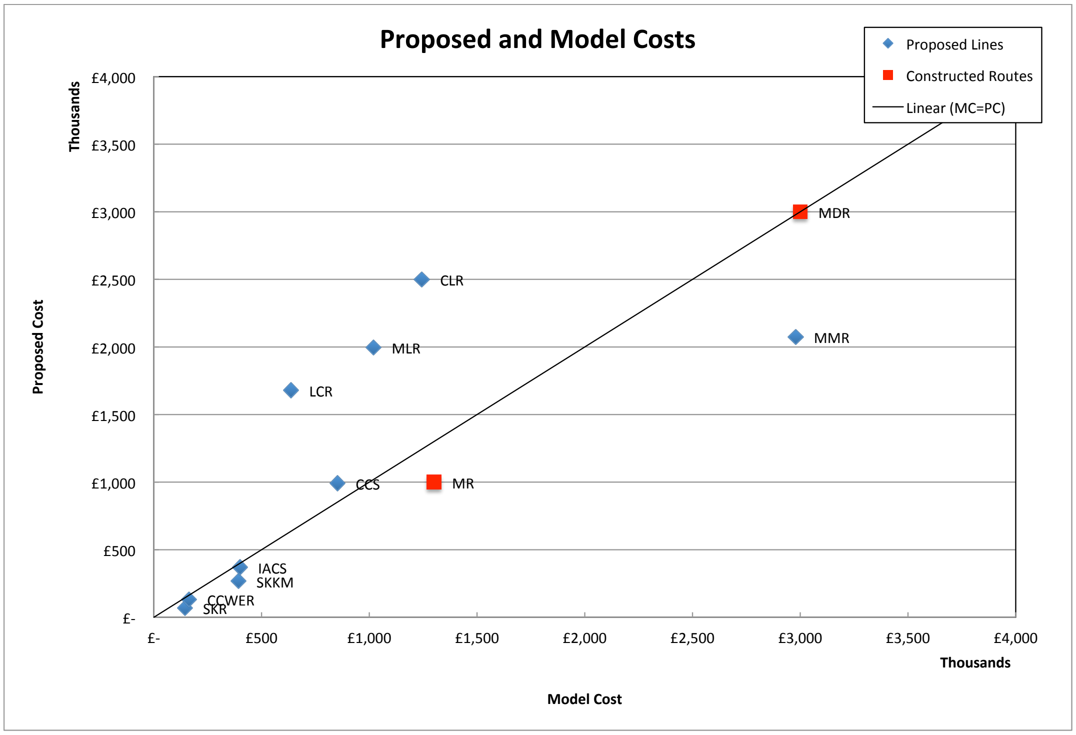

Figure 3: Proposed cost versus model cost (£174,000/km).

many metropolitan planning agencies may have made different decisions if they had accurately estimated actual ridership levels (Pickrell 1989). Generally ranges are better than single-point estimates, though forecasting has usually produced and published the latter.

The Metropolitan Railway would operate independently until 1933, at which point it was amalgamated. Data on annual ridership and revenue are reported through 1909. Figure 4 shows an S-Curve approximation of the maturation of the Metropolitan Railway in ridership. The actual ridership each year has some fluctuation. Perhaps most notably, a remarkable increase in ridership occurs in the years following the opening of the District line, perhaps indicative of network effects. Completion of the inner circle does not seem to have as great an impact on Metropolitan Railway ridership. From Figure 4, it is clear that in 1909 the Metropolitan Railway was near maturity (about 100 million annual rides). Less than 15 years later, the still-profitable Metropolitan Railway company was consolidated into an integrated and publicly owned London Transport.

We posit PWA is important because it explains ridership and revenue.

Figure 5 shows annual passengers versus annual revenue for the Metropolitan Railway company. These numbers are highly correlated ($r^2 = 0.94$). A linear curve fits this data well.

Figure 6 shows annual PWA versus annual ridership. This relationship is also highly linear, though we fit an exponential curve, with $r^2 = 0.98$.

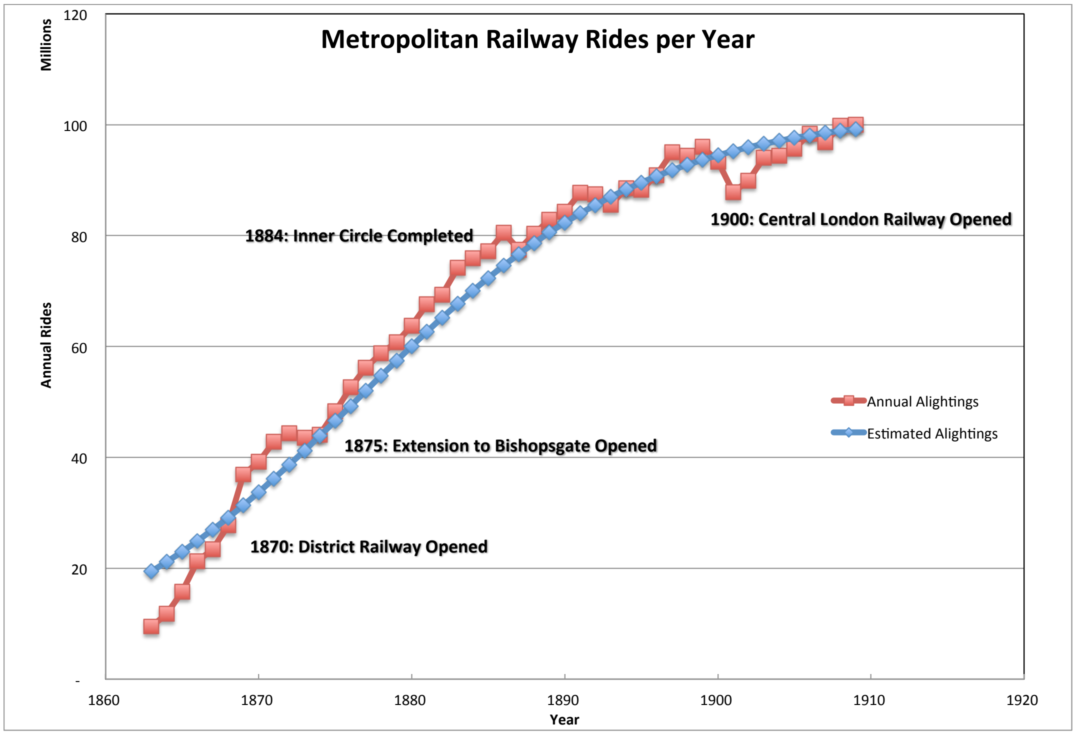

Figure 4: S-Curve of Metropolitan Railway annual ridership.

4.2 Locational accessibility

Figure 7 shows the accessibility in central London just before the Metropolitan Railway opened (early 1863). Surface lines are shown, many of which lead near London but not too deep within the city. Figure 7 thus shows the potential demand for rail in the inner city before any lines opened underground.

Over the next decade, transport would drastically change in London (see Figure 8). Though these were not the colors of the lines in operation at the time, in all of these figures modern Tube map coloring is used to help identify relations between the early stages and the modern Underground network.

Figure 9 shows an inner circle that clearly indicates higher levels of accessibility around circle stations. As expected, the greatest accessibility is found along the northern half of what is now the inner circle. This was where the Underground began in 1863 with connections to the northern suburbs, which came to be dubbed "Metro-Land," particularly at the center of the original Metropolitan Railway. In the lower left of Figure 9, accessibility along what is now part of the District line is clear around stations as it travels out of the city.

In comparison with Figure 9, there are only minor changes with 1891 (Figure 10), with the most noticeable ones in the northern areas of Southwark. Part of the current Northern line is added, and the northern part of Lambeth also sees an increase in accessibility. The measurements are made with the populations of their time, which changed between 1881 and 1891.

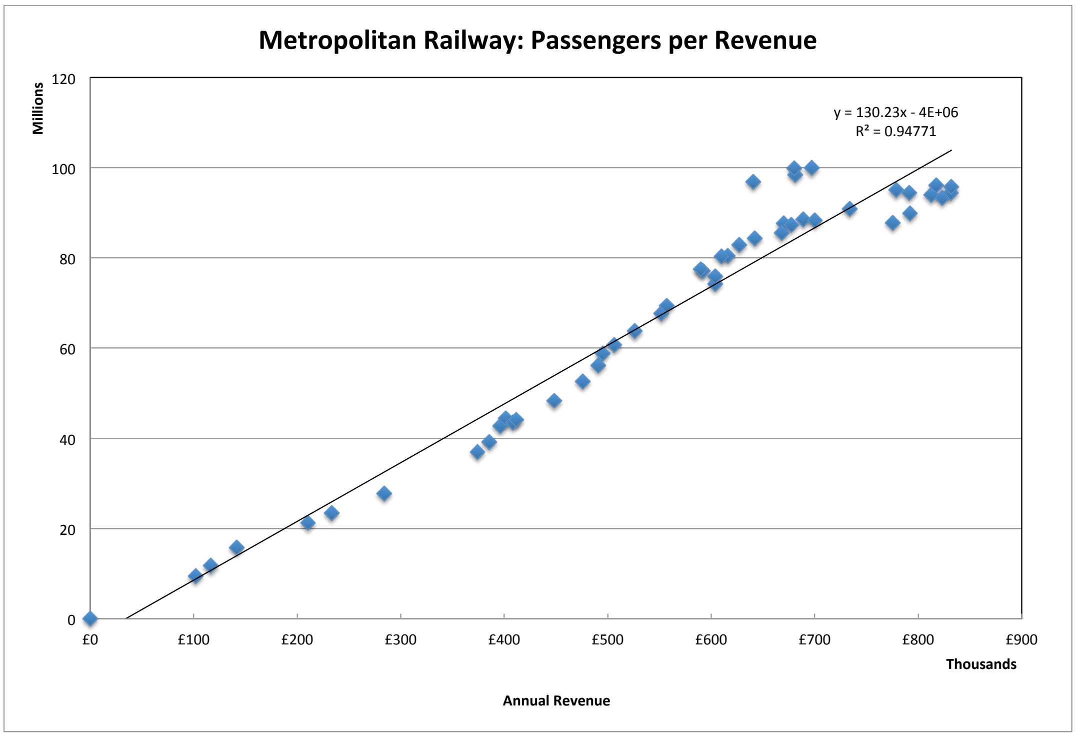

Figure 5: Annual passengers versus annual revenue, Metropolitan Railway.

Figure 6: Person-weighted accessibility versus annual passengers, Metropolitan Railway.

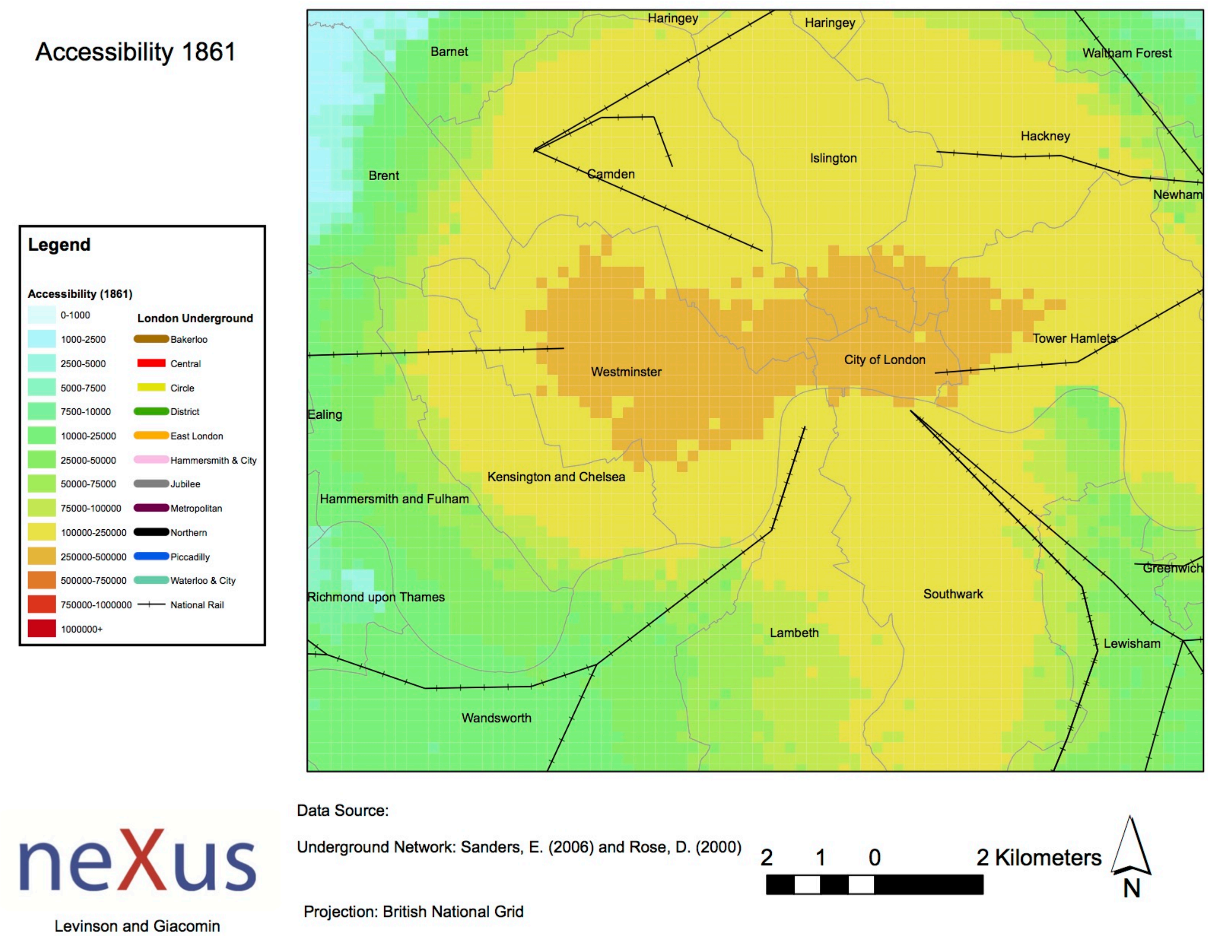

Figure 7: London accessibility in 1861.

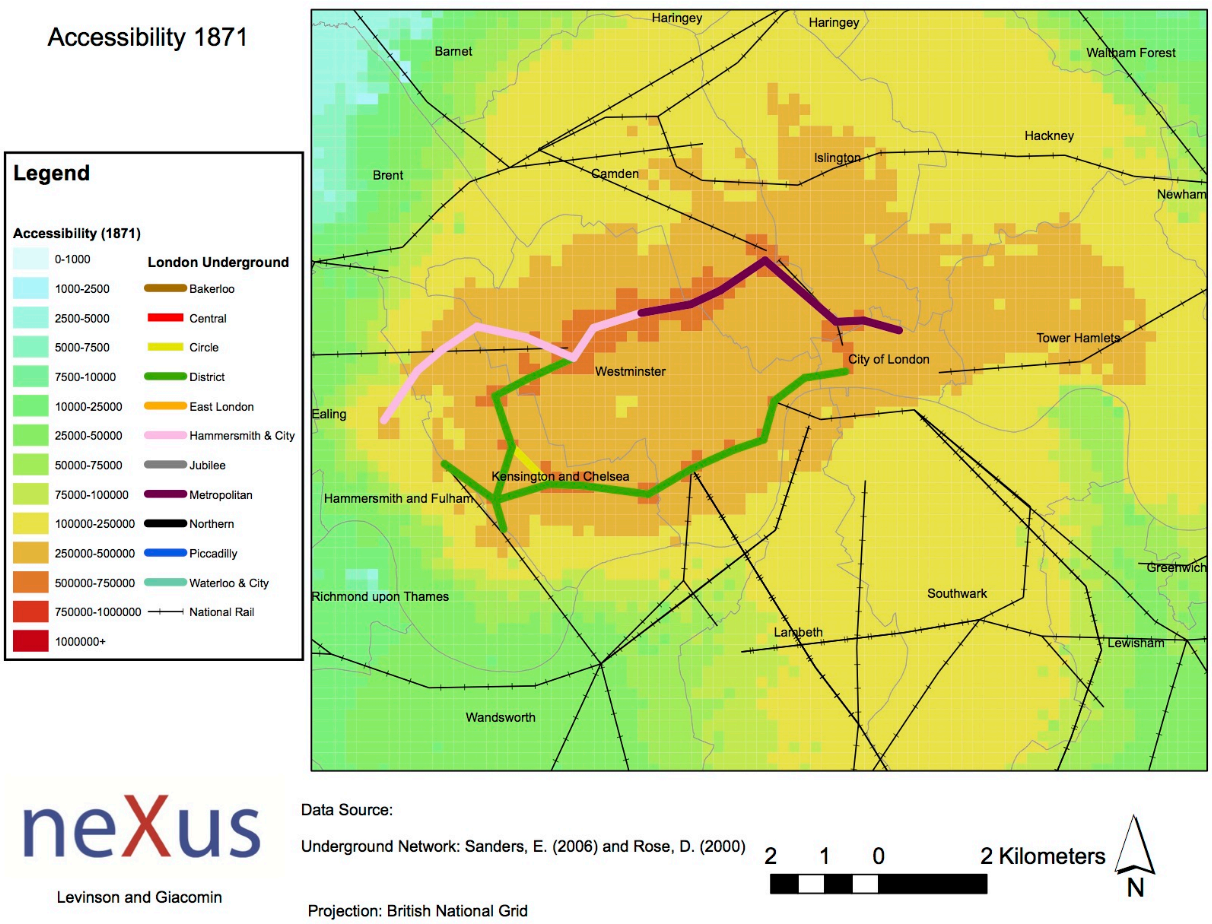

Figure 8: London accessibility in 1871.

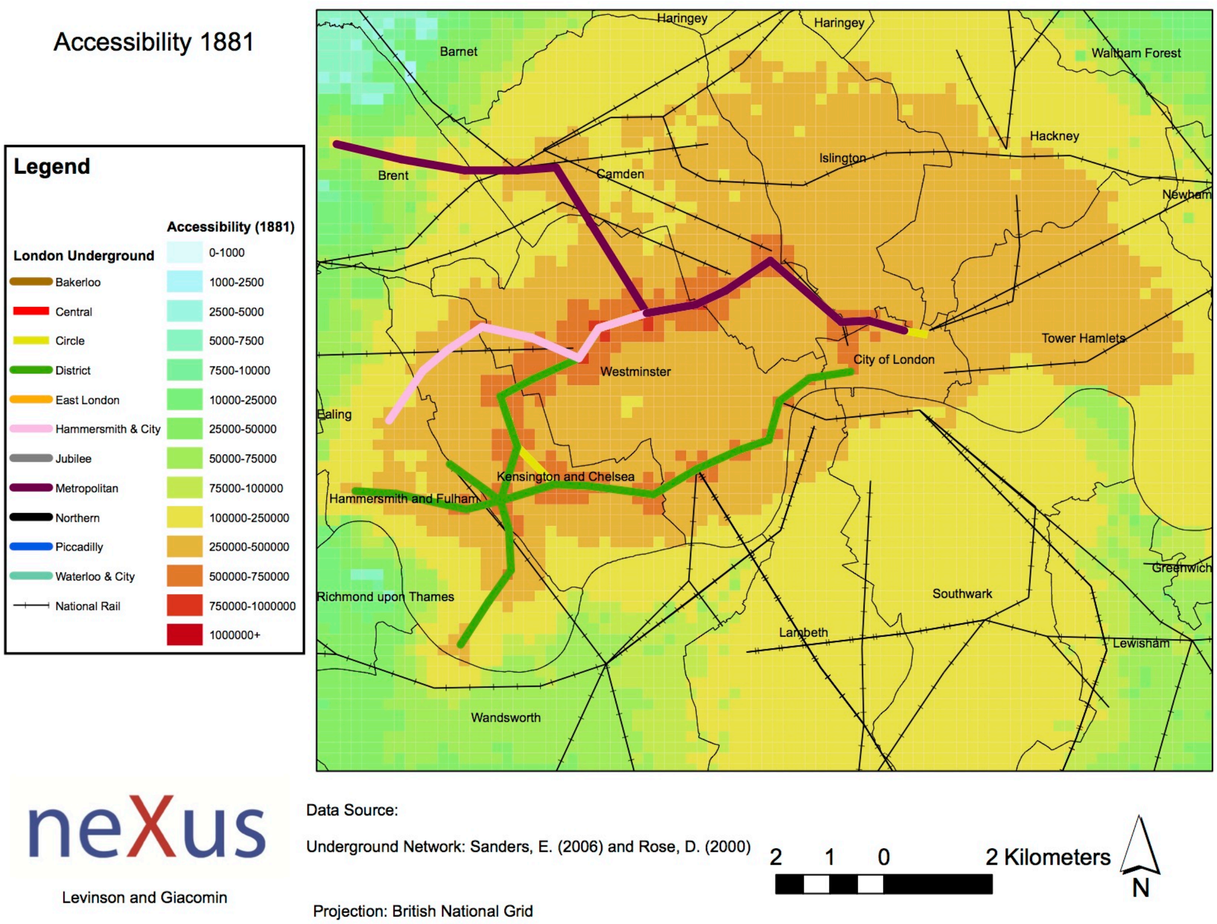

Figure 9: London accessibility in 1881.

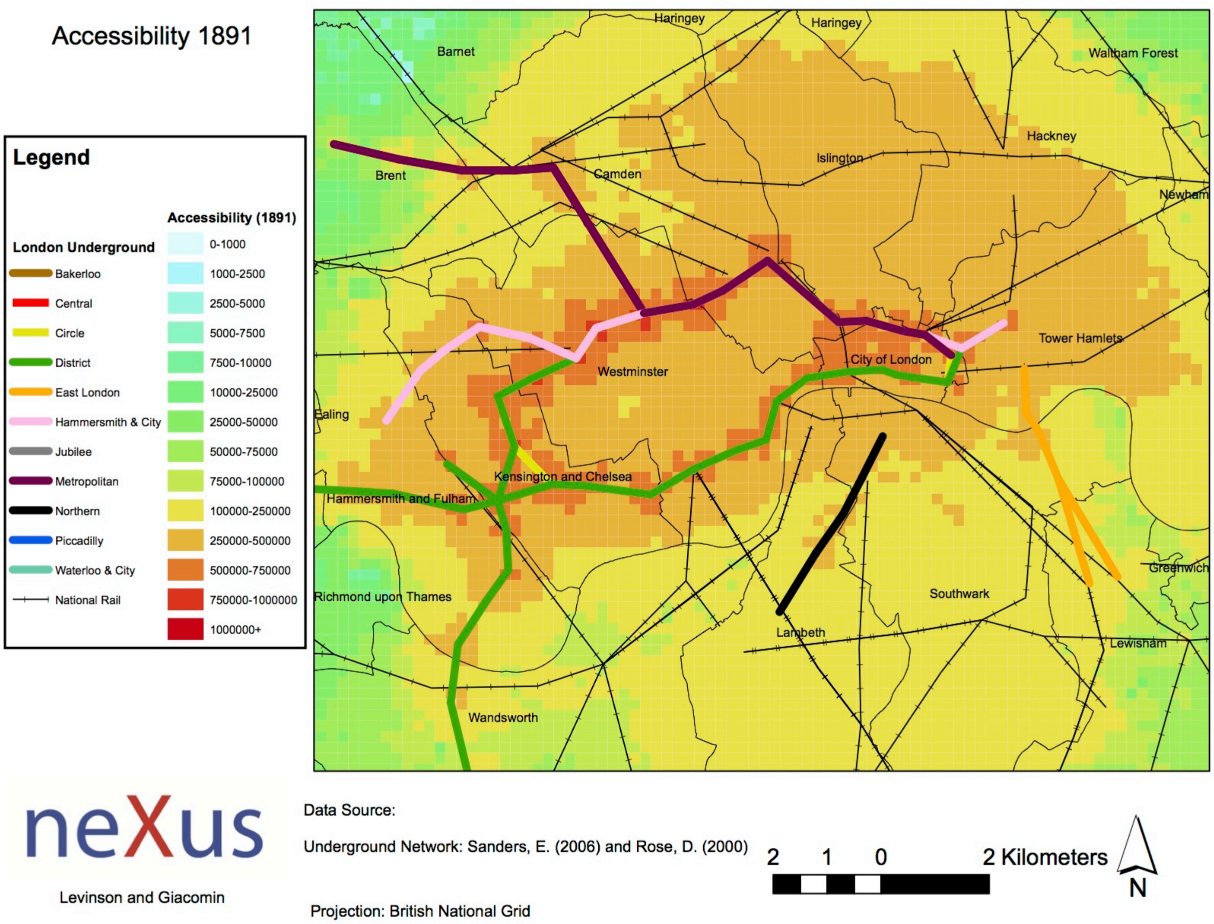

Figure 10: London accessibility in 1891.

4.3 Person-weighted accessibility

Table 2 shows that the most cost-effective choice for additions to the Underground was almost always made over the period 1860–1890. This shows cost efficiency based on a model of expected costs and not on the proposed costs that would have been submitted to Parliament at the time. From the table, it is clear that the strongest indicator for success (construction) of a proposed addition to the London Underground is the percentage increase in PWA the project offers per pound (£) spent. It has much less to do with the cost of the project in isolation. With almost no variation, the threshold requirements for Parliament to approve an addition to the network was around 20,000 additional opportunities per pound.

The only exception is the East London line of 1884, which differs significantly from other lines that are part of the Underground system (Barker et al. 1975). First, it carried significantly more freight traffic than other routes, so its rationale was more than the passenger flows dominating the other lines. Second, it was significantly longer, serving a different kind of market than typical Underground lines. Third, it was largely above ground, which indicates the cost from our model may overestimate its true cost.

Table 2: Proposals and implementations to the London Underground by ΔPWA/£.

Year	Name	Built	PWA	%ΔPWA	Length	Est. Cost (£)	ΔPWA/£
1885	**Population Incr.**		10.40	7.30%	0.00	0	inf
1864	**MR Extension**	1868	5.12	2.13%	1.98	255,648	41,803
1872	**District**	1874	7.21	0.76%	1.10	142,299	38,057
1885	London Central		9.77	1.11%	3.05	393,811	27,362
1856	**Metropolitan**	1863	5.01	6.09%	5.50	1,300,000	22,124
1885	KCCC & WS		9.78	1.22%	4.28	553,300	21,336
1881	Mid-Metro Railway		9.73	4.09%	17.12	2,213,019	17,264
1872	Mid-London Railway		7.28	1.77%	5.86	757,646	16,717
1864	London Central Rwy		5.06	0.91%	3.66	472,780	9,654
1885	MARC & CS		9.73	0.67%	5.23	675,954	9,643
1885	CC & ER		9.69	0.29%	2.38	307,049	9,270
1885	Islington & City		9.69	0.25%	2.29	296,489	8,011
1885	SK & K & MAS		9.15	0.29%	2.26	291,578	7,855
1881	**E. London & Others**	1884	9.73	4.01%	37.34	4,826,437	7,762
1872	So. Kensington Rwy		7.16	0.08%	0.83	106,844	5,096
1885	Clapham & City		9.68	0.17%	4.90	633,303	2,593
1864	OS & CR		5.02	0.17%	3.80	491,392	1,733
1881	Charing Cross & WE		9.35	0.01%	0.94	121,555	1,104
1861	Pre-Underground		4.72		0.00	0	

Notes: PWA x 10^{11}
Length in km
Bold indicates built proposal
Abbreviations:
OS & CR – Oxford Street & City Railway,
KCCC & WS – King's Cross, Charing Cross & Waterloo Subway,
CC & ER – Charing Cross & Euston Railway,
MARC & CS – Marble Arch, Regent Circus & City Subway,
SK & K & MAS – South Kensington & Knightsbridge & Marble Arch Subway.

5 Conclusion

As the London Underground was the world's first subway, it provides a basis for understanding and framing network growth in transit networks. Today, public transit is central to travel in many urban areas. The networks that exist influence travel behavior and location choice. Businesses locate based on proximity to their clients and employees. Transit networks such as the London Underground increase that proximity.

Such analysis as described in Section 3 was not possible in the 1800s. Simply put, Figures 7–10 could not have been generated, and the numbers behind them could not have been calculated. Measuring accessibility at every location provides important qualitative maps to aid in understanding the accessibility impact to an area. To do this systematically, PWA was used in analysis. Often, the most cost-efficient increase in PWA to the Underground was chosen. This is pleasing to see, indicating that PWA may indicate the most desirable (or most frequently chosen) addition to a transit network. As the surface network changed over time, it influenced the accessibility impact of the Underground.

Odlyzko (2014b) notes that the use of gravity models by rail promoters could have made the intercity British rail network much more efficient, and this could have lessened huge economic losses in Britain. Had gravity models been considered in the British railway mania of the 19th century, a greater focus may have been placed on local travel, namely travel within London. Whether this would have affected the London Underground is unclear since accessibility, a core element of gravity models, well explains the choice of investments. Further, the London Underground as a whole was more successful than British intercity rail, less overbuilt, and had much higher demand. While this is in large part due to the very high density of London itself, it is perhaps indicative of more serious consideration before approval because of the disruptive nature and higher costs of urban construction. In the end, in contrast with the intercity system, very few stations or segments on the Underground have been closed after opening and almost none on the earliest lines.

It is important to understand the cost of each project. To compare small additions to bigger projects, cost efficiency can be measured. For the many proposals that never saw construction, it is possible that the quoted costs of the projects were wrong. Many may have been underquoted to increase the chance of Parliamentary approval. This would agree with some projects that were actually built since it was common for projects to require additional funding during construction or simply stop construction short of the intended project goal. For proposals that were never implemented, a cost estimate per kilometer is used to estimate the likely cost of the proposal were it constructed.

At the time, many aspiring London investors wanted to be first-movers in this newly discovered industry of Underground transportation. This is evidenced by the large number of proposals brought before Parliament for consideration. Funding was often a factor that silenced many proposers. Had the measures of PWA and accessibility existed in the 1800s, discussion regarding proposals for additional metro links could have been far more quantitative. Nevertheless, Parliament, with its wisdom, mental models, and local knowledge, seems to have largely replicated what a more quantitative model might have achieved by maximizing accessibility per expenditure.

References

Achuthan, K., H. Titheridge, and R. Mackett. 2007. Measuring pedestrian accessibility. In *Proceedings of the Geographical Information Science Research UK (GISRUK) Conference, National Centre for Geocomputation, National University of Ireland*, pp. 264–269. Citeseer.

Antrim, A., S. J. Barbeau, et al. 2013. The many uses of GTFS data–opening the door to transit and multimodal applications. *Location-Aware Information Systems Laboratory at the University of South Florida*.

Badsey-Ellis, A. 2005. *London's Lost Tube Schemes*. Capital Transport.

Baker, B. 1885. *The Metropolitan and Metropolitan District Railways*, volume 81. The Institution of Civil Engineers.

Barker, T. C., M. Robbins, and L. T. Executive. 1975. *A History of London Transport: passenger travel and the development of the metropolis*. Allen and Unwin for the London Transport Executive.

Batty, M., H. Couclelis, A. Getis, H. Miller, and M. Wilson. 2000. Measuring and Representing Accessibility in the Information Age.

Bettencourt, L. and G. West. 2010. A Unified Theory of Urban Living. *Nature*, 467(7318):912–913.

Bettencourt, L. M., J. Lobo, D. Helbing, C. Kühnert, and G. B. West. 2007. Growth, Innovation, Scaling, and the Pace of Life in Cities. *Proceedings of the National Academy of Sciences*, 104(17):7301–7306.

Borley, H. V. 1982. *Chronology of London Railways*. Railway & Canal Historical Society.

British Railways Board. 1966. *Annual Report and Accounts*, p. 43. H.M. Stationery Office.

Brown, J. 2012. *London Railway Atlas*. 3rd edition.

Darroch, N. 2014. A brief introduction to London's Underground railways and land use. *Journal of Transport and Land Use*, 7(1):105–116.

El-Geneidy, A. and D. Levinson. 2006. Access to Destinations: Development of Accessibility Measures. Technical Report 2006-16, Minnesota Department of Transportation.

Erath, A., M. Löchl, and K. W. Axhausen. 2009. Graph-Theoretical Analysis of the Swiss Road and Railway Networks over time. *Networks and Spatial Economics*, 9(3):379–400.

Farber, S., T. Neutens, H. J. Miller, and X. Li. 2013. The Social Interaction Potential of Metropolitan Regions: A Time-Geographic Measurement Approach using Joint Accessibility. *Annals of the Association of American Geographers*, 103(3):483–504.

Flyvbjerg, B., M. S. Holm, and S. Buhl. 2004. What causes cost overrun in transport infrastructure projects? *Transport Reviews*, 24(1):3–18.

Geurs, K. T. and B. Van Wee. 2004. Accessibility evaluation of land-use and transport strategies: review and research directions. *Journal of Transport Geography*, 12(2):127–140.

Giacomin, D. 2014. *Accessibility and the choice of network investments in the London Underground*. Master's thesis, University of Minnesota.

Greater London Council and Office for National Statistics. n.d. Historic Census Population.

Gutiérrez, J. 2001. Location, Economic Potential and Daily Accessibility: An Analysis of the Accessibility Impact of the High-Speed Line Madrid–Barcelona–French border. *Journal of Transport Geography*, 9(4):229–242.

Gutiérrez, J. and P. Urbano. 1996. Accessibility in the European Union: the Impact of the Trans-European Road Network. *Journal of Transport Geography*, 4(1):15–25.

Hansen, W. 1959. How Accessibility Shapes Land Use. *Journal of the American Institute of Planners*, 25(2):73–76.

Huang, A. and D. Levinson. 2012. Accessibility, Network Structure, and Consumers' Destination Choice: A GIS Analysis of GPS Travel Data and the CLUSTER Simulation Module for Retail Location Choice.

Iacono, M., K. Krizek, and A. El-Geneidy. 2008. Access to Destinations: How Close is Close Enough? Estimating accurate distance decay functions for multiple modes and different purposes. Technical Report 2008-11, Minnesota Department of Transportation.

Iacono, M., K. J. Krizek, and A. El-Geneidy. 2010. Measuring non-motorized accessibility: issues, alternatives, and execution. *Journal of Transport Geography*, 18(1):133–140.

Ingram, D. R. 1971. The Concept of Accessibility: A Search for an Operational Form. *Regional Studies*, 5(2):101–107.

Krizek, K. 2005. Perspectives on Accessibility and Travel. *Access to Destinations*, pp. 109–130.

Kwan, M.-P. 2000. Human Extensibility and Individual Hybrid-Accessibility in Space-Time: A Multi-Scale Representation Using GIS. In *Information, Place, and Cyberspace*, pp. 241–256. Springer.

Kwan, M.-P. and J. Weber. 2008. Scale and Accessibility: Implications for the Analysis of Land Use–Travel Interaction. *Applied Geography*, 28(2):110–123.

Levine, J., J. Grengs, and Q. Shen. 2012. Does Accessibility Require Density or Speed? *Journal of the American Planning Association*, 78(2):157–172. doi: 10.1080/01944363.2012.677119.

Levinson, D. 2008a. Density and dispersion: the co-development of land use and rail in london. *Journal of Economic Geography*, 8(1):55–77.

Levinson, D. 2008b. The orderliness hypothesis: The correlation of rail and housing development in london. *The Journal of Transport History*, 29(1):98–114.

Levinson, D. and R. Karamalaputi. 2003. Predicting the construction of new highway links. *Journal of Transportation and Statistics*, 6(2):81.

Levinson, D. and A. Kumar. 1995. Activity, travel, and the allocation of time. *Journal of the American Planning Association*, 61(4):458–470.

Levinson, D. and P. Parthasarathi. 2012. Using Twin Cities Destinations and their Accessibility as a Multimodal Planning Tool.

Levinson, D., F. Xie, and N. M. Oca. 2012. Forecasting and Evaluating Network Growth. *Networks and Spatial Economics*, 12(2):239–262.

Levinson, D. M. 1998. Accessibility and the Journey to Work. *Journal of Transport Geography*, 6(1):11–21.

Levinson, D. M. 1999. Space, money, life-stage, and the allocation of time. *Transportation*, 26(2):141–171.

Levinson, D. M. 2012. Network Structure and City Size. *PLoS ONE*, 7(1):e29721. doi: DOI10.1371/journal.pone.0029721.

Levinson, D. M. and K. J. Krizek. 2005. *Access to Destinations*. Elsevier.

Levinson, D. M. and Y. Wu. 2005. The rational locator reexamined: Are travel times still stable? *Transportation*, 32(2):187–202.

Liu, S. and X. Zhu. 2004. An Integrated GIS Approach to Accessibility Analysis. *Transactions in GIS*, 8(1):45–62.

Miller, H. J. 1991. Modelling Accessibility Using Space-Time Prism Concepts within Geographical Information Systems. *International Journal of Geographical Information System*, 5(3):287–301.

Miller, H. J. 1999. Measuring Space-Time Accessibility Benefits within Transportation Networks: Basic Theory and Computational Procedures. *Geographical Analysis*, 31(1):1–26.

Miller, H. J. 2005. Place-Based versus People-Based Accessibility.

Miller, H. J. and Y.-H. Wu. 2000. GIS Software for Measuring Space-Time Accessibility in Transportation Planning and Analysis. *GeoInformatica*, 4(2):141–159.

Nair, R., C. Coffey, F. Pinelli, and F. Calabrese. 2013. Large-scale transit schedule coordination based on journey planner requests. *Transportation Research Record: Journal of the Transportation Research Board*, 2351(1):65–75.

Novak, D. C. and J. L. Sullivan. 2013. A Link-Focused Methodology for Evaluating Accessibility to Emergency Services. *Decision Support Systems*.

Odlyzko, A. 2014a. The early british railway system, the Casson counterfactual, and the effectiveness of central planning. *Available at SSRN 2466811*.

Odlyzko, A. 2014b. The forgotten discovery of gravity models and the inefficiency of early railway networks. *Available at SSRN 2490241*.

Office for National Statistics. 1860-1900. Price Indices and Inflation. URL http://www.ons.gov.uk/ons/taxonomy/index.html?nscl=Price+Indices+and+Inflation.

Owen, A., P. Anderson, and D. Levinson. 2012. Relative Accessibility and the Choice of Modes. *Publication Pending*.

Pickrell, D. H. 1989. Urban rail transit projects: forecast versus actual ridership and costs. final report. Technical report.

Pirie, G. H. 1979. Measuring Accessibility: A Review and Proposal. *Environment and Planning A*, 11(3):299–312.

Public. 2013. Open Street Map - United Kingdom. URL http://www.openstreetmap.com/.

Roth, C., S. M. Kang, M. Batty, and M. Barthelemy. 2012. A Long-Time Limit for World Subway Networks. *Journal of The Royal Society Interface*, 9(75):2540–2550.

Southworth, M. and E. Ben-Joseph. 2003. *Streets and the Shaping of Towns and Cities*. Island Press.

Ulmer, J. 2003. *Evaluating the Accessibility of Residential Areas for Bicycling and Walking using GIS*. Ph.D. thesis, University of Virginia.

Vickerman, R., K. Spiekermann, and M. Wegener. 1999. Accessibility and Economic Development in Europe. *Regional Studies*, 33(1):1–15.

Wu, Y.-H. and H. J. Miller. 2001. Computational Tools for Measuring Space-Time Accessibility within Dynamic Flow Transportation Networks. *Journal of Transportation and Statistics*, 4(2/3):1–14.

Xie, F. and D. M. Levinson. 2011. *Evolving Transportation Networks*, volume 1. Springer.

Zahavi, Y. and A. Talvitie. 1980. Regularities in travel time and money expenditures. *Transportation Research Record: Journal of the Transportation Research Board*, (750).