

The Busiest Railway in the United Kingdom: A Case Study Analysis of London's Elizabeth Line

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Abstract and Keywords

The London Elizabeth Line project was officially completed on May 26th, 2023, after opening in a series of phases that started in 2017. Announced in 2007, with construction beginning in 2009, the project included the construction of a 21 km long tunnel below the City of London, which connected to existing mainline railways. While it was only recently completed, the project dates back to proposals from the 20th century. The Crossrail project also includes upgrading adjacent railway lines to Reading and Heathrow in the west and Shenfield and Abbey Wood in the east. The project aims to provide further transit capacity for the routes into London, hoping to relieve the pressure from overcrowded transit links. Furthermore, the project seeks to help London achieve its sustainability goals within its design and development. Nevertheless, the project has had many setbacks that have delayed its completion and prevented it from reaching its full potential. In a joint effort between the UK Department for Transport and Transport for London, 14.8 billion pounds of funding were raised from the mayor of London, the UK Government, Network Rail, Transit Fares, and further economic beneficiaries like Heathrow Airport. The cost-benefit-analysis showed that the project is economically viable and adds value to the population with the benefit-cost-ratio standing at 1.1. Furthermore, this report includes risk and sensitivity analyses. The Monte Carlo simulations showed a 100% chance that the Net Present Value (NPV) is positive. Sensitivity analysis identified consumer surplus and the discount rate as critical factors influencing financial success.

Keywords: Crossrail, Elizabeth Line, Transport for London, Cost-Benefit-Analysis

1. Introduction

The Elizabeth Line is a transformative transportation infrastructure development project in London that seeks to relieve congestion and prepare the network for future growth. From its ambitious goals to its enormous construction scale, the Elizabeth Line is like no other recent undertaking in London. Already earning the status of the busiest rail line in England, the line represents a significant technological advancement. The line increases connectivity across the city, as reflected in its other name, the Crossrail. First conceived in the early 20th century, completing the line proved an engineering and political challenge. The project experienced numerous delays and repeated budget overruns. However, it promises to expand London's transport network and contribute sustainably to the broader UK economy.

2. Project Description

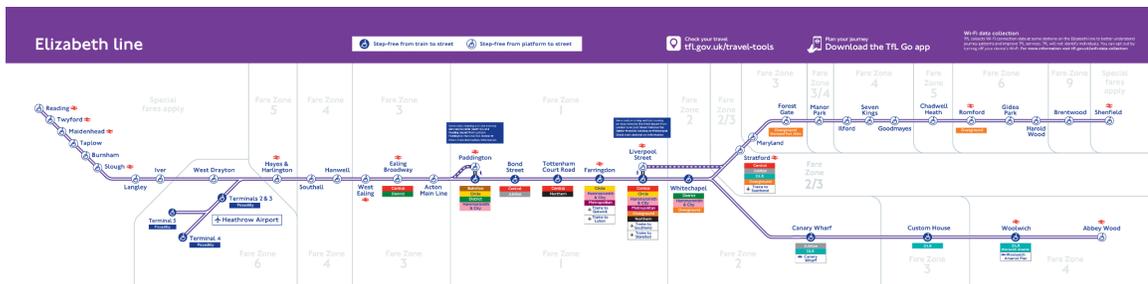
2.1. Background

Before Crossrail, London's rail and street links were struggling with congestion. In the late 1900s, as future population prognosis indicated further city growth, it was clear to city authorities that transport links had to be made futureproof. As seen in continental European cities like Munich or Paris, a new commuter rail system with a trunk tunnel under the city was one of the measures mentioned in the 1989 Central London Rail study to meet the ever-increasing demand for transportation in London (The Department of Transport et al. 1989). The idea was to address these challenges by constructing a new east-west connecting tunnel under the city center, linking up and improving the rail capacity of existing adjacent transport links (ibid.).

The origins of Crossrail can be traced back to the early 1900s when the first concepts for a cross-city railway were proposed (Crossrail, 2020, p. 1). However, it took until the 21st century for momentum to act on the proposals and turn this idea into reality. After extensive feasibility studies and public consultations, the UK government formally approved the Crossrail Act in 2008 (The National Archives, 2024).

Despite its sheer size and the following complexities and funding obstacles, the Crossrail project managed to persist because of its expected long-term benefits and the already noticeable pressure on existing infrastructure. The new Elizabeth Line addresses immediate transport needs and anticipates future population growth and urban development. As a critical component of London's evolving infrastructure, the Elizabeth Line represents a strategic investment in the city's sustainability, connectivity, and economic prosperity (Institution of Civil Engineers, 2022).

The Elizabeth Line represents the latest addition to London's historic transit infrastructure, which has served the city since the 1800s. Transport for London (TfL) operates this extensive network, including over 900 trains, 8,700 buses, 580 kilometers of highways, and 760 kilometers of rail (TfL Quarterly Performance Reports, 2024). With a budget exceeding nine billion pounds and revenues in the four billion, TfL is a significant organization.



Transport for London's Elizabeth Line (TfL Elizabeth Line, 2024) (Figure 1)

2.2. Goals and Alternative

As a public transport project, the London Crossrail delivers a sustainable goal by relieving overcrowding in existing underground and train services, adding 10% extra rail capacity for London, and decreasing trip times across London (Silva et al., 2015). It provides ten new stations, 42 km of new tunnels, further works on surface railways, and associated depots and maintenance facilities (Crossrail, 2020, p. 3).

Regarding economics, the goal of building the Elizabeth Line in London is to enhance rail capacity in central London by 10%, thereby alleviating congestion on existing rail and Tube lines. Additionally, it aims to extend the reach of London's key business districts, including the West End, City, and Docklands, to approximately 1.5 million more people within a 45-minute commute (Pollalis et al., 2019). Most notably, it will directly connect Heathrow Airport with the commercial heart of London on Oxford Street and the business hubs of the City of London and Canary Wharf. The Elizabeth line reduces journey times for the estimated 200 million annual users by improving connections and boosting capacity (Pollalis et al., 2019). For instance, the commute from Heathrow to the West End will be shortened to approximately 30 minutes compared to the current 50-minute journey (Warren et al., 2022). Moreover, the Elizabeth Line is expected to stimulate economic growth by supporting regeneration efforts across the capital, facilitating job accessibility, creating new transport links, and fostering significant new developments around its stations. It is projected to contribute an estimated £42 billion to the UK economy, leaving a lasting economic legacy.

Before the Elizabeth Line, there were (and are still) multiple alternatives from Reading and Heathrow in the west to Shenfield and Abbey Wood in the east. These alternative transportation routes include a combination of different London rail lines, bus routes, and car-share modes. It is worth noting that the Elizabeth Line's primary objective is to relieve overcrowded transit links. Thus, its primary goal is not to extend the transit line to unserved areas but to increase the capacity and efficiency of the system as a whole. In examining the alternative routes, the best approach is to look at four nodes that the Elizabeth Line connected to London's city center, which was a primary justification for the project's creation. As Mclaughlin notes, the new line puts "an additional 1.5 million people within 45 minutes of the heart of the capital" (Mclaughlin, 2022).

Using Liverpool Street Station as a marker for London city center, both according to map view, transit maps, and public perception, the routes of interest are therefore 1) Reading to Liverpool Street, 2) Heathrow to Liverpool Street, 3) Abbey Wood to Liverpool Street, and 4) Shenfield to Liverpool Street. Gathered from Google Maps data and the Transport for London, table 1 below highlights possible alternative routes between these destinations. Studying the multiple routes reinforces that the Elizabeth Line's main objective was to provide additional capacity and efficiency. Not only does the Elizabeth Line provide the quickest mode of travel options compared to public transportation alternatives, but in most cases, it also enables a quicker mode of transportation than travel by automobile would. However, it is worth noting that the Elizabeth Line only operates between 4:30 and 00:30 (Transport for London). During late night hours, travelers must still rely on other routes. For much of the day, however, the Elizabeth Line

significantly enhances the efficiency and capacity of London's transit system by offering faster and more convenient route options for traversing the London area from east to west. Moreover, recognizing that these alternative routes remain available 24/7, the Elizabeth Line provides the best time value of money mode of public transit and almost all transit options.

Routes	Time by Elizabeth Line	Time (by Car) to Liverpool Street	Alternative Routes Include
Reading Rail Station	~ 69 minutes	~ 70 minutes	Great Western Railway to 205 Great Western Railway to Circle Line Great Western Railway to Central Line
Heathrow Airport	~ 42 minutes	~ 50 minutes	N9 to N26 285 to 105 to N207 to (N242 or N8) N9 to Circle Line N30 to N11 to Circle Line Piccadilly Line to Central Line Piccadilly Line to Hammersmith & City Line
Abbey Wood Railway Station	~ 23 minutes	~ 35 minutes	N1 to 47/ 35/ 76 472 to N53 to 21 Southeastern to Central Line Thameslink to 35/ 149
Shenfield Railway Station	~ 50 minutes	~ 50 minutes	Greater Anglia Greater Anglia to Central Line Greater Anglia to N8/ 388/ (N86 and N205)

Elizabeth Line Alternative Route Guide (Table 1)

2.3. Modeling and Assumptions

The Cost-Benefit Analysis (CBA) of transport projects is commonly conducted using a few measurement rules obtained from changes in prices and quantities of the derived demand for transport (Rus et al., 2022). The CBA provides a systematic approach to quantify and compare the benefits and costs of different transport projects, allowing decision-makers to make informed choices based on their potential socio-economic impacts. In the London Crossrail Project's model, we run some measurement rules, including demand analysis, financial analysis, economic analysis, and risk assessment. The project also calculates Economic Net Present Value (ENPV) and Financial Net Present Value (FNOV) to determine the economic performance indicators to express monetary costs and benefits over a time period. Furthermore, we also derive other externalities, such as environmental and social benefits, to comprehensively evaluate the project's overall impact. These externalities help assess the project's sustainability and contribution to the Londoners.

Making assumptions is necessary to overcome uncertainty in data projects. In the Crossrail Project, the assumption is related to the implementation period, growth factor, discount rate, and supply and demand elasticity. However, the assumption in CBA could lead to bias or error in analysis. Therefore, to adjust our assumption, we perform a sensitive analysis. Sensitivity analysis provides information about how changes in different variables will affect the overall costs and benefits of the proposed regulation. It shows how sensitive predicted net benefits are to different values of uncertain variables and changes in assumptions (oia.pmc.gov.au)

There is no standard approach to modeling and assumption in cost-benefit analysis. Each county has guidelines and methodologies for conducting CBAs for transport projects but must follow similar principles. The extended Cost-Benefit Analysis model focuses on welfare impacts and needs to consider a wide range of factors beyond direct costs and benefits. It also begins to focus on how transport changes change the accessibility of places and perhaps also the perception of that accessibility or connectivity to the rest of the economy (Vickerman, 2017). Overall, the use of different sources and methodologies in cost-benefit analysis allows decision-makers to understand better and compare the potential socio-economic impacts of different transport

Expanding the evaluation of transport projects beyond traditional Cost-Benefit Analysis (CBA) models could also involve incorporating various tools and methodologies to comprehensively understand a project's impacts, feasibility, and benefits. This broader approach includes spatial analysis through maps, Geographic Information Systems (GIS), and three-dimensional (3D) modeling technologies. These tools complement the CBA by providing visual and spatial insights that can enhance decision-making and stakeholder engagement. They allow for a more holistic assessment of a project's potential impacts on land use, environment, accessibility, and socio-economic factors. Through integrating spatial analysis and 3D modeling, decision-makers can consider non-market elements and non-quantifiable benefits that may be important for evaluating a transport project's social equity and sustainability.

3. *Financial Analysis*

The financial analysis involves multiple components, including a cost-benefit analysis, risk analysis, assessment of traffic patterns, revenue and ridership analysis, and sensitivity analysis. Combined, they paint a portrait of an immensely important and beneficial addition to London's transit system.

3.1. Cost–Benefit Analysis

The cost-benefit analysis of the project's ongoing costs and revenues over the project's lifecycle, itemizing assumptions and quantifying the implications of anticipated changes in travel patterns. Because the Elizabeth Line is relatively new, many project costs were based on assumptions calculated from Transport for London, Standisierte Bewertung data, and other sources dating back to 2016. These assumptions are critical to the analysis and seek to reflect the direct and indirect effects of the project. Although based on the best available and most recent data, these projections are still uncertain. Given that the project has a lifespan of at least 120 years, today's NPV's 50-year projections should not be expected to be final. As more actual data becomes available in the years ahead, the accuracy of the cost-benefit analysis should improve as it is reworked to reflect world conditions (Lappas, 2019, p. 2). Indeed, even one full year of real-world data would significantly reduce uncertainty.

Although planning and construction of the Elizabeth Line has been in the works for years, recent events have dramatically, and probably temporarily, reshaped the transit landscape. Specifically, the COVID-19 pandemic, which emerged in March 2020, still affects transit patterns and

ridership. As is well known, the pandemic caused an unprecedented shift in travel patterns, including reduced ridership, higher costs, and a potentially permanent shift in demand patterns. Its effects and their long-term implications are still unfolding. Understanding these effects, notably reduced ridership and the impact on revenue, is critical for analyzing the Elizabeth Line.

It is worth recalling that the line was still under construction during COVID and was not fully operational, only after the pandemic eased. Considering this is important when conducting the cost-benefit analysis as it affects the base year we use to compare to the 2022/23 data. There were two main options we could choose from (1) use the 2016/17 data (when the phased opening began) or (2) use the 2021/22 data (the year before the Elizabeth line fully opened, but also heavily affected by the lingering COVID-19 effects).

To make this decision, we examined quarterly (Q1, Q2, Q3, Q4) ridership and revenue data back to 2015/16, which, unlike 2020/21 data, displayed the like-growth ratios between each quarter (TFL Quarterly Performance Reports, 2024). The average growth ratios between periods are Q1:Q2 = 0.99, Q2:Q3 = 1.13, and Q3:Q4 = 1.19, see Table 2 (TFL Quarterly Performance Reports, 2024). Note, for 2021/22, there is growth from Q1:Q2 as the pandemic eased and ridership began to return to pre-pandemic patterns. Given this, comparing 2022/23 data to 2021/22 is justifiable because it uses the most recent data, and the financial conditions mirror the pre-pandemic patterns. However, it is essential to recognize that the data is skewed by the absence of 2020/21 data and the long-term impact of the pandemic when compared to pre-pandemic activity.

Year	Quarter 1 Ridership (Million)	Quarter 2 Ridership (Million)	Ridership Growth Rates (Q2/Q1)	Quarter 2 Ridership (Million)	Quarter 3 Ridership (Million)	Ridership Growth Rates (Q3/Q2)	Quarter 3 Ridership (Million)	Quarter 4 Ridership (Million)	Ridership Growth Rates (Q4/Q3)
2022/23	717	714	0.9958158996	714	821	1.14985994	821	1,001	1.219244823
2021/22	482	533	1.105809129	533	674	1.26454034	674	794	1.178041543
2020/21	-----	-----	-----	-----	-----	-----	-----	-----	-----
2019/20	907	889	0.980154355	889	969	1.08998875	969	1,075	1.109391125
2018/19	922	888	0.9631236443	888	978	1.10135135	978	1,211	1.238241309
2017/18	938	903	0.9626865672	903	982	1.08748616	982	1,186	1.207739308
2016/17	966	903	0.9347826087	903	985	1.09080842	985	1,198	1.216243655
The Average			0.9903953672			1.13067249			1.19481696

Travel for London’s Quarterly Ridership Data (Table 2)

The financial findings in Table 3, presented below, show the cost-benefit analysis results. The table presents both direct data and statistical metrics. The financial inputs and outputs are detailed in the following section. Each financial input is quantified using a specific unit and converted to pounds per year based on a valuation factor. This enables a summary output reflected in monetary values reflecting the costs and benefits. This data is also used in the net present value, risk, and sensitivity analyses.

Items	Output	Unit
Consumer Surplus	£1,610,892,569.16	pounds/y
PT Revenue	£221,000,000.00	pounds/y
Operating Costs	-£200,000,000.00	pounds/y
Emissions	£75,933,333.33	pounds/y
Wear/Tear PT	-£1,259,309.59	pounds/y
PT Safety	-£3,978,481.78	pounds/y
Wear/Tear Car	£5,600.00	pounds/y
Car safety	£10,115.00	pounds/y
Sum	£1,702,603,826.13	pounds/y

Elizabeth Line’s Financial Findings (Table 3)

- Consumer Surplus:* Consumer surplus captures what consumers are *willing* to pay for a service. A change in consumer surplus is derived from the variation in consumer benefit that comes with a market shift. The introduction of the Elizabeth line would have produced such a change in consumer surplus. The data used to calculate the change in consumer surplus is sourced from 2021/22 and 2022/23 Office of Rail and Road estimates of station usage, the Greater London Authority's Executive fair price summary for 2021/22 and 2022/23, the Travel for London 2023 focus report, and the Travel for London’s Value of Time (Office of Rail and Road, 2023) (The Greater London Authority, 2023) (Transport for London, 2023) (TFL Value of Time, 2024). Key data features include stations' yearly ridership, associated stations' ranks, travel time savings (in minutes to the center), value of time, and train fare. The assumption of only using travel times to the city's center is because the center is not only the urban hub of the city but also provides a benchmark for consistency and simplicity. London’s yearly ridership data was used to estimate travel time savings in 2023 and time value. The value of time was calculated to be 0.2056666667 pounds per minute, which allowed us to estimate the monetary value of the change in travel time in 2022/23 (TFL Value of Time, 2024). In addition, ridership data were normalized against an index of 100. Value normalization was completed using Travel for London's report data to find travel time savings in 2023. This was used to calculate each station's associated value from travel time savings. The stations’ consumer surplus was calculated using yearly ridership data, the value of travel time savings, the absolute value of price fare changes multiplied by the increase in consumer revenue (25%), and the number of workdays per year 222 (Zelt, 2023). The value of time translated time savings into a monetary value on a per-minute basis. The final step was to sum up all of Elizabeth's stations' consumer surplus into a total consumer surplus value for the new metro line. Because a reduction in travel times increases consumer benefits, the sign of these figures is reversed. The data thus shows a net increase in consumer surplus of GBP -1,610,892,569. The consumer surplus calculations can be seen in Table 4 below.

Stations	Yearly Ridership (2022/23)	Travel Time Savings [min]	Value of Time [pounds/minute]	Valued Change in Travel Time Savings 2022/23	Train Fare 2021/22	Train Fare 2022/23	Absolute Change	Valued Change in Fare	Consumer Surplus
Abbey Wood 1	7118664	29	0.2056666667	2.982166667	4.00	4.40	-0.40	-0.1	-471284743.3
Woolwich 2	8339576	22	0.2056666667	2.262333333	4.00	4.40	-0.40	-0.1	-418845197.1
Custom House 3	5,272,498	15	0.2056666667	1.5425	3.40	3.70	-0.30	-0.075	-135411588.9
Canary Wharf 4	9,924,606	9	0.2056666667	0.9255	3.00	3.40	-0.40	-0.1	-203911947.3
Whitechapel 5	23,307,210	10	0.2056666667	1.028333333	3.00	3.40	-0.40	-0.1	-532080297.1
Liverpool Street 6	80,448,194	0	0.2056666667	0	2.40	2.80	-0.40	-0.1	0
Manor Park Rail Station 36	3,719,684	7	0.2056666667	0.7198333333	3.4	3.7	-0.30	-0.075	-44581249.67
Forest Gate Rail Station 37	4,883,572	6	0.2056666667	0.617	3.4	3.7	-0.30	-0.075	-50169179.33
Maryland Rail Station 38	2,788,146	6	0.2056666667	0.617	3.4	3.7	-0.30	-0.075	-28642763.27
Stratford (London) Rail Station 39	44,136,784	0	0.2056666667	0	3	3.4	-0.40	-0.1	0
The Sum								1.025	-1610892569

Elizabeth Line Stations Ridership, Fare, and Consumer Surplus Assessment (Table 4)

- Public Transit Revenue:* Public transit revenue refers to the income the public transportation system generates. In the analyses, the public transit revenue is primarily calculated using the fares passengers pay. However, it is worth noting that the transit system generates other sources of income. Data gathered from Travel for London Quarterly Performance Reports shows that in 2021/22 and 2022/23, Elizabeth line revenue changed from 93 million pounds to 314 million pounds (TFL Quarterly Performance Reports, 2024). Combined with the Travel for London financial findings, the change in public transit revenue contributed to the Elizabeth Line is calculated to be GBP 221,000,000.
- Operating Costs:* Operating costs are defined as expenses for which an organization incurs costs from ongoing business activities. For the transportation industry, this refers to the business of running the transportation system. For the Elizabeth Line, the operating costs reported by Travel for London were 200,000,000 pounds per year (TFL Elizabeth Line, 2024).
- Emissions:* Emission costs are another factor conceded when conducting an economic valuation of public transportation projects. Data gathered from Crossrail’s Information for Developers and Crossrail’s Energy Efficiency and Carbon provides inputs for the emissions cost analysis. These expenses include carbon dioxide emissions during the construction of -14,166 tons of CO₂ per year and annual benefits from lower emissions due to a reduction in car travel of 147,500 CO₂ (Crossrail, 2019) (Crossrail, 2023). Using the Standisierten Bewertung methodology, an economic value of emissions was calculated at GBP -569 per ton of CO₂, or GBP 75,933,333 per year (Intrapan Consult GmbH, 2023). (Standisierte Bewertung is Germany’s national cost-benefit-analyst schema methodology for transit projects). This analysis used the Elizabeth Line timetable from Travel for London to project the cost.
- Wear and Tear Public Transit:* Wear and tear public transit cost refers to the deterioration of public transit infrastructure over time due to use. According to Travel for London, the line accounted for 369,863 daily trips. Using Andersson’s data on wear and tear per person per kilometer, converted to monetary terms, we found maintenance cost per average person per kilometer to be -3.4048 (TFL Quarterly Performance Reports, 2024)

(Andersson, 2009, p. 12). The total annual wear and tear cost per pound was calculated at GBP 1,259,309.

- *Public Transit Safety:* This entails assigning a monetary value to the safety of the transportation system. Calculated based on vehicle kilometers per year and using the Standisierten Bewertung methodology and the Elizabeth Line timetable, a public transit safety monetary value was calculated to be GBP 3,978,481 per year (Intraplan Consult GmbH, 2023) (TFL Elizabeth Line, 2024).
- *Wear and Tear Car:* Like the wear and tear cost for public transit, the wear and tear cost for cars is associated with the degradation and maintenance of vehicles due to use. Calculating the wear and tear cost for the car as a positive value is essential, as the Elizabeth line increases public transit use and decreases the car as a transit mode. Using the Elizabeth Line Committee's insight on estimated additional journeys of 140,000, paired with Winkelmolens research on vehicle expenses (Winkelmolens, 2023). The total wear and tear cost for a car is calculated to be 5,600 pounds per year. Note that the car reduction value is a positive for the new public transportation link, as the Elizabeth line is taking people from private vehicles to public transit journeys.
- *Car Safety:* As above, the car safety metric seeks to assign a monetary value to the safety of travel by automobile. Because the Elizabeth Line reduces car travel, it has reduced the economic costs of auto accidents. Using the estimated net reduction of 140,000 car trips and coupling this figure with Standisierten Bewertung methodology, the total economic impact of car-related casualties is calculated to be GBP 10,115 per year (Elizabeth Line Committee, 2023) (Intraplan Consult GmbH, 2023).
- *Data Not Presented in Table:* Data not included in the financial findings but critical to the net present value analysis includes initial investment and project lifespan. The project investment, up to the year 2022, was approximately -18,700,000,000 pounds. Furthermore, the expected lifespan of the project is 120 years (Mayor of London Office, 2023, p. 4) (Lappas, 2019, p. 2).

The various financial entries related to the cost-benefit analysis evaluation add a total positive output per year of GBP 1,702,603,826. This value is the sum of all benefits and costs.

The cost-benefit analysis evaluation is used to calculate the net present value. The net present value plays a role in evaluating the project's attractiveness over time, considering both upfront investment and annual benefits. As seen in Table four, the calculator for net present value analysis identifies the investment's total net present value, benefit-cost ratio, and break-even year. The project's initial investment and discount rates were identified using data from the Mayor of London Office, Lappas, and Transport for London's financial statements. For project year 0 (2022), the initial investment is set at GBP 18,700,000,000. The NPV time frame is set at 50 years, the norm for evaluating transportation investments (Mayor of London Office, 2023, p. 4) To find the approximate discount rates, we calculated the average rate between 2014 to 2020,

using data provided by Transport for London's financial statements. This was calculated to be 3.585% (Transport for London Annual Reports, 2024). For 2022, 2023, and 2024, the discount rates were stated in Transport for London's financial statements. Note that the discount rate discounts future cash flows to their present value. Each year, the discounted annual net benefit of the project applies the discount rate to account for the time value of the money. For year 1, the discounted annual net benefit is derived from the cost-benefit analysis sum value of 1,702,603,826 pounds per year. Furthermore, the net present value provides the sum of net present value up to the corresponding year, thus indicating cash flow over a designated period. The identified total net present value is 20,636,278,474 pounds, indicating that the project will generate more value than its cost over the 50-year time horizon. Moreover, its break-even year is 2037, and its benefit-cost ratio is 1.103544303. Because this is greater than 1, it means that the project's benefits outweigh its cost, and its future break even year shows that the project will generate a benefit in the relatively short term. In short, the data in the net present value table demonstrates the Elizabeth line's long-term financial success and viability despite its high initial cost.

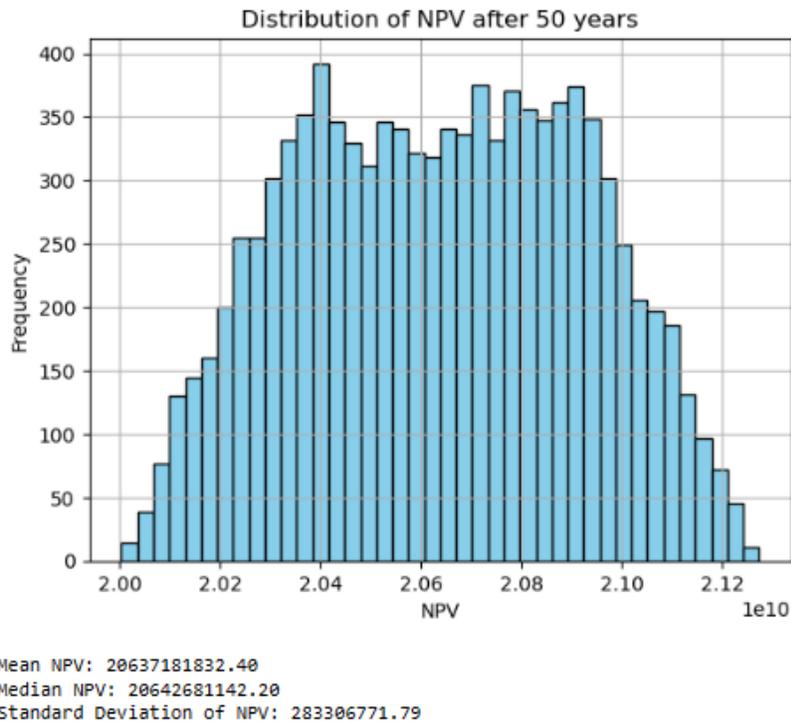
	Discounted Annual Net Benefit	Net Present Value	Discount Rate	Year
2022	-£18,700,000,000.00	-£18,700,000,000.00	3.20%	0
2023	£1,646,618,787.36	-£17,053,381,212.64	3.40%	1
2024	£1,589,398,890.18	-£15,463,982,322.47	3.50%	2
2025	£1,531,873,819.33	-£13,932,108,503.14	3.585%	3
2026	£1,478,856,802.94	-£12,453,251,700.20	3.585%	4
2027	£1,427,674,666.16	-£11,025,577,034.04	3.585%	5
2028	£1,378,263,905.16	-£9,647,313,128.87	3.585%	6
2029	£1,330,563,213.94	-£8,316,749,914.93	3.585%	7
2030	£1,284,513,408.25	-£7,032,236,506.68	3.585%	8
2031	£1,240,057,352.18	-£5,792,179,154.50	3.585%	9
2032	£1,197,139,887.22	-£4,595,039,267.28	3.585%	10
2033	£1,155,707,763.89	-£3,439,331,503.39	3.585%	11
2034	£1,115,709,575.60	-£2,323,621,927.79	3.585%	12
2035	£1,077,095,694.94	-£1,246,526,232.85	3.585%	13
2036	£1,039,818,212.04	-£206,708,020.82	3.585%	14
2037	£1,003,830,875.16	£797,122,854.35	3.585%	15
2038	£969,089,033.32	£1,766,211,887.66	3.585%	16
2039	£935,549,580.84	£2,701,761,468.51	3.585%	17
2040	£903,170,903.94	£3,604,932,372.44	3.585%	18
2041	£871,912,829.02	£4,476,845,201.46	3.585%	19
2042	£841,736,572.88	£5,318,581,774.34	3.585%	20
2063	£401,737,080.71	£17,591,928,836.16	3.585%	41
2064	£387,833,258.40	£17,979,762,094.56	3.585%	42
2065	£374,410,637.06	£18,354,172,731.62	3.585%	43
2066	£361,452,562.69	£18,715,625,294.31	3.585%	44
2067	£348,942,957.66	£19,064,568,251.97	3.585%	45
2068	£336,866,300.77	£19,401,434,552.74	3.585%	46
2069	£325,207,608.03	£19,726,642,160.77	3.585%	47
2070	£313,952,413.99	£20,040,594,574.75	3.585%	48
2071	£303,086,753.86	£20,343,681,328.61	3.585%	49
2072	£292,597,146.17	£20,636,278,474.78	3.585%	50
Total Net Present Value		£20,636,278,474.78		
Benefit/Cost Ratio		1.103544303		
Break Even Year		2037		

Net Present Value Analysis for the Elizabeth Line (Table 5)

4. Economic Analysis

4.1. Risk Analysis

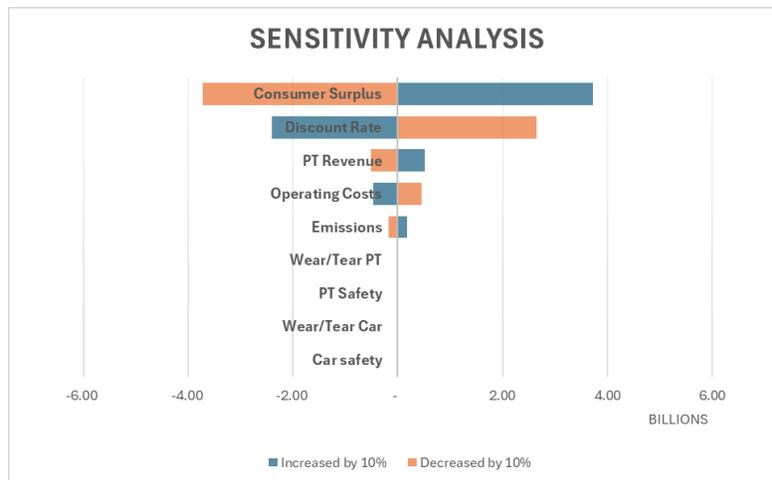
Monte Carlo analysis is a crucial tool in decision-making and risk assessment processes. It involves running multiple simulations with random inputs to analyze the range of possible outcomes. In our project, we employ Monte Carlo analysis to simulate various scenarios and assess the likelihood of achieving our desired outcomes. The histogram (See Figure 2) displays the results of a Monte Carlo analysis, particularly highlighting the distribution of Net Present Value (NPV) over 50 years. This analysis was conducted with 10,000 samples, indicating that 10,000 iterations of the NPV calculation were made using a random uniform distribution for input variables such as operating cost, emissions, and safety.



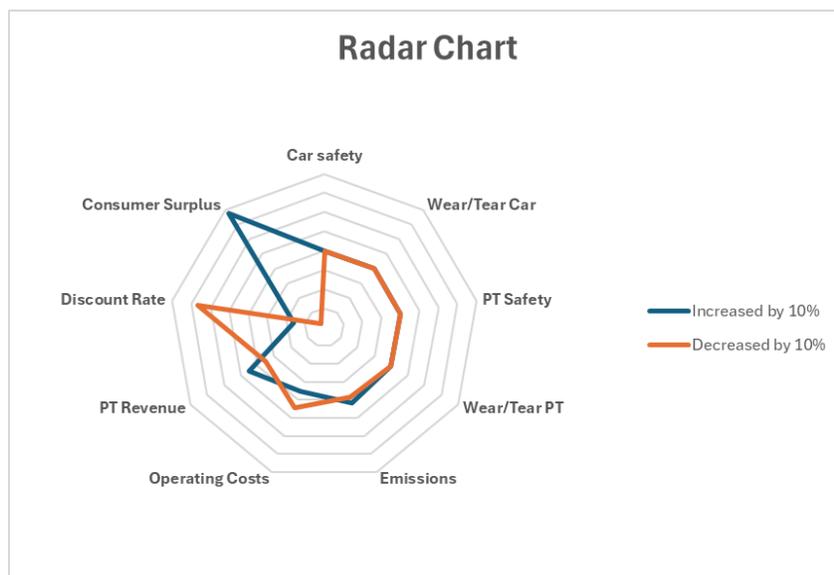
Distribution of NPV after 50 years (Figure 2)

Moreover, The histogram's risk analysis shows the simulated NPV spread across a range with a relatively uniform probability for each value within the range. Descriptive statistics of the simulated NPV values, including the mean and median, provide insights into the outcomes' central tendency and variability. The results for the Elizabeth Line project indicate a 100% probability of achieving a positive NPV, suggesting a high likelihood of financial success with a mean NPV of £2.06 billion and a median NPV of approximately £2.06 billion. The proximity of the mean and median values suggests that the NPV distribution is roughly symmetric.

Sensitivity analysis is another important tool used in decision-making and risk assessment processes. It helps us understand how changes in individual input variables can impact the output or outcome of our analysis. By conducting sensitivity analysis, we can identify the most influential variables in our model and prioritize them for further analysis or mitigation strategies. In the Elizabeth line project, we use +/- 10% change in key input variables such as consumer surplus, operating cost, PT revenue and discount rate to assess their impact on the project's Net Present Value. The reason for using +/- 10% change is to test the sensitivity of the NPV because A 10% change is considered to be a significant enough deviation to capture potential uncertainties or variations in the inputs. Moreover, The 10% change represents a reasonable range and simplicity for sensitivity analysis and allows us to observe the potential impact of plausible variations in the input variables and the result easier to interpret and communicate.



Sensitivity Analysis Result of One-at-a-Time-Method (Figure 3)



Sensitivity Analysis Result of One-at-a-Time-Method (Figure 4)

We can determine the most sensitive factors from the provided sensitivity analysis charts by looking at the extent of their impact when increased or decreased by 10%. For instance, in the Elizabeth Line project, sensitivity analysis revealed that changes in consumer surplus had the most significant impact on the NPV, followed by the discount rate, PT revenue, and operating costs. Other factors like emissions, wear and tear, and safety measures had a relatively smaller impact on the NPV. This result confirms that the financial success of the Elizabeth Line project heavily depends on consumer surplus, discount rate, PT revenue, and operating costs. Consumer surplus is a key profitability driver, directly affecting demand and revenue. On the other hand, the discount rate is crucial as it impacts the present value of future cash flows, making it an important factor in determining the project's profitability. Therefore, it is essential for decision-makers to accurately estimate and account for these factors in the project selection process.

5. Discussion

5.1. Policy Implications

In this paragraph, the Crossrail project will be analyzed in terms of its policy implications. Policy implications, in general, are the practical consequences and recommendations that result from implementing a specific project or policy. In the case study of the Elizabeth Line in London, the mentioned implications go beyond just the immediate infrastructure improvements. They include broader effects on urban development, sustainability, economic growth, and public welfare that should also be considered. Therefore, in the following chapter, the findings of the various analyses are to be discussed, and a comment on the recommendability of the project is to be made.

A significant factor in the evaluation of the Crossrail project is the cost-benefit analysis, which was presented in this paper. The analysis involved several monetized outputs, incorporating consumer surplus, public transit revenue, externalities (including emissions and safety costs), and a Net Present Value (NPV) assessment. Further temporal considerations, particularly the impact of the COVID-19 pandemic on travel patterns, were recognized during the execution. A sensitivity analysis assesses the influence of specific parameters in the analysis.

The NPV analysis indicates a positive financial return on investment over the project's 50-year lifespan, with a benefit-cost ratio greater than 1 and a break-even year in 2037. Risk analysis reveals a relatively low standard deviation, suggesting a lower level of financial risk. But what does this mean for policymakers and society?

First, the positive NPV and benefit-cost ratio suggest that the Crossrail project is economically viable over the long term and adds value to society. That is especially important considering the money spent comes from the taxpayers. The risk analysis further showed that the project is resilient. Decision-makers can interpret this as an indicator of the project's relatively stable economic outcomes. The sensitivity analysis further highlights the impact of consumer surplus benefits and public transit revenues on the project's success, as they significantly impact the NPV.

Decision-makers should pay attention to and monitor factors affecting fare revenues and fare prices to ensure the project's economic success. In addition to that, the sensitivity analysis has shown that the discount rate has a significant impact on the NPV. As transport planners usually do not control this, policymakers should keep this fact in mind when taking further action.

Including externalities, such as emissions and safety costs, into the CBA completes the holistic approach to analyzing the project's impact on society. In the era of global warming and the climate crisis, the environmental impact of the Elizabeth Line is of great importance. The carbon impact is high because the new railway features many tunnel tracks under the city of London. However, because many car trips are saved due to the Elizabeth line being the more attractive offer, many trips will be made using the more climate-friendly Crossrail. With the construction emissions distributed over the expected lifespan, the annual savings in emissions exceed the expenses. Further policies should encourage using the new rail system to reduce reliance on private vehicles and decrease air pollution and congestion.

Qualitatively speaking, the Elizabeth Line had and will have a significant impact on urban development in London. City planners can now use the increased connectivity provided by the new rail system to improve sustainable urban development around the line's stations. More areas can be developed using transit-oriented development (TOD), increasing housing density and numbers and encouraging mixed-use developments, including affordable housing and commercial spaces at highly connected points. This approach is familiar to London and aligns with best practices in other major cities like Tokyo and Singapore, where efficient transit systems drive urban development (Japan International Cooperation Agency, 2022, p. 4). As a measure of transport justice, accessibility is a significant indicator driving policy decisions. The new Elizabeth line connects diverse neighborhoods with different demographics, and policies should ensure that the new potential connectivity benefits are accessible to all socioeconomic groups. This includes affordable fare structures and measures to prevent gentrification that could displace existing communities.

To sum up, the Elizabeth Line is more than just a transportation project for London; it returns value to the urban population and can further catalyze urban transformation and economic growth. The CBA implies that Crossrail is a financially sound and strategically important project. Still, decision-makers should continue being incredibly attentive to revenue-related factors while prioritizing consumer satisfaction and considering the project's broader societal and environmental implications. By further addressing issues of accessibility, sustainability, economic development, and technology integration, policymakers can further improve the impact on society and receive the full benefits of the Elizabeth Line.

6. *Conclusion*

The Elizabeth Line represents a transformative transportation infrastructure development in London, England. According to TfL Quarterly Performance Reports, it successfully alleviated overcrowding in existing underground and train services by adding 10% extra rail capacity for London, meeting expectations (TfL Quarterly Performance Reports, 2024). Moreover, the project effectively reduced travel times across London, enhancing the efficiency and convenience of public transportation for over 200 million annual users (TfL Quarterly Performance Reports, 2024). The Elizabeth Line aimed to extend the reach of London's key business districts, including the West End, City, and Docklands, making them accessible to approximately 1.5 million more people within a 45-minute commute (Office of Rail and Road, 2023). However, since population growth is a long-term process, the final outcome is yet to be observed in the future. As designed, the Elizabeth Line operates between 4:30 and 00:30, offering faster and more convenient route options for traversing the London area from east to west (TfL Quarterly Performance Reports, 2024). Also, while recognizing the availability of alternative routes 24/7, the Elizabeth Line serves as a comprehensive transit solution for much of the day, providing the quickest and most efficient mode of travel compared to other public transportation alternatives and, in many cases, even private automobiles (Andersson, 2009, p. 12).

In the cost-benefit analysis, based on our assumptions, the break-even year of this project is estimated to be 2037, with a benefit-cost ratio of 1.1, indicating that the project's benefits outweigh its costs. The projected future break-even year suggests that even in the relatively short term, the project will be able to repay the investment and generate a positive return. As for economic benefits, the project is expected to contribute an estimated £42 billion to the UK economy, leaving a lasting economic legacy. Our analysis shows a net increase in consumer surplus of 1,610,892,569 pounds. However, without explicit mention of the expected achievement timeframe, underlying assumptions, and statistical rigor, it's challenging to evaluate whether the goal has been achieved accurately. The net present value table demonstrates the Elizabeth Line's long-term financial success and viability despite its high initial cost. According to the results of risk analysis, the level of risk associated with the project is relatively low. Overall, the Crossrail project is expected to be economically viable over the long term and add value to society.

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